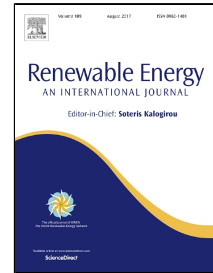


Accepted Manuscript

Development of groundnut shells and bagasse briquettes as sustainable fuel sources for domestic cooking applications in Uganda

Michael Lubwama, Vianney Andrew Yiga



PII: S0960-1481(17)30348-8
DOI: 10.1016/j.renene.2017.04.041
Reference: RENE 8736
To appear in: *Renewable Energy*
Received Date: 02 July 2016
Revised Date: 29 March 2017
Accepted Date: 19 April 2017

Please cite this article as: Michael Lubwama, Vianney Andrew Yiga, Development of groundnut shells and bagasse briquettes as sustainable fuel sources for domestic cooking applications in Uganda, *Renewable Energy* (2017), doi: 10.1016/j.renene.2017.04.041

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.

Highlights

- Groundnut shells and bagasse briquettes were developed with 30, 50, 70 and 90 grams of cassava and wheat binder
- Non-carbonized briquettes had higher drop strength at 99% than carbonized briquettes
- Non-carbonized briquettes had average HHV of 16MJ/kg
- The average heating values for carbonized groundnut shell and bagasse briquettes were between 21 and 23 MJ/kg

1 **1. Introduction**

2
3 Currently, biomass provides only about 15-20% of global energy needs. In developing nations
4 biomass provides 20-33% of total energy demand (Vargas-Moreno et al., 2012). In Uganda,
5 Firewood/charcoal accounts for over 90% of domestic fuel sources used for cooking (Uganda
6 Bureau of Statistics, 2014). Between 1990 and 2013, Uganda lost over 46% of its forest cover.
7 The current rate of deforestation stands at 1.8% per annum (Uganda Bureau of Statistics, 2014;
8 Uganda Bureau of Statistics, 2015). If the status quo continues, then Uganda is projected to
9 become a biomass deficient country by 2020. This will exacerbate the effects of climate change
10 due to the substantial reduction of CO₂ capture provided by forest cover (Kanabahita, 2001;
11 Okello et al., 2013a; Okello et al., 2013b). The smoke produced from using firewood/charcoal for
12 domestic cooking applications has negative health implications on women and children,
13 especially (Raymer, 2006; Rehfuess, 2006).

14
15 In addition, Uganda has one of the highest population growth rates (about 3%) in the world with a
16 current population of 34.9 million people (Uganda Bureau of Statistics, 2015). This implies that
17 more energy will be required for domestic cooking applications. Agriculture generates large
18 amount of by-products that could be used to produce energy and reduce on the amount of
19 fuelwood required to meet daily cooking needs, especially in developing countries (Government
20 of Uganda, 2007; Yank et al., 2016). By 2007, over 1.2 million tons of agricultural wastes were
21 generated annually in Uganda (Government of Uganda, 2007). By 2013, the documented amounts
22 of agricultural wastes had risen to over 19 million tonnes (Okello et al. 2013a). The disposal of
23 these wastes are very problematic as majority of them are burned in open fields which has
24 negative environmental impacts (Government of Uganda, 2007). Two common readily available
25 agricultural wastes in Uganda are groundnut shells and bagasse. Estimates of the total energy
26 potential available from the utilization of groundnut shells and bagasse agricultural residues in

1 Uganda are 5.38 and 0.38 PJ per year, respectively. This indicates that groundnut shells and
2 bagasse are potential energy resources in the development of bioenergy technologies in Uganda
3 (Okello et al., 2013a).

4

5 One sustainable way of utilizing this energy potential is the development of groundnut shell and
6 bagasse briquettes which will provide more energy per unit of volume (Ndindeng et al., 2015).
7 The development of groundnut shell and bagasse briquettes will reduce on the deforestation
8 taking place for wood/charcoal for domestic cooking applications as well as mitigate climatic
9 changes, environmental degradation and pollution (Okello et al., 2013b). Greenhouse gas
10 mitigation potential by utilizing briquettes from agricultural wastes is also gaining significant
11 interest in the literature (Thao et al., 2011). The fact that groundnut shells and bagasse agricultural
12 wastes form the main raw material for the briquettes implies that as long as consumption of
13 groundnuts and sugarcane continues, there will always be a sustainable resource of groundnut
14 shells and bagasse for the briquettes. Briquettes developed from groundnut shells and bagasse will
15 provide a low cost and simple, cleaner energy source for domestic cooking applications.

16

17 The technological process involved in briquetting is relatively well known (Bhattacharya et al.,
18 1989). However, the number of studies on briquettes developed from agricultural wastes are still
19 few given the different types and quantities of agricultural wastes generated worldwide (Amaya et
20 al., 2007; Blesa et al., 2001; Chen et al., 2009; Chin and Siddiqui, 2000; Chou et al., 2009a; Chou
21 et al., 2009b; Gangil, 2014; Haykiri-Acma et al., 2013; Hu et al., 2015; Kaliyan and Morey,
22 2009a; Kaliyan and Morey, 2009b; Kaliyan and Morey, 2010a; Kaliyan and Morey, 2010b; Kong
23 et al., 2012; Liu et al. 2013; Liu et al., 2014; Lu et al., 2014; Muazu and Stegemann, 2015; Musa,
24 2012; Mwampamba et al., 2013; Oladeji, 2012; Panwar, 2009; Singh et al. 2007; Srivastava et al.,
25 2014; Stelte et al., 2011; Stolarski et al., 2013; Tembe et al., 2014). It is also very important to
26 note that differences in hydrogeological conditions will most likely affect physical properties of

1 agricultural wastes from one geographical region to another, making it difficult to transfer
2 performance results from different geographical regions (Vassilev et al., 2010; Vassilev et al.,
3 2012; Vassilev et al., 2013). Very few studies have been undertaken and documented in the
4 literature regarding briquettes developed from agricultural wastes in Uganda despite the fact that
5 they are a potential energy resource.

6
7 Also, very few studies exist in the literature on the utilization of starch based organic binders in
8 the development of briquettes from agricultural wastes (Hu et al., 2015; Kaliyan and Morey,
9 2010b; Muazu and Stegemann, 2015; Rezanian et al., 2015; Rezanian et al., 2016; Razuan et al.,
10 2011; Sotande et al., 2010; Yank et al., 2016). In this study, cassava and wheat starch were used
11 as binder material because of their organic nature and availability. Wheat and cassava starch have
12 been shown to improve strength at low temperature due to the amylose content in them (Han et
13 al., 2014; Oladunmoye et al. 2014). Amylose content affects drop strength performance of
14 briquettes (Dureja et al., 2011; Goesaert et al., 2005; Oladunmoye et al. 2014; Zaidul et al. 2007).
15 The presence of Protein in both wheat (12.43%) and cassava (1.4%) starch enhances bonding due
16 to its ability to plasticize under application of heat. This generally results in an increase in
17 bonding and strength of the densified bio-char or briquettes (Dureja et al., 2011; Kaliyan and
18 Morey, 2009a; Mani et al., 2006; Oladunmoye et al., 2014; Rezvani et al., 2014; Serrano et al.,
19 2011). Therefore, in this study, groundnut and bagasse agricultural wastes were used to develop
20 briquettes with cassava and wheat starch as binders.

22 **2. Experimental**

24 **2.1. Briquette Development**

25 Groundnut shells and bagasse (from sugarcane) raw materials were sun dried for 6 - 8 hours. The
26 dried groundnut shells and bagasse were then fed into a carbonizer. The carbonizer was made

1 from a steel drum of 200 litre capacity with height and diameter of 1m and 0.5m, respectively.
2 These drums are locally available on the market which is very important for sustainability. The
3 carbonizer has openings of diameter 0.02m on its surface. These openings are used to regulate the
4 amount of air intake after ignition of agricultural waste at the top. A schematic of the carbonizer is
5 shown in Figure 1.

6
7 During the carbonization process, these holes were covered with mud/clay to limit the amount of
8 air available for complete combustion in the carbonizer. The top of the drum was covered. After
9 carbonization, bio-char was formed (Bazargan et al., 2014; Hu et al., 2015; Tsai et al., 2012). Bio-
10 char was then measured into 1000g portions which were mixed with 30, 50, 70 and 90g of wheat
11 flour and cassava flour starch binder. The starch binders were prepared by mixing 30, 50, 70 and
12 90g of wheat and cassava flour in water and boiling them in order to obtain a uniform starchy
13 binder (Rezania et al. 2016; Yank et al. 2016). These were each mixed with the biochar and
14 compressed at a pressure of ≤ 7 MPa using a briquetting machine. A longitudinal schematic of the
15 briquetting machine is shown in Figure 2. This pressure (≤ 7 MPa) is similar to the pressure used
16 by other researchers developing low cost briquettes (Barzargan et al., 2014; Furtado et al., 2010;
17 Husein et al., 2002). The briquetting machine consists of 12 compression moulds and a foot pedal
18 for lifting the moulds to meet an oncoming compressor arm as shown in Figure 2. The resulting
19 briquettes were black solids of dimensions 0.05m diameter and 0.05m height. Composite
20 briquettes were also developed using a combined mixture of groundnut shells bio-char (500g) and
21 bagasse (500g) bio-char with both cassava and wheat flour starch binder. Two sets of composite
22 briquettes were made. One set had 25g of cassava binder and 25g of wheat binder. The second set
23 had 35g of cassava binder and 35g of wheat binder. Process parameters used in the development
24 of the briquettes are shown in Table 1.

25

1 For high pressure briquette development, groundnut shells and bagasse raw materials were first
2 sun dried for 6-8 hours. Materials were dried to 10%-15% moisture content. They were then fed
3 into an automated feed section that transferred it to a hopper using a screw mechanism run by an
4 electric motor (see Figure 3) (Kaliyan and Morey, 2009b; Kaliyan and Morey, 2010a; Muazu and
5 Stegemann, 2015). From the hopper the raw materials move to a compression chamber where a
6 piston ram of 5.5 cm diameter and 40 cm length continuously densifies them. The piston gets
7 mechanical energy from rotary motion of wheels that are run by a motor at 1470 rpm. Due to
8 internal friction, the temperature of the raw material increased to about 200 °C - 250 °C. The die
9 temperature at this time was also between 280 °C - 290 °C. Compaction pressure of 230MPa was
10 maintained throughout the entire process. The formed briquette passed through a cooling
11 conveyor. High pressure was used to produce briquettes using groundnut shells (1000g) without a
12 binder, groundnut shells (1000g) with cassava binder (250g) and groundnut shells (1000g) with
13 wheat binder(250g). Development of bagasse briquettes using high pressure failed because of its
14 high moisture content (22.5%), dust-like nature and feathery structural morphology (Vassilev et
15 al., 2010).

16

17 **2.2. Thermogravimetric analysis (TGA) and bomb calorimetry.**

18 An Eltra Thermostep non-isothermal Thermogravimetric analyzer was used to determine physical
19 properties of the developed briquettes. The TGA was executed with a heating rate of 16°C min⁻¹
20 for dynamic runs (Chen et al., 2012; Munir et al., 2009). TGA was used to determine moisture
21 content, ash content, fixed carbon and volatiles in the developed briquettes. TGA analysis was
22 also used to represent the weight loss, first derivative and temperature evolution profiles versus
23 time for each of the groundnut shell and bagasse briquettes developed (Avelar et al., 2016; Gil et
24 al., 2010; Hu et al., 2015; Liu et al., 2014; Virmond et al. 2012). The higher heating values for the
25 groundnut shell and bagasse briquettes were determined using an IKA C 2000 oxygen bomb
26 calorimeter (Chen et al., 2012; Fernandez et al., 2014 ; Olupot et al., 2016; Rezanian et al., 2016).

1

2 **2.3. Mechanical Characterization**

3 The drop test was used to determine the integrity of the briquettes under impact. In order to
4 determine the drop strength, the briquettes were elevated up to 2m and then dropped onto a thick
5 steel plate. The ratio of weight after dropping to weight before dropping was recorded as the drop
6 strength. This is very important because it determines whether the briquettes will retain their form
7 during packaging, storage and transportation (Fengmin and Mingquan, 2011; Tumuluru, 2014).
8 Bulk density was determined from the ratio of the mass of material to the volume of a standard
9 cylinder. Particle density of the briquettes was determined from actual measurements of the mass,
10 diameter and length of the developed briquettes (Fernandez et al., 2013; Obernbergera and Thek,
11 2004; Srivastava et al., 2014).

12

13 **2.4. Thermal characterization**

14 The water boiling test was used to determine how long it would take 200g of briquettes to boil 0.5
15 liters of water in an improved stove (Chen et al., 2016; Tumutegyereize et al., 2016). The flame
16 after boiling the water was observed and the highest temperature of the briquettes at this point
17 was recorded using a DT-8865 non-contact infra red thermometer gun (Dual laser up to 1000 °C;
18 30:1 D/S ratio) for each category of groundnut shell and bagasse briquettes developed.

19

20 **3. Results and Discussion**

21

22 The resulting bio-char from the carbonization of bagasse and groundnut shells showed structural
23 characteristics very much in line with the structure of the pre-carbonized raw material as shown in
24 the Figure 4 (Chen et al., 2012; Mustelier et al., 2012; Vassilev et al., 2013). The bio-chars have
25 different morphologies, but the original textures and structures of the bagasse and groundnut
26 shells were maintained in the char particles. Bio-char from bagasse maintained its feathery dust-

1 like characteristics, whereas bio-char from groundnut shells maintained the integral structure of
2 the shell, however, their surface finish appeared much smoother and shinier (see Figure 4). This
3 may be due to the presence of unburned matter in coarse grain fractions of biomass ash (Fenandez
4 et al., 2012). A comparison of the surface morphology of the bagasse and groundnut shells shows
5 more structural damage for the bagasse, indicating possibly higher hemicellulose content in the
6 bagasse (Chen et al., 2012; Saidur et al., 2011).

7
8 The particle size of bagasse ($37.9\pm 21.9\text{mm}$) varied significantly (see Figure 4a) when compared
9 to the particle size for groundnut shells ($21.1\pm 4.6\text{mm}$) (see Figure 4b). This high variation in the
10 particle size of bagasse coupled together with its feathery loose particles resulted in its failure to
11 densify using high pressure. Samples of briquettes developed after carbonization using low
12 pressure and non-carbonized briquettes developed using high pressure are shown in Figure 5a and
13 Figure 5b respectively. The surface finish for the low pressure developed carbonized briquettes
14 were generally rough with loose particles visible on the circumference. The surface finish for the
15 high pressure developed non-carbonized briquettes were smooth and shiny and with no loose
16 particles visible on the circumferential area. This shiny glassy appearance is a characteristic of
17 solid bridge bonding in briquettes (Kaliyan and Morey, 2010a). Briquettes developed using high
18 pressure and temperatures develop solid bridge bonding mechanisms as a result of crystallization
19 of the raw material, chemical reactions between the cassava and wheat binder with the groundnut
20 shells and solidification of melted components during the cooling phase (Kaliyan and Morey,
21 2010a; Kong et al., 2012). The bonding in briquettes developed after carbonization is
22 characterized by short range forces such as hydrogen bridges and van der Waals' forces, which
23 are generally weak (Kaliyan and Morey, 2009a; Kaliyan and Morey, 2010a). The surface finish
24 observed also indicates that briquettes developed after carbonization of the raw material will have
25 lower drop strengths compared to briquettes developed using high pressure.

26

1 The TGA (Eltra Thermostep) is non-isothermal and as such during the first phase all of the
2 samples are dried at 105°C to ensure that the moisture content in the samples is acceptable before
3 dynamic runs with constant heating rate can begin. The TGA was executed with a heating rate of
4 16°C min⁻¹. Physical properties for groundnut shells raw material were: Fixed Carbon: 19.3%;
5 Volatile matter: 67.7%; Ash content: 3.8%; and, Moisture Content: 9.2%. Physical properties for
6 the bagasse raw material were: Fixed carbon: 12.2%; Volatile matter: 62.7; Ash content 2.5%;
7 and Moisture content 22.5%. TGA profile results for the combustion of bagasse and groundnut
8 shell raw material are shown in Figure 6. TGA results for carbonized groundnut shell briquettes
9 with cassava binder (a); carbonized groundnut shell briquettes with wheat binder (b); carbonized
10 bagasse briquettes with cassava binder (c); and carbonized bagasse briquettes with wheat binder
11 (d) for 30g of cassava and 30 g of wheat binder are shown in Figure 7. The slight decrease in
12 weight observed during the initial drying phase was due to moisture loss and molecular
13 degradation (Gil et al., 2010; Liu et al., 2014). After initial drying, additional mass loss occurs
14 during the dynamic runs at 16°Cmin⁻¹. During this period the drying phase changes to biomass
15 volatilization where volatile matter due to hemicellulose (190 °C – 320 °C), cellulose (280 °C – 400
16 °C) and lignin (320 °C – 450 °C) decomposition is released (Avelar, 2016; Chen et al., 2012;
17 Fernandez et al., 2012).

18
19 The results for the physical properties of the developed carbonized groundnut shells and
20 carbonized bagasse briquettes with cassava and wheat binder are shown from Figure 8 to Figure
21 12. For all of the briquettes developed from carbonized groundnut shells and carbonized bio-char,
22 the moisture content was considerably less than the moisture content in the raw material. These
23 results are similar to those obtained in previous studies where the combination of pyrolytic bio-
24 char and binders have been used (Hu et al., 2015; Muazu and Stegemann, 2015). The results
25 indicate that the combination of the carbonization process and the presence of cassava and wheat
26 binders had a positive effect on reducing moisture content. The carbonization process inhibites

1 moisture adsorption which is a very important result for increased shelf life and storage of the
2 briquettes by preventing rotting and decomposition (Fernandez et al., 2013; Liu et al., 2013). The
3 decrease in absorption of moisture by carbonized briquettes is due to the destruction of
4 hydrophilic groups, such as hydroxyl groups, in the carbonization process (Liu et al., 2013). As
5 evaporation is an endothermic process, moisture decreases the briquette fuel's useful energy
6 content. This negatively affects both the combustion efficiency and quality. High moisture
7 content inhibits ignition of the briquette and reduces combustion temperature. This in turn hinders
8 the combustion of the reaction products and consequently affects the quality of the combustion
9 process (Saenger et al., 2001; Werther et al., 2001). Additionally, high moisture levels require
10 larger equipment and present with more maintenance difficulties, thus increasing processing costs
11 (Fernandez et al., 2014; Mani et al., 2004).

12
13 The volatile matter results are shown in Figure 9. Generally, the briquettes developed with
14 carbonized bagasse with both cassava and wheat binders had volatile matter values that were
15 higher than for briquettes developed with carbonized groundnut shells. However, the volatile
16 results are much lower than the volatile matter in groundnut shell and bagasse raw material which
17 are over 60%. This result was expected due to the fact that in the process of carbonization, more
18 volatiles are expended from groundnut shells as compared to bagasse in the formation of bio-char.
19 High volatile matter eases ignition and enhances combustion due to increased chemical reactivity
20 (Fernandez et al., 2014; Mckendry, 2002; Vargas-Moreno et al., 2012; Werther et al., 2001).
21 Ideally for agricultural residues which typically have high percentages of volatiles, devolatilization
22 starts at low temperatures as soon as the fuel is exposed to a high temperature medium because of
23 the rapid consumption of oxygen. For the carbonized groundnut shell and bagasse briquettes, the
24 volatile combustion phase will be much shorter followed by a longer char combustion phase
25 (Werther et al., 2001).

26

1 As expected, an opposite trend was observed for the ash content results shown in Figure 10.
2 Briquettes developed from carbonized groundnut shells had higher ash content percentages than
3 briquettes developed from carbonized bagasse. This is attributed to the high ash content in the
4 groundnut shells compared to ash content in bagasse (Vassilev et al. 2010). Generally, ash content
5 increases with increase in cassava binder for carbonized groundnut shell and bagasse briquettes.
6 Also, bagasse briquettes made with wheat binder had higher ash content than bagasse briquettes
7 made with cassava binder. High ash content levels reduce heating value, increase thermal
8 resistance to heat transfer, and lead to generation of slag deposits which requires more equipment
9 maintenance (Fernandez et al., 2014; Mckendry, 2002, Vargas-Moreno et al., 2012).

10

11 The carbonization process employed in this study was responsible for the increased fixed carbon
12 percentages that were observed and shown in Figure 11 (Amaya et al., 2007). All of the
13 developed carbonized briquettes had fixed carbon percentages of over 45%. However, closer
14 inspection of the results suggest that briquettes developed from carbonized groundnut shells with
15 wheat binder had higher fixed carbon percentages irrespective of the grams of wheat binder used
16 in their development.

17

18 Physical properties for composite briquettes developed with 500g of both carbonized groundnut
19 shells and carbonized bagasse with 25g and 35g of both cassava and wheat binders are shown in
20 Figure 12. The results were generally in line with the results explained for Figure 7 to Figure 11.
21 The composite briquettes developed with 35g of both cassava and wheat binder had marginally
22 higher values for moisture content and volatile matter. The composite briquettes developed with
23 25g of both cassava and wheat binder had marginally higher values for ash content and fixed
24 carbon. The results indicate that development of the composite briquettes had limited influence on
25 their overall physical properties.

26

1 Physical properties of non-carbonized briquettes developed under high pressure for groundnut
2 shells without binder, with cassava binder and wheat binder are shown in Figure 13. In all cases,
3 the moisture content remains higher than for carbonized briquettes developed after carbonization
4 of the groundnuts shells and bagasse (see Figure 8). The volatile matter results are all over 70%
5 which is much higher than the volatile matter recorded for carbonized briquettes (see Figure 9).
6 The ash content and fixed carbon values are lower than for briquettes developed after
7 carbonization of the groundnuts shells and bagasse as expected (Liu et al., 2013) . The results
8 from Figure 13 suggest that the inclusion of cassava and wheat starch binders before high
9 pressure compaction has very little effect on the physical properties of the developed non-
10 carbonized briquettes.

11
12 The results for the higher heating values (HHV) for briquettes developed from carbonized
13 groundnut shells and bagasse with cassava and wheat binders are shown in Figure 14. The
14 average heating value for all of the carbonized briquettes was about 22.5 MJ/kg. Generally for
15 briquettes developed from carbonized bagasse, HHV was observed to decrease with an increase in
16 the amount of binder. The highest HHV of about 24 MJ/kg was measured for briquettes
17 developed from carbonized groundnut shells with 30g of cassava binder. The HHV for the non-
18 carbonized briquettes developed under high pressure were 16MJ/kg irrespective of the binder
19 amount and the presence or absence of binder. This results was expected because the presence of
20 cassava and wheat binder had no significance on the physical properties of these briquettes as
21 discussed in Figure 13. The developed carbonized composite briquettes had similar HHV values
22 of about 23 MJ/kg irrespective of the differences in amount of binder used.

23
24 The drop strength results for the carbonized briquettes are shown in Figure 15. Generally, an
25 increasing trend was observed in the drop strength results for both carbonized groundnut shell
26 and bagasse briquettes when cassava binder was used. For briquettes developed from carbonized

1 bagasse with wheat binder the drop strength initially increases as the binder present increases
2 until almost 100%. The results indicate a positive effect due to the presence of cassava and wheat
3 binder in the carbonized groundnut shells and carbonized bagasse briquettes. Higher values of
4 drop strength are indicative of the ability of the developed briquettes to be stored without
5 disintegrating (Fengmin & Mingquan, 2011). Cassava binder has lower amounts of phosphorus
6 compared to wheat (Zhu, 2015). Lower amounts of phosphorus are linked to increased amounts of
7 amylose which positively affects resistance to heat and shear force (Zaidul et al., 2007). Water
8 addition and heating results into the formation of intermolecular hydrogen bonds between the
9 amylose and amylopectin components of starch. This is followed by loss of crystallinity in the
10 structure of the two components which leads to the formation of a viscous solution that undergoes
11 retro-gradation. This results in briquettes attaining a higher strength at room temperature (Tako
12 and Hizukuri, 2002). The results in Figure 15 agree with this assertion for both carbonized
13 groundnut shell briquettes and carbonized bagasse briquettes with cassava and wheat binder. The
14 amount of phosphorus in groundnut shells is higher than that in bagasse (Vassilev et al., 2010).
15 This explains the consistently good performance of drop strength of carbonized groundnut shell
16 briquettes with cassava binder. In the carbonization process, 'natural binders' are softened as
17 temperatures increase which can enhance bonding of carbonized briquettes (Liu et al., 2013). The
18 bonding in briquettes developed after carbonization are characterized by short range forces such
19 as hydrogen bridges and van der Waals' forces, which are generally weak (Kaliyan and Morey,
20 2009a; Kaliyan and Morey, 2010b). Carbonized composite briquettes with 25g of cassava and
21 wheat binder had a lower drop strength of 70% compared to carbonized composite briquettes with
22 35g of cassava and wheat binder which had a drop strength of 85%. (see Figure 16). These results
23 indicate that a marginal increase in composite binder formulation had a positive impact on the
24 drop strength. This may be due to an increase in the total amount of proteins available in the
25 composite cassava and wheat binder which enhance platisization when heat is applied, and thus
26 increase bonding and strength (Kaliyan and Morey, 2009a). Non-carbonized briquettes developed

1 using high pressure had drop strengths of 99%. This implies that they can be stored and
2 transported very well without disintegration (Fengmin and Mingquan, 2011; Serrano et al., 2011).
3 Their high drop strengths are due to the formation of solid bridge type bonding due to the
4 application of high pressure (230 MPa) and generation of instantaneous temperature that enhance
5 crystallization between the binder and the groundnut shell raw material (Kaliyan and Morey,
6 2009a; Kaliyan and Morey, 2009b; Kaliyan and Morey, 2010a; Kaliyan and Morey, 2010b; Kong,
7 2012).

8
9 Bulk density for groundnut shells and bagasse were 258.8 kg/m^3 and 182.7 kg/m^3 , respectively.
10 The results of drop strength in Figure 15 and Figure 16 are validated by the results of particle
11 density for the briquettes shown in Figure 17. For briquettes developed after carbonization,
12 groundnut shells with cassava binder had the highest particle density irrespective of the binder
13 amount. This result corresponds very well with the result for drop strength in Figure 15. Highest
14 particle density was recorded for briquettes developed using high pressure.

15
16 The water boiling tests were conducted in an open air environment in order to obtain practical
17 results for the performance of the briquettes. This is very important because in sub-Saharan
18 Africa, domestic cooking is usually carried out in the open. The water boiling tests were
19 performed using an improved stove (Briketi). From Figure 18a), it can be observed that the
20 ignition of the briquettes and flame distribution around them is non-uniform. A typical aluminium
21 pan and covering used for domestic cooking application for boiling water is shown in Figure 18b.
22 The results for time taken to boil 0.5 litres of water using 200 g of developed briquettes are shown
23 in Figure 19. The results generally indicate that non-carbonized briquettes with binders required
24 the least amount of time (4-5 minutes) to boil 0.5 litres of water. The performance for non-
25 carbonized briquettes is expected due to the fact that they have a higher percentage of volatiles

1 present (see Figure 13). This is despite the fact that the heating value of the non-carbonized
2 briquettes is lower than that for the carbonized briquettes.

3
4 The highest flame temperature for the non-carbonized briquettes with cassava and wheat binders
5 were less than 800°C (see Figure 20). The binderless non-carbonized groundnut shell briquettes
6 attained a maximum temperature of about 630°C. The carbonized composite briquettes with 25g
7 of cassava and 25g of wheat binder attained a higher maximum flame temperature of 890°C than
8 that for composite briquettes developed with 35g cassava and 35g wheat binder. For carbonized
9 groundnut shells briquettes with wheat binder, the maximum flame temperature generally
10 increased with an increase in the amount of binder. For carbonized bagasse briquettes with wheat
11 binder, it was observed that the maximum flame temperature reduced with an increase in the
12 amount of binder. The results for the maximum attainable flame temperature correlated very well
13 with the HHV results for the developed briquettes.

14

15 **4. Conclusions**

16

17 In this study, groundnut shells and bagasse briquettes with cassava and wheat binder were
18 developed as sustainable fuel sources for domestic cooking applications. The briquettes were
19 developed using both low and high pressures. The low pressure briquettes were developed after
20 carbonization of the raw material in a limited air environment to form bio-char. The resulting bio-
21 char was mixed with 30, 50, 70 and 90 grams of cassava and wheat flour starch binder for each
22 1000g of groundnut shells and bagasse bio-char. Also, groundnut shell briquettes were produced
23 at 230 MPa. These high pressure developed briquettes were produced using groundnut shells
24 (1000g) without a binder, groundnut shells (1000g) with cassava flour starch binder (250g) and
25 groundnut shells with wheat flour starch binder(250g). Thermo-physical properties of the
26 briquettes were determined using thermo gravimetric analysis. A Bomb calorimeter was used to

1 determine the higher heating value of the briquettes. Thermal characteristics were determined by
2 observing the flame temperature during combustion. The mechanical integrity of the briquettes
3 were determined using the drop test method. The average higher heating values for carbonized
4 groundnut shell and carbonized bagasse briquettes developed using low pressure techniques were
5 between 21 and 23 MJ/kg when both wheat and cassava flour starch were used as binder
6 materials. The results were all above 16 MJ/kg, which were recorded for non-carbonised
7 groundnut shell briquettes developed using high pressure. The results indicate a positive effect
8 due to the presence of cassava and wheat binder in the carbonized groundnut shells and
9 carbonized bagasse briquettes with regards to drop strength. Non-carbonized briquettes developed
10 using high pressure had drop strengths of 99%. The maximum attainable flame temperatures were
11 generally in line with the higher heating values of the specific briquettes.

12

13 **Acknowledgement**

14

15 The authors would like to acknowledge the research grant provided by Sida from the College of
16 Engineering, Design, Art and Technology, Makerere University that facilitated the reseach work
17 presented in this paper.

18

19 **References**

20

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

23

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

26

- 1 Bazargan A, Rough SL, McKay G. Compaction of palm kernel shell biochars for application as
2 solid fuel. *Biomass and Bioenergy* 2014; 70: 489-497
3
- 4 Bhattacharya SC, Sett S, Shrestha RM. State of the art for Biomass Densification. *Energy Sources*
5 1989;11(3): 161-182
6
- 7 Blesa MJ, Fierro V, Miranda JL, Moliner R, Palacios JM. Effect of the pyrolysis process on the
8 physiochemical and mechanical properties of smokeless fuel briquettes. *Fuel Processing*
9 *Technology* 2001; 74(1): 1-17
10
- 11 Chen L, Xing L, Han L. Renewable energy from agro-residues in China: Solid biofuels and
12 biomass briquetting technology. *Renewable and Sustainable Energy Reviews* 2009; 13(9): 2689-
13 2695
14
- 15 Chen Y, Shen G, Su S, Du W, Huangfu Y, Liu G, Wang X, Xing B, Smith KR, Tao S.
16 Efficiencies and pollutant emissions from forced-draft biomass-pellet semi-gasifier stoves:
17 Comparison of International and Chinese water boiling test protocols. *Energy for Sustainable*
18 *Development*. 2016; 32: 22-30
19
- 20 Chen WH, Lu KM, Tsai CM. An experimental analysis on property and structural variations of
21 agricultural wastes undergoing torrefaction. *Applied Energy* 2012; 100: 318-325
22
- 23 Chin OC, Siddiqui KM. Characteristics of some biomass briquettes prepared under modest die
24 pressures. *Biomass and Bioenergy* 2000; 18(3) 223-228
25

- 1 Chou C, Lin S, Peng C, Lu W. The optimum conditions for preparing solid fuel briquette of rice
2 straw by a piston-mold process using the Taguchi Method. *Fuel Processing Technology* 2009;
3 90(7): 1041-1046
4
- 5 Chou C, Lin S, Peng C, Lu W. Preparation and characterization of solid biomass fuel made from
6 rice straw and rice bran. *Fuel Processing Technology* 2009; 90(7) 980-987
7
- 8 Dureja H, Khatak S, Khatak M, Kalra M. Amylose Rich Starch as an aqueous based
9 pharmaceutical coating Material - Review. *International Journal of Pharmaceutical Sciences and*
10 *Drug Research* 2011; 3(1) 8-12
11
- 12 Fengmin L, Mingquan Z. Technology Parameters of Biomass Briquetting of Macrophytes in
13 Nansi Lake, *Energy Procedia* 2011; 5: 2449-2454
14
- 15 Fernandez RG, Garcia CP, Lavin AG, Bueno de las Heras JL. Study of main combustion
16 characteristics for biomass fuels used in boilers, *Fuel Processing Technology* 2012; 103: 16-26
17
- 18 Fernandez RG, Garcia CP, Lavin AG, Bueno de las Heras J.L. Influence of physical properties of
19 solid biomass fuels on the design and cost of storage installations. *Waste Management* 2013;
20 33(5): 1151 – 1157
21
- 22 Fernandez RG, Garcia CP, Lavin AG, Bueno de las Heras JL. Spanish biofuels heating value
23 estimation. Part II: Proximate analysis data. *Fuel* 2014; 117: 1139-1147.
24
- 25 Furtado T.S, Valin M, Brand MA, Bellote AFJ. Briquetting process variables and quality of forest
26 biomass briquettes, *Brazilian Forestry Research*. 2010; 30: 101-106

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26

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

Goesaert H, Brijs K, Veraverbeke WS, Courtin CM, Gebruers K, Delcour JA. Wheat flour constituents: how they impact bread quality, and how to impact their functionality. *Trends in food Science & Technology* 2005; 16(1): 12-30

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 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

Husain Z, Zainac Z, Abdullah Z. Briquetting of palm fibre and shell from the processing of palm nuts to palm oil. *Biomass Bioenergy* 2002; 22(6): 505-509

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

- 1 Kaliyan N, Morey VR. Constitutive model for densification of corn stover and switch grass.
2 Biosystems Engineering 2009b; 104(1) 47-63
3
- 4 Kaliyan N, Morey VR. Natural binders and solid bridge type binding mechanisms in briquettes
5 and pellets made from corn stover and switch grass. Bioresource Technology 2010a; 101(3):
6 1082-1090.
7
- 8 Kaliyan N, Morey VR. Densification characteristics of corn cobs. Fuel Processing Technology
9 2010b; 91(5): 558-565
10
- 11 Kanabahita C. (2001) Forestry outlook studies in Africa (FOSA): Uganda. Forestry Department.
12 Ministry of Water, Lands and Environment. Government of Uganda.
13
- 14 Kong L, Tian S, He C, Du C, Tu Y, Xiong Y. Effect of waste wrapping paper fiber as a “solid
15 bridge” on physical characteristics of biomass pellets made from wood sawdust. Applied Energy
16 2012; 98: 33-39
17
- 18 Liu Z, Jiang Z, Cai Z, Fei B, Yu Y, Liu X. Effects of carbonization conditions on properties of
19 bamboo pellets. Renewable Energy 2013; 51: 1-6
20
- 21 Liu Z, Quek A, Balasubramanian, R. Preparation and characterization of fuel pellets from woody
22 biomass, agro-residues and their corresponding hydrochars. Applied Energy 2014; 113: 1315-
23 1322
24
- 25 Lu D, Tabil LG, Wang D, Wang G, Emani S. Experimental trials to make wheat straws pellets
26 with wook residue and binders. Biomass and Bioenergy 2014; 69: 287-296

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25

Mani S, Tabil LG, Sokhansanj .S. Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses. *Biomass and Bioenergy* 2006; 30(7): 648-654

Mani S., Tabil L.G., Sokhansanj S. Evaluation of compaction equations applied to four biomass species. *Canadian Biosystems Engineering* 2004; 46(3): 55-61

Mckendry P. Energy Production from biomass (part 1) ; overview of biomass. *Bioresource Technology* 2002; 83(1): 37-46

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

Munir S, Daood SS, Nimmo W, Cunliffe AM, Gibbs BM. Thermal analysis and devolatilization kinetics of cotton stalk, sugar cane bagasse and shea meal under nitrogen and air atmospheres. *Bioresource Technology*. 2009; 100: 1413-1418

Mustelier NL, Almeida MF, Cavalheiro J, Castro F. Evaluation of pellets produced with undergrowth to be used as biofuel. *Waste Biomass Valorization* 2012; 3(3): 285 – 294

Musa NA. Determination of chemical compositions, heating values and theoretical parameters of composite agricultural waste briquettes. *International Journal of Scientific and Engineering Research* 2012; 3(6)1-5

- 1 Mwampamba TH., Owen M, Pigaht M. Opportunities, challenges and way forward for the
2 charcoal briquette industry in Sub-Saharan Africa, *Energy for Sustainable Development* 2013;
3 17(2): 158 – 170
4
- 5 Ndindeng SA, Mbassi JEG, Mbacham WF, Manful J, Graham-Acquaah S, Moreira J, Dossou J,
6 Futakuchi K. Quality optimization in briquettes made from rice milling by-products, *Energy for*
7 *Sustainable Development* 2015; 29: 24-31
8
- 9 Obernberger I, Thek G., Physical characterisation and chemical composition of densified
10 biomass fuels with regards to their combustion behaviour. *Biomass and Bioenergy* 2004; 27(6):
11 653-669
12
- 13 Okello C, Pindozi S, Faugno S, Boccia L. Bioenergy potential of agricultural and forest residues
14 in Uganda. *Biomass and Bioenergy* 2013; 56: 515-525
15
- 16 Okello C, Pindozi S, Faugno S, Boccia L. Development of bioenergy technologies in Uganda: A
17 review of progress. *Renewable and Sustainable Energy Reviews* 2013; 18: 55-63
18
- 19 Oladeji JT. Comparative study of briquetting of few selected agro-residues commonly found in
20 Nigeria. *The Pacific Journal of Science and Technology* 2012; 13(2) 80-86
21
- 22 Oladunmoye OO, Aworh OC, Maziya-Dixon B, Erukainure OL, Elemo GN. Chemical and
23 functional properties of cassava starch, Durum wheat, semolina flour and their blends. *Food*
24 *Science and Nutrition* 2014; 2(2): 132-138.
25

- 1 Olupot PW, Candia A, Menya E, Walozi R, Characterization of rice husk varieties in Uganda for
2 biofuels and their techno-economic feasibility in gasification. *Chemical Engineering Research*
3 *and Design*. 2016; 107: 63-72
4
- 5 Panwar NL. Design and performance evaluation of energy efficient biomass gasifier based
6 cookstove on multi-fuels. *Mitigation and Adaptation Strategies for Global Change* 2009; 14(7)
7 627-633
8
- 9 Raymer AKP. A comparison of avoided green house gas emissions when using different kinds of
10 wood energy. *Biomass and Bioenergy* 2006; 30(7): 605-617
11
- 12 Razuan R, Finney KN, Chen Q, Sharifi VN, Swithenbank J. Pelletised fuel production from palm
13 kernel cake *Fuel Processing Technology* 2011; 93(3) 609-615
14
- 15 Rehfuess E. (2006) *Fuel for Life. Household energy and health*. World Health Organization.
16 Geneva. Switzerland.
17
- 18 Rezania S, Ponraj M, Din MFM, Songpin AR, Sairan FM, Chelliapan S. The diverse applications
19 of water hyacinth with main focus on sustainable energy and production for new era: An
20 overview. *Renewable and sustainable Energy Reviews* 2015; 41: 943-954
21
- 22 Rezania S, Din MFM, Kamaruddin SF, Taib SM, Singh L, Yong EL, Dahalan FA. Evaluation of
23 water hyacinth (*Eichhornia crassipes*) as a potential raw material source for briquette production.
24 *Energy* 2016; 111: 768-773
25

- 1 Rezvani Z., Chegini G.R., Arabhosseini A., Kianmehr M.H. Natural energy of Briquette,
2 definitions, benefits and technologies. Journal of Automotive and applied Mechanics 2014; 2(1).
3
- 4 Saenger M., Hartge E.-U., Werther J., Ogada T. Cobustion of coffee husks. Renewable Energy
5 2001; 23(1) 103-121
6
- 7 Saidur R, Abdelaziz EA, Demirbas A, Hossain MS, Mekhilef S. A review on biomass as s fuel for
8 boilers. Renewable and Sustainable Energy Reviews 2011; 15(5): 2262 – 2289
9
- 10 Sotannde OA, Oluyeye AO, Abah GB. Physical and combustion properties of briquettes from
11 sawdust of *Azadirachta indica*. Journal of Forestry Research 2010; 21(1): 63-67
12
- 13 Serrano C, Monedero E, Lapuerta M, Portero H. Effect of moisture content, particle size and pine
14 addition on quality parameters of barley straw pellets. Fuel processing technology 2011; 92(3):
15 699-706
16
- 17 Singh RN, Bhoi PR, Patel SR. Modification of commercial briquetting machine to produce 35mm
18 diameter briquettes suitable for gasification and combustion. Renewable Energy 2007; 474-479
19
- 20 Srivastava NSL, Narnaware SL, Makwana JP, Singh SN, Vahora S. Investigating the energy use
21 of vegetable market waste by briquetting. Renewable Energy 2014; 68: 270-275
22
- 23 Stelte W, Holm JK, Sanadi AR, Barsberg S, Ahrenfeldt J, Henriksen UB. A study of bonding and
24 failure mechanisms in fuel pellets from different biomass resources. Biomass and Bioenergy
25 2011; 35(2): 910-918
26

- 1 Stolarski MJ, Szczukowski S, Tworkowski J, Krzyzaniak M, Gulczynski P, Mleczek M.
2 Comparison of quality and production cost of briquettes made from agricultural and forest origin
3 biomass. *Renewable Energy* 2013; 57: 20-26
4
- 5 Tako M., Hizukuri S. Gelatinization mechanism of potato starch, *Carbohydrate Polymers* 2002;
6 48(4) 397-401
7
- 8 Tembe ET, Otache PO, Ekhuemelo DO. Density, shatter index and combustion properties of
9 briquettes produced from groundnut shells, rice husks and saw dust of *Daniellia Oliveri*. *Journal*
10 *of Applied Biosciences* 2014; 82: 7372-7378
11
- 12 Thao P.T.M., Kurisu K.H., Hanaki K. Greenhouse gas emission mitigation potential of rice husks
13 for An Giang province, Vietnam. *Biomass and Bioenergy* 2011; 35(8): 3656 – 3666
14
- 15 Tsai W., Liu S., Hsieh C. Preparation of fuel properties of biochars from the pyrolysis of
16 exhausted coffee residue. *Journal of Analytical and Applied Pyrolysis* 2012; 93: 63-67
17
- 18 Tumuluru JS. Effect of process variables on the density and durability of the pellets made from
19 high moisture corn stover. *Biosystems engineering*. 2014; 119: 44-57
20
- 21 Tumutegyereize P., Mugenyi R., Ketlogetswe C., Gandure J. A comparative performance analysis
22 of carbonized briquettes and charcoal fuels in Kampala-urban, Uganda. *Energy for Sustainable*
23 *Development* 2016: 31: 91-96
24
- 25 Uganda Bureau of Statistics (UBOS) 2014. *Statistical Abstract*. Kampala Uganda
26

- 1 Uganda Bureau of Statistics (UBOS) 2015. Statistical Abstract. Kampala Uganda
- 2
- 3 Vargas-Moreno JM, Callejón-Ferre AJ, Pérez-Alonso J, Velázquez-Martí B. A review of the
4 mathematical models for predicting the heating value of biomass materials. Renewable and
5 sustainable energy reviews 2012; 16(5) 3065-3083.
- 6
- 7 Vassilev SV, Baxter D, Andersen LK, Vassileva CG. An overview of the chemical composition
8 of biomass. Fuel 2010; 89(5) 913 - 933
- 9
- 10 Vassilev SV, Baxter D, Andersen LK, Vassileva CG, Morgan TJ. An overview of the organic and
11 inorganic phase composition of biomass. Fuel 2012; 94: 1-33
- 12
- 13 Vassilev SV, Baxter D, Vassileva CG. An overview of the behavior of biomass during
14 combustion: Part 1: Phase mineral transformations of organic and inorganic matter. Fuel 2013;
15 112: 391 - 449
- 16
- 17 Virmond E, Sena RF, Albrecht W, Althoff CA, Moreira RFPM, Jose HJ. Characterization of
18 agroindustrial solid residues as biofuels and potential application in thermochemical processes.
19 Waste Management 2012; 32(10): 1952-1961
- 20
- 21 Werther J, Saenger M, Hartge EU, Ogada T, Siagi Z. Combustion of agricultural residues.
22 Progress in Energy and Combustion Science 2001; 26(1): 1 -27
- 23
- 24 Yank A, Ngadi M, Kok R. Physical properties of rice husk and bran briquettes under low pressure
25 densification for rural applications. Biomass and Bioenergy 2016; 84: 22-30
- 26

- 1 Zaidul ISM, Yamauchi H, Kim S, Hashimoto N, Noda T. RVA study of mixtures of wheat flour
2 and potato starches with different phosphorus contents. Food Chemistry 2007; 102(4): 1105-1111
3
- 4 Zhu F. Composition, structure, physico-chemical properties, and modifications of cassava starch.
5 Carbohydrate Polymers 2015; 122: 456-480

6

List of Figures

Figure 1: Schematic representation of the carbonizer

Figure 2: Longitudinal cross-sectional view of the low pressure briquetting machine

Figure 3: Schematic representation of the high pressure briquetting system

Figure 4: Picture of bio char of (a) bagasse, and (b) groundnut shells after carbonization

Figure 5: Picture of carbonized (low pressure) briquettes (a) and non-carbonized (high pressure) briquettes

Figure 6: TGA results for bagasse (a) and groundnut shells (b) raw material

Figure 7: TGA results for briquettes for Groundnut shells with cassava binder (a); groundnut shells with wheat binder (b); bagasse with cassava binder (c); and bagasse with wheat binder (d). For all cases (a – d) 30g of both cassava and wheat binder is considered.

Figure 8. Moisture content % for groundnut shell and bagasse briquettes with different amounts of cassava and wheat flour binder

Figure 9: Volatile matter % for groundnut shell and bagasse briquettes with different amounts of cassava and wheat flour binder

Figure 10: Ash Content % for groundnut shell and bagasse briquettes with different amounts of cassava and wheat flour binder

Figure 11: Fixed Carbon % for groundnut shell and bagasse briquettes with different amounts of cassava and wheat flour binder

Figure 12: Physical properties for composite briquettes developed with 500g of both groundnut shells and bagasse with 25g and 35g of both cassava and wheat binders

Figure 13: Physical properties of non-carbonized groundnut shells without binder and with cassava and wheat binders

Figure 14: HHV for groundnut shell and bagasse briquettes with cassava and wheat starch binders

Figure 15: Drop strength of groundnut shells and bagasse with different amounts of binder

Figure 16: HHV and drop test results for non-carbonized and composite briquettes

Figure 17: Particle density for groundnut shells and baggase briquettes with different binder amounts developed after carbonization and under high pressure without carbonization

Figure 18: Figure 17: Improved cook stoves with ignited briquettes (200 g) (a) boiling 0.5 liters of water (b).

Figure 19: Time (in minutes) taken to boil 0.5 liters of water with 200g of briquettes

Figure 20: Maximum attainable flame temperatures during the water boiling test

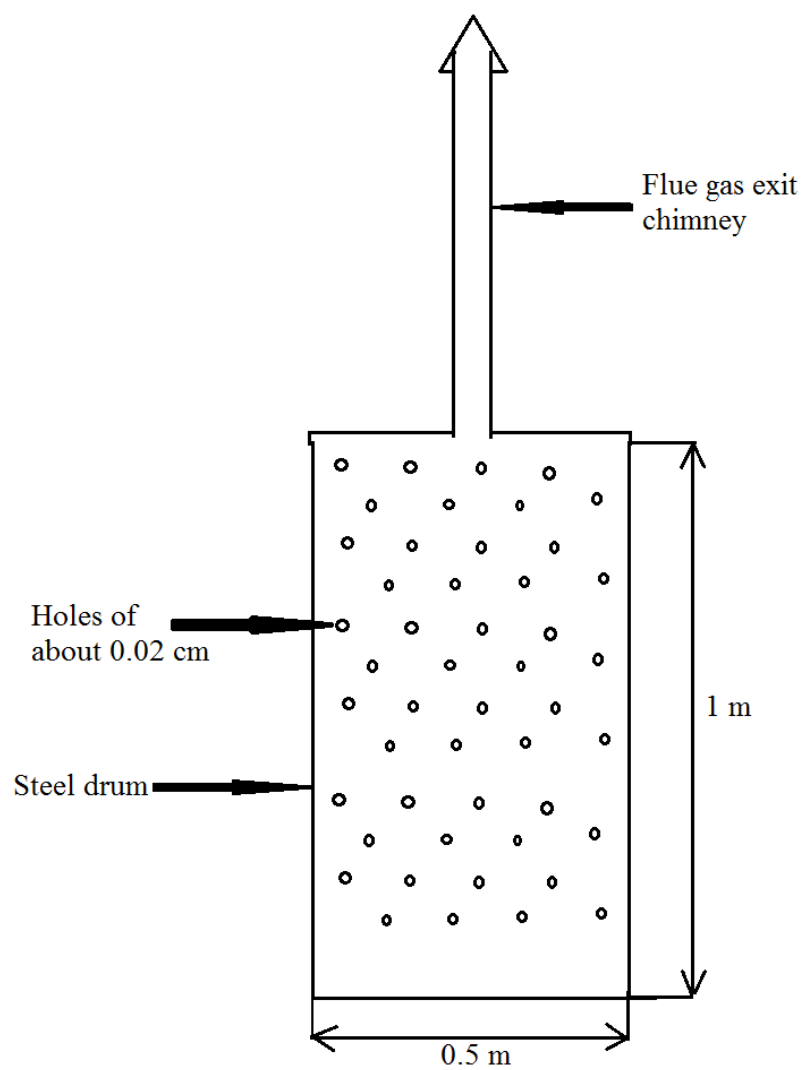


Figure 1: Schematic representation of the carbonizer

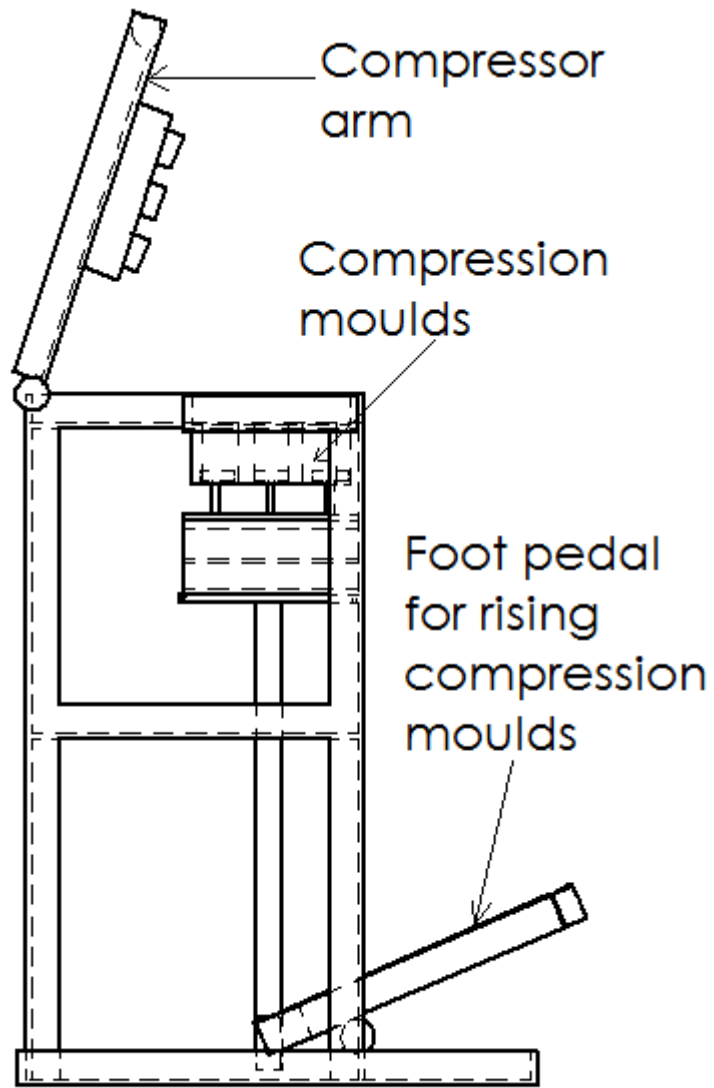


Figure 2. Longitudinal cross-sectional view of the low pressure briquetting machine

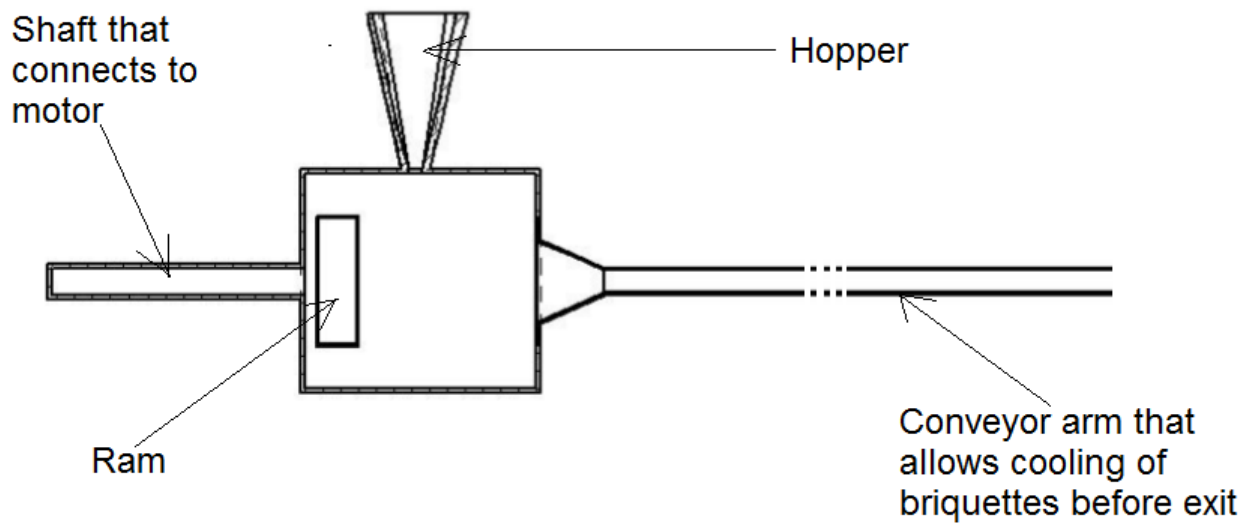


Figure 3: Schematic representation of the high pressure briquetting system



Figure 4: Picture of bio char of (a) bagasse, and (b) groundnut shells after carbonization



Figure 5: Picture of carbonized (low pressure) briquettes (a) and non-carbonized (high pressure) briquettes

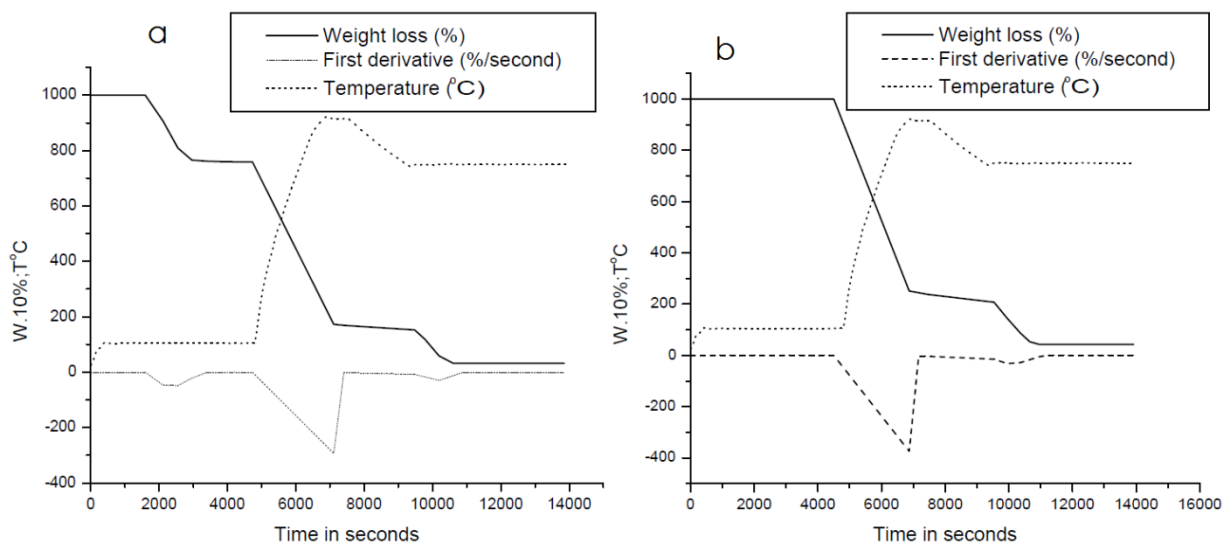


Figure 6: TGA results for bagasse (a) and groundnut shells (b) raw material

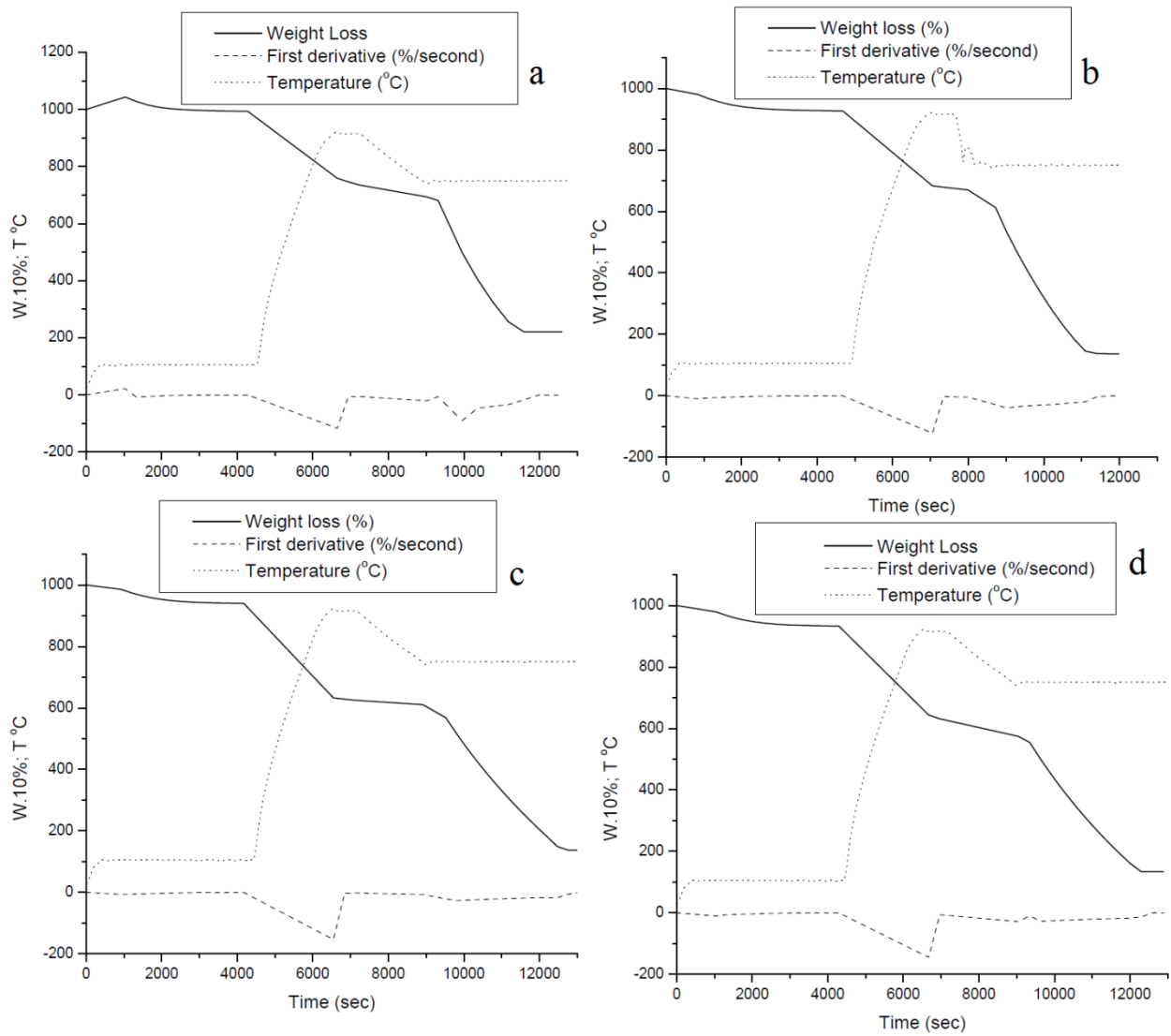


Figure 7. TGA results for briquettes for carbonized groundnut shell briquettes with cassava binder (a); carbonized groundnut shell briquettes with wheat binder (b); carbonized bagasse briquettes with cassava binder (c); and carbonized bagasse briquettes with wheat binder (d). For all cases (a – d) 30g of both cassava and wheat binder is considered.

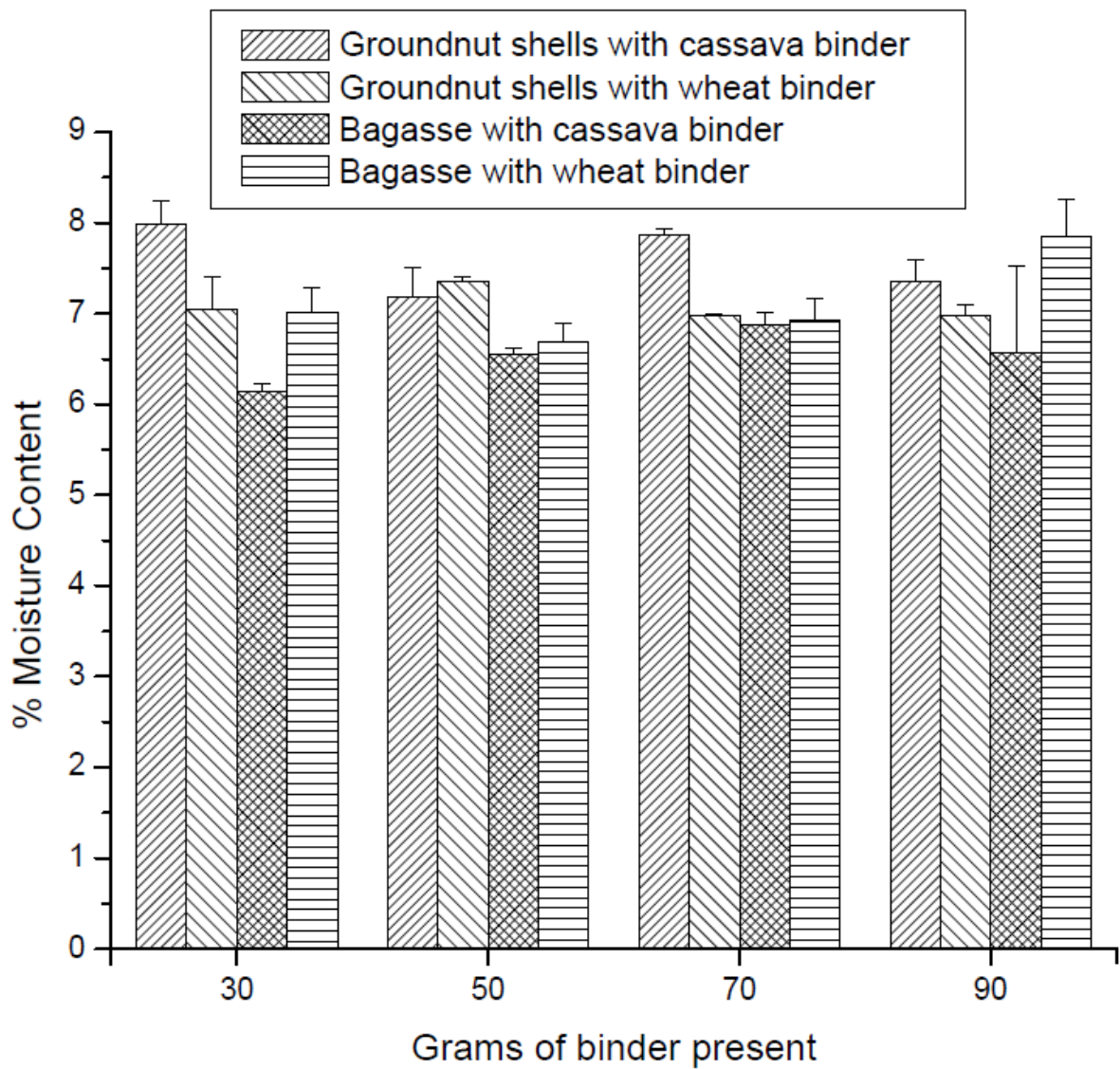


Figure 8. Moisture content % for carbonized groundnut shell briquettes and carbonized bagasse briquettes with different amounts of cassava and wheat flour binder

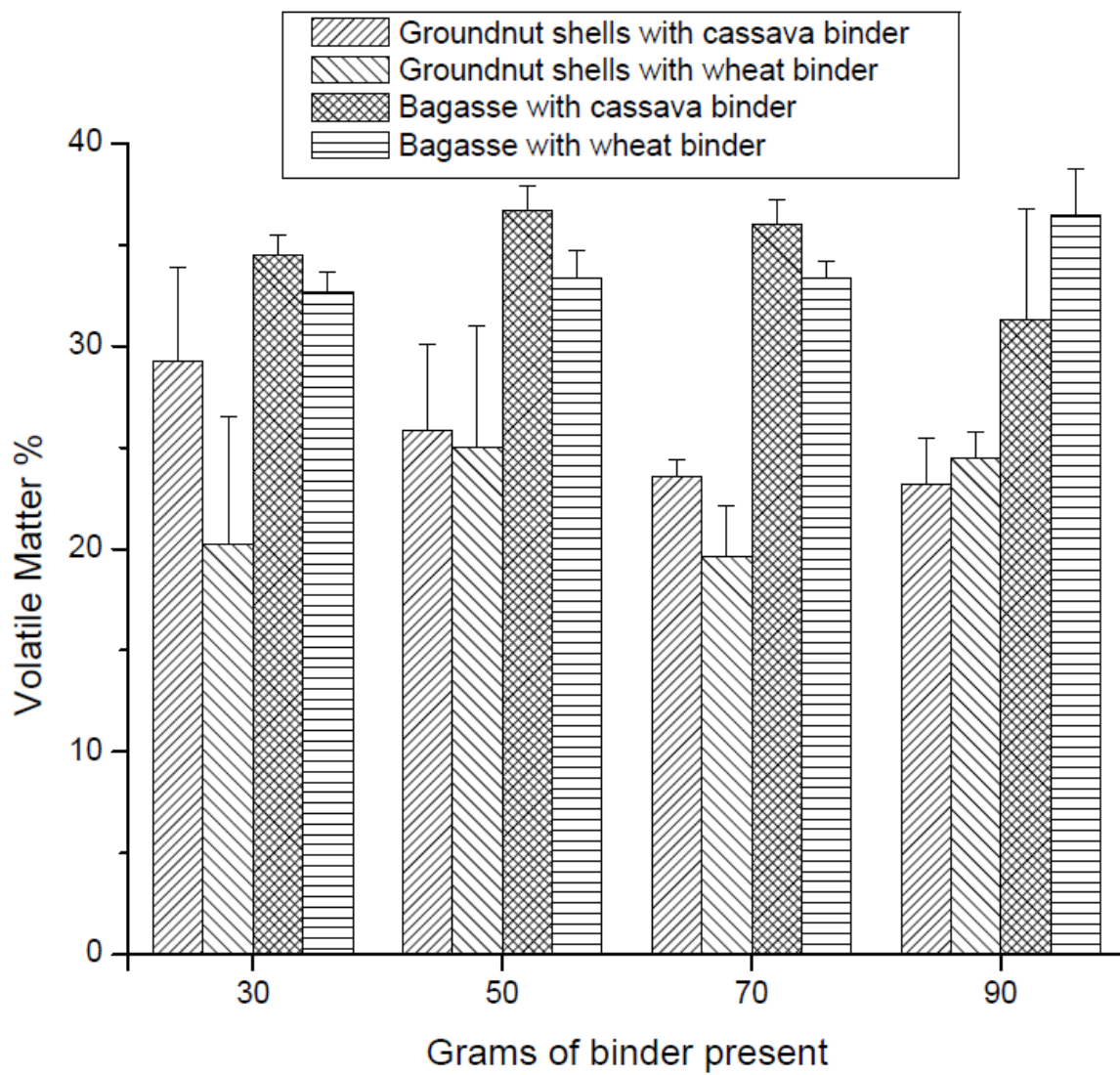


Figure 9: Volatile matter % for carbonized groundnut shell briquettes and carbonized bagasse briquettes with different amounts of cassava and wheat flour binder

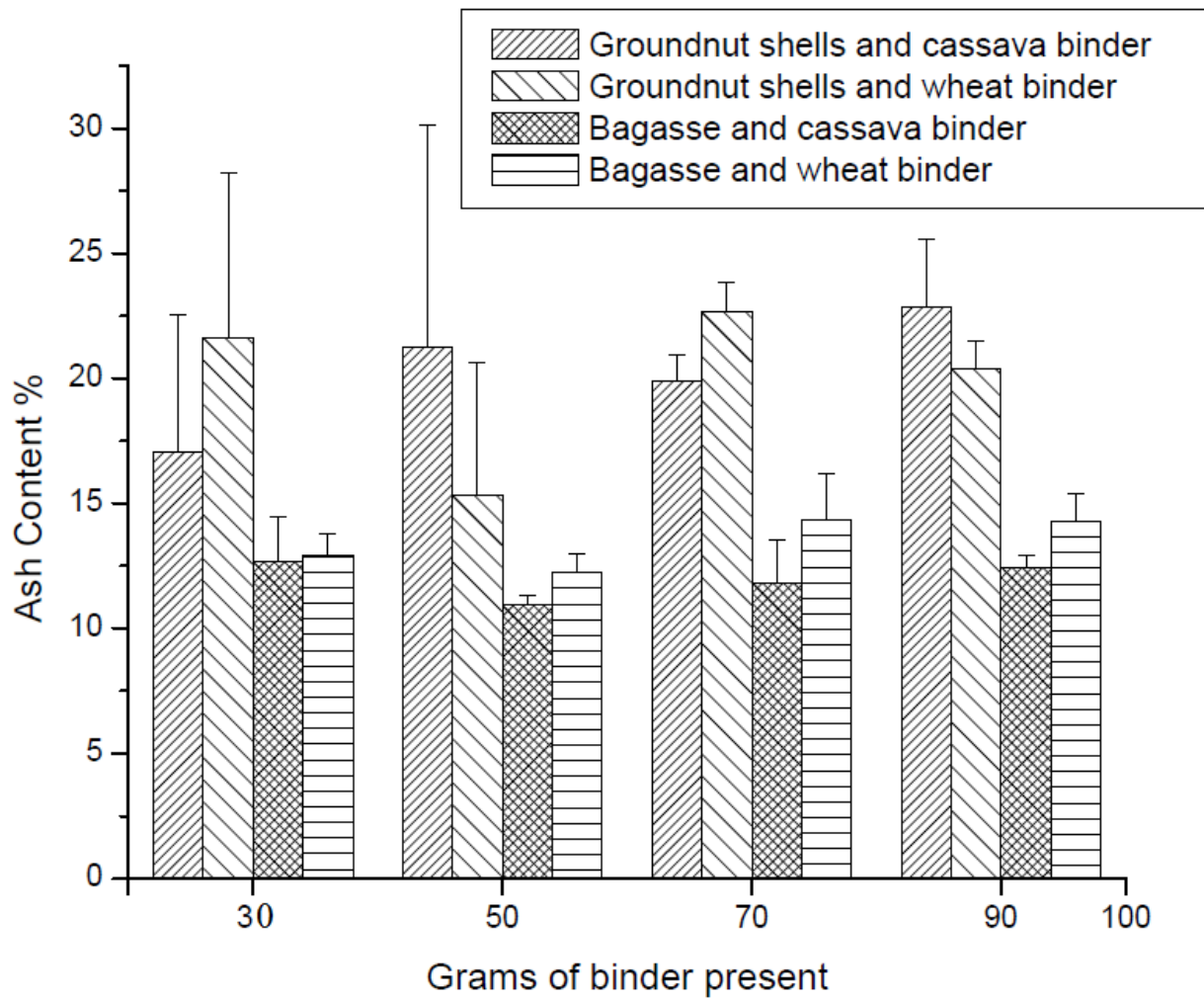


Figure 10: Ash Content % for carbonized groundnut shell briquettes and carbonized bagasse briquettes with different amounts of cassava and wheat flour binder

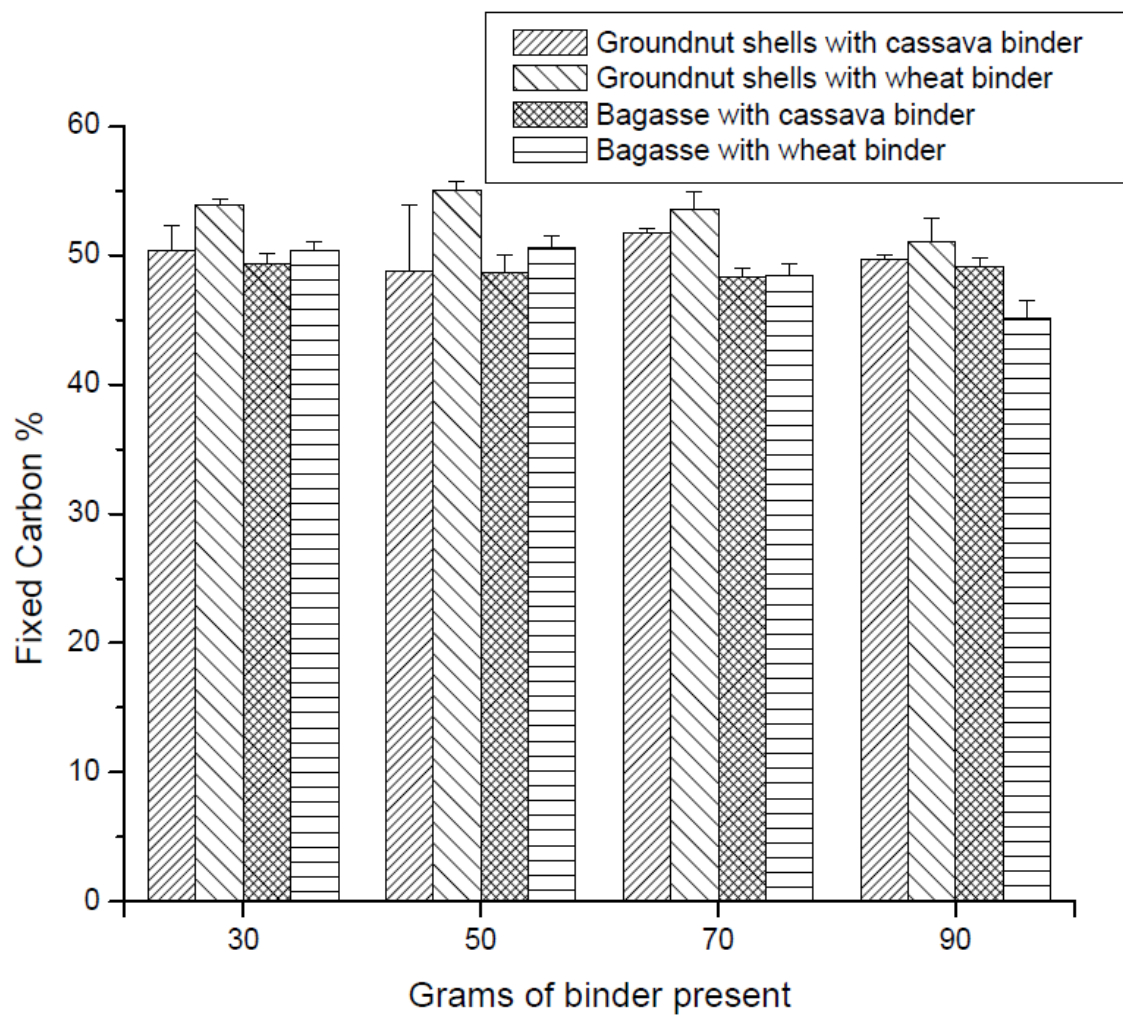


Figure 11: Fixed Carbon % for carbonized groundnut shell briquettes and carbonized bagasse briquettes with different amounts of cassava and wheat flour binder

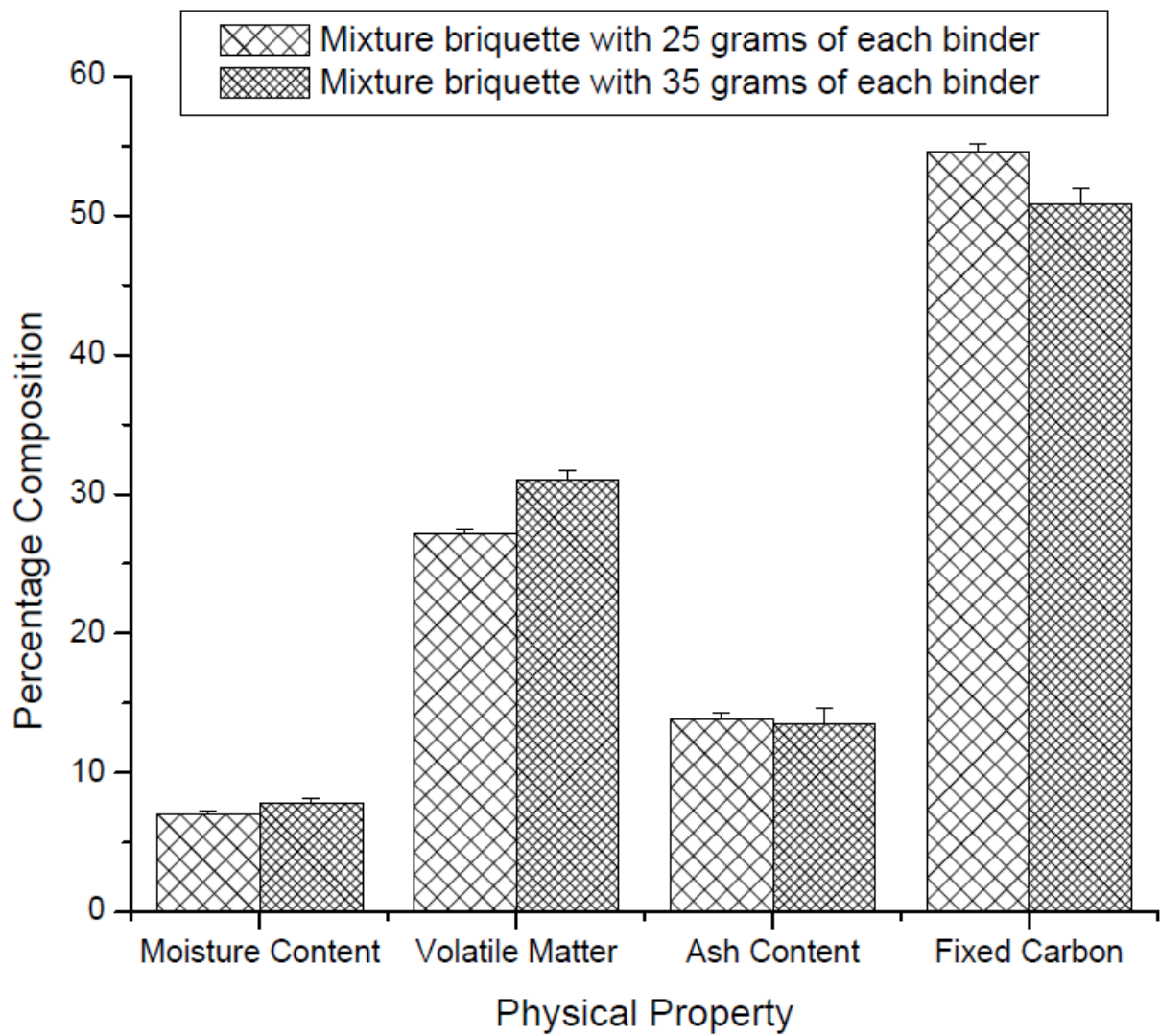


Figure 12: Physical properties for carbonized composite briquettes developed with 500g of both groundnut shells and bagasse with 25g and 35g of both cassava and wheat binders

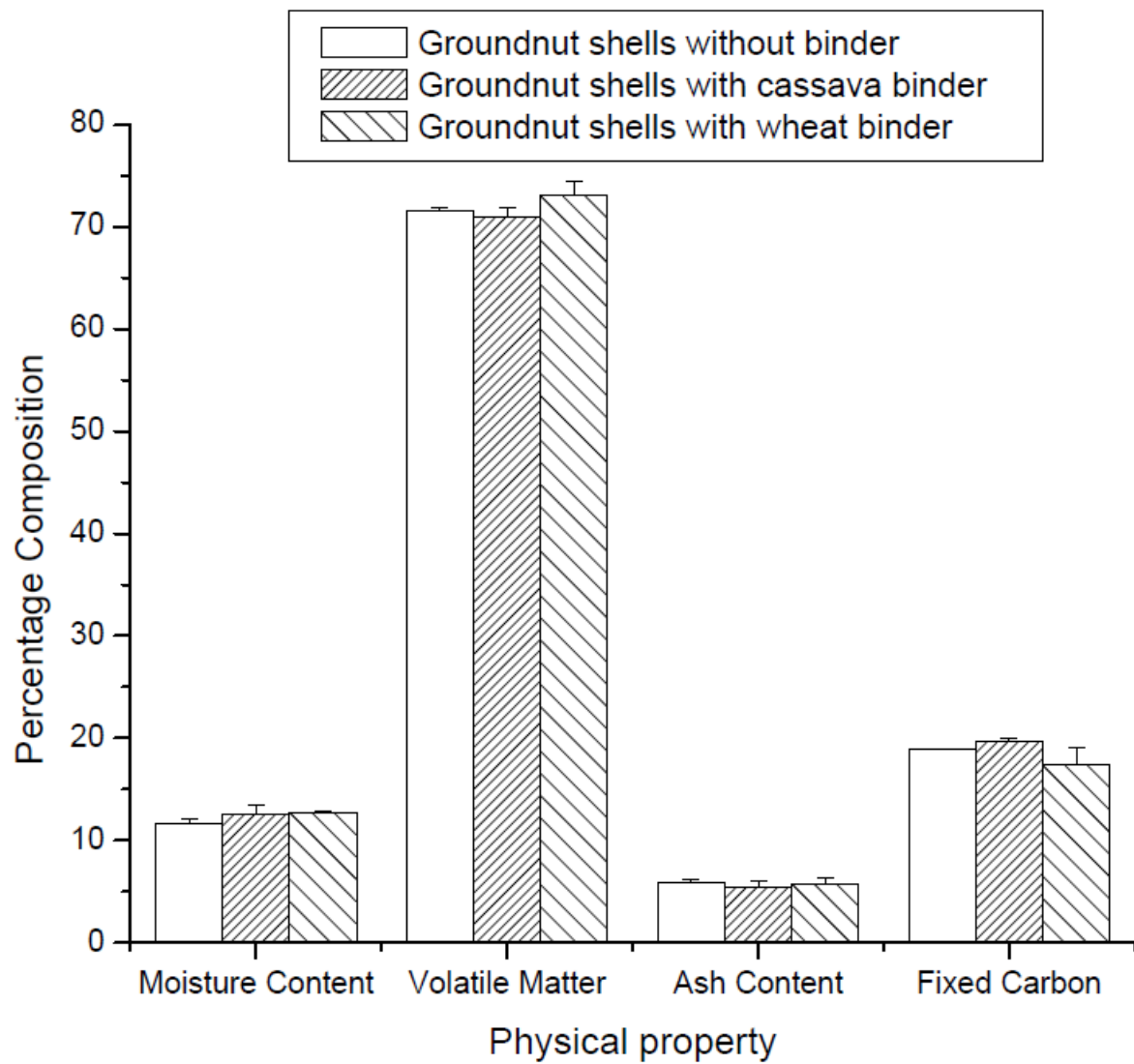


Figure 13: Physical properties of non-carbonized groundnut shells without binder and with cassava and wheat binders

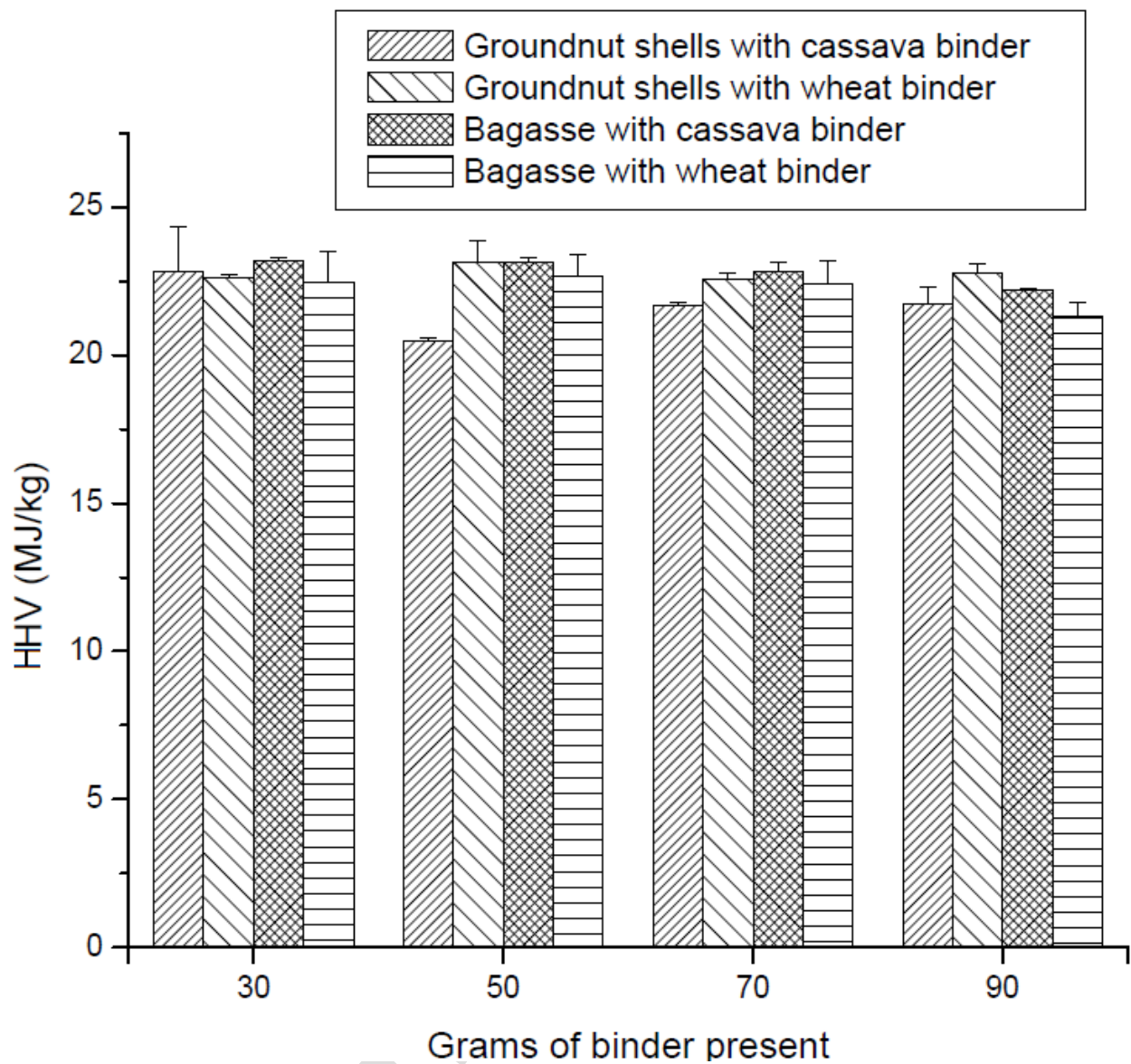


Figure 14: HHV for carbonized groundnut shell briquettes and carbonized bagasse briquettes with cassava and wheat starch binders

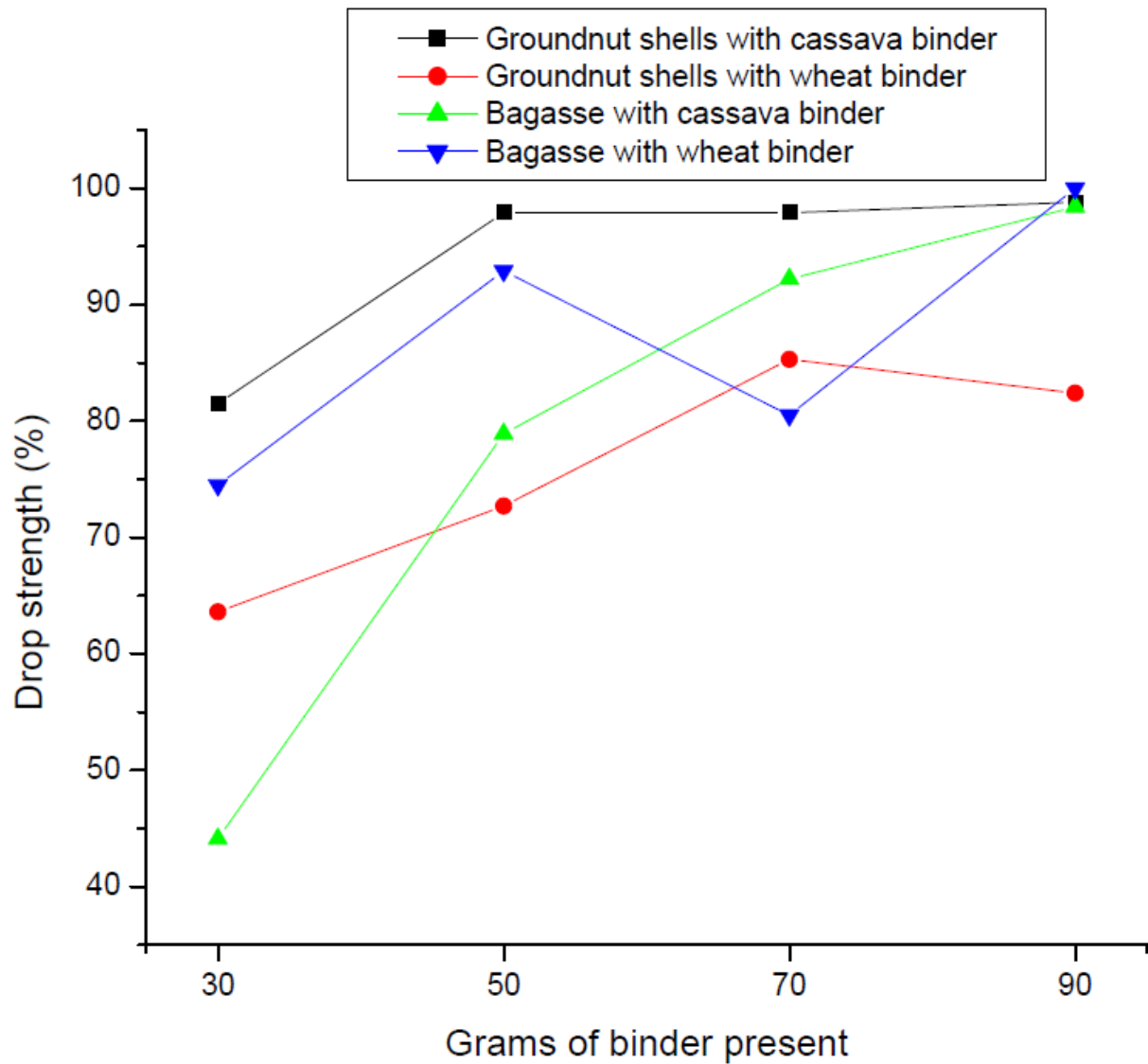


Figure 15: Drop strength of carbonized groundnut shell briquettes and carbonized bagasse briquettes with different amounts of binder

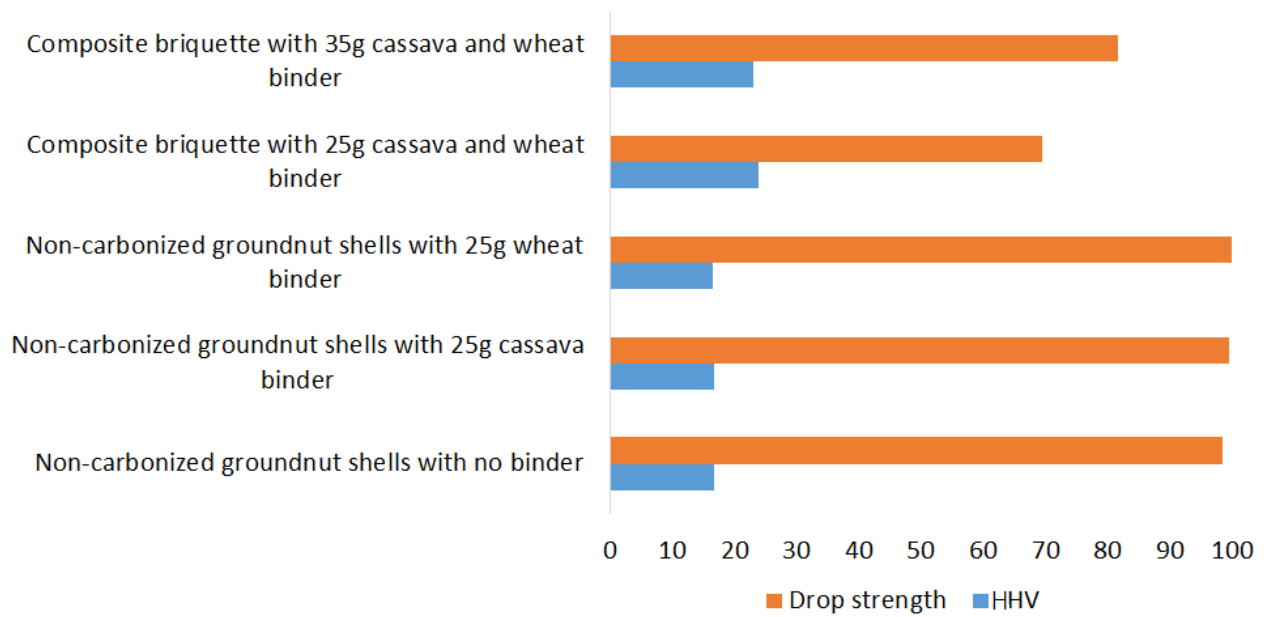


Figure 16: HHV and drop strength results for non-carbonized groundnut shell briquettes and carbonized composite briquettes

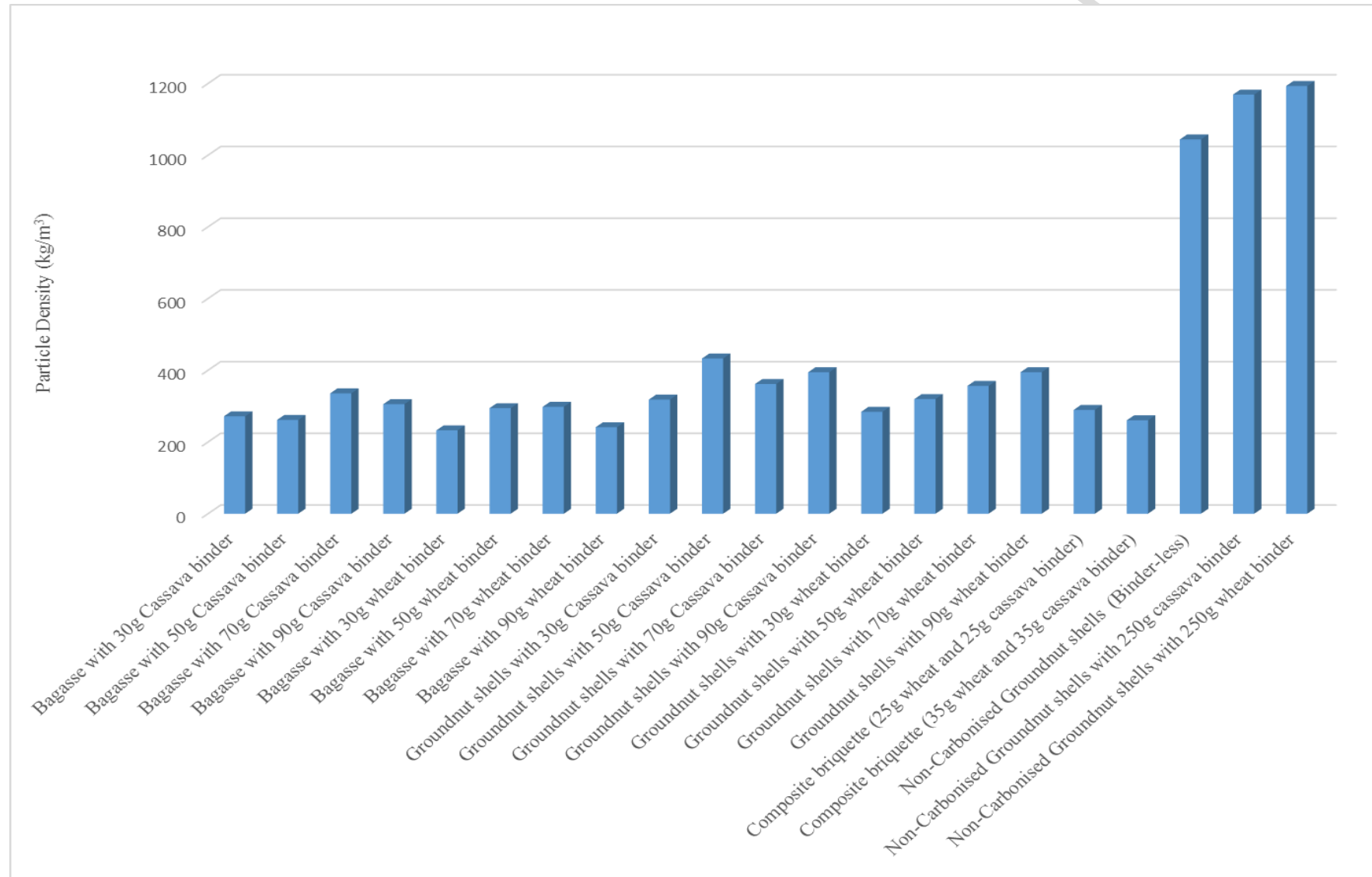


Figure 17: Particle density for Groundnut shell briquettes and bagasse briquettes with different binder amounts developed after carbonization and under high pressure without carbonization



Figure 18: Improved cook stoves with ignited briquettes (200 g) (a) boiling 0.5 liters of water (b).

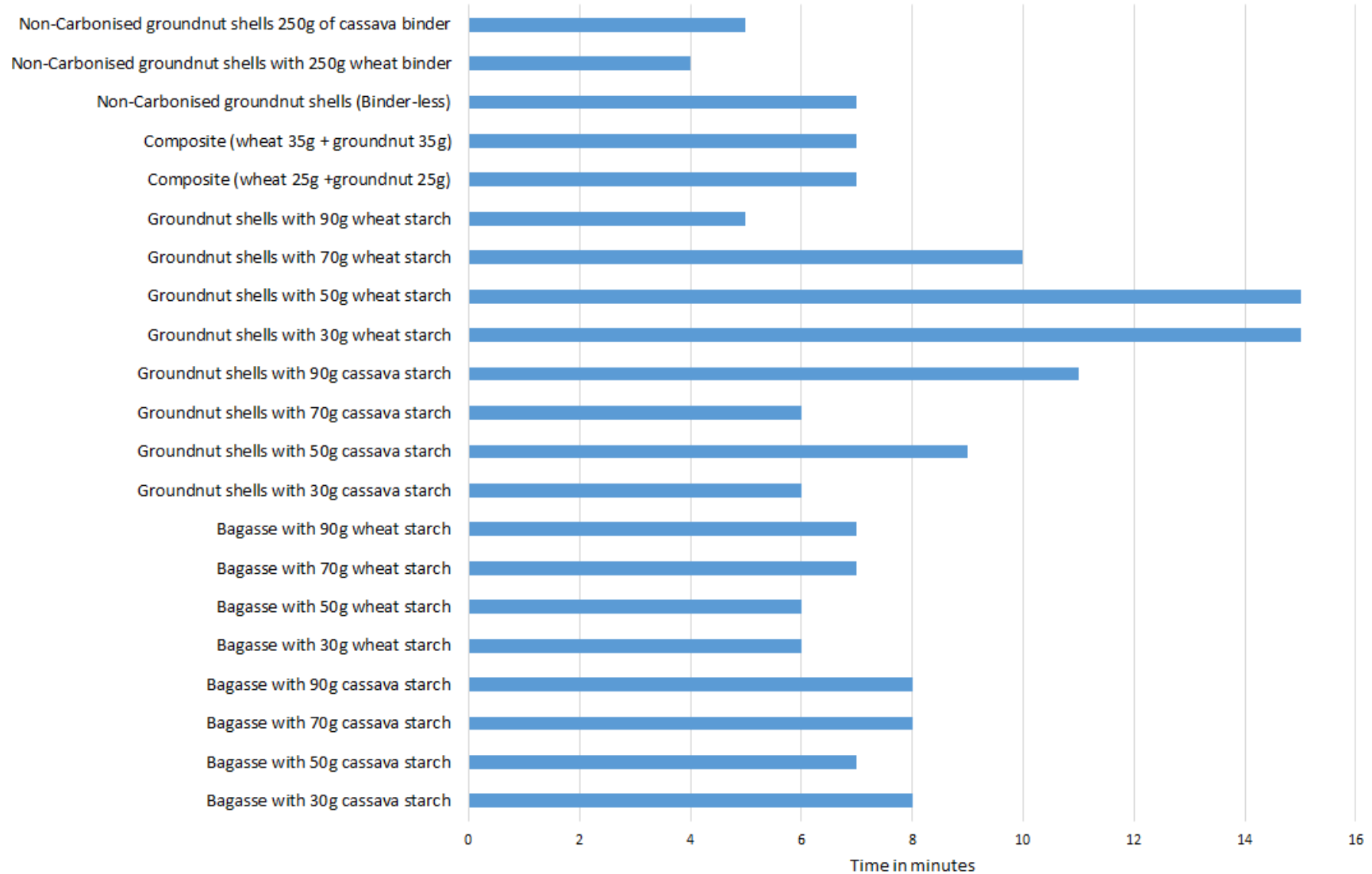


Figure 19: Time (in minutes) taken to boil 0.5 liters of water with 200g of briquettes

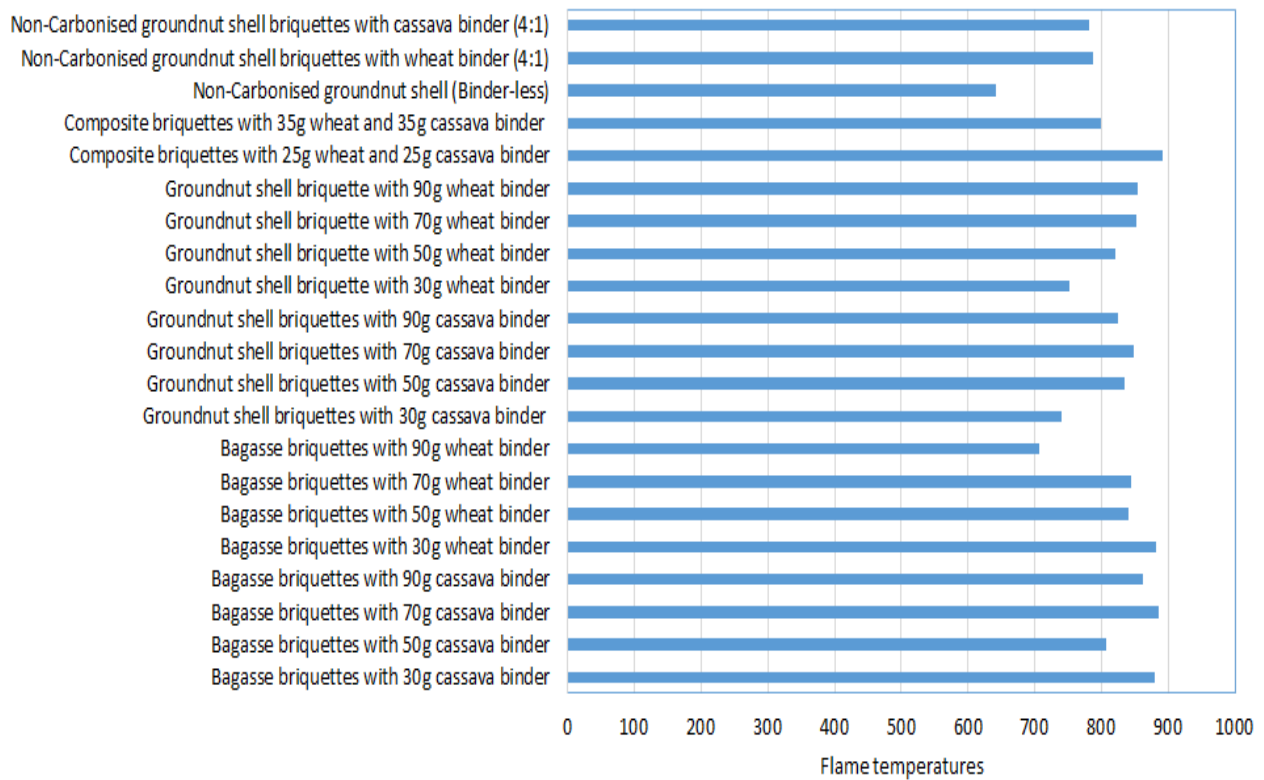


Figure 20: Maximum attainable flame temperatures during the water boiling test

Tables

Table 1: Process parameters used in the development of the groundnut shells and bagasse briquettes

Raw material	Briquette development pressure	State of material at briquettes development	Binder Used	Ratio of raw material to starch binder
Groundnut shells	≤ 7 MPa	Carbonized	Cassava starch	100:3
Groundnut shells	≤ 7 MPa	Carbonized	Cassava starch	100:5
Groundnut shells	≤ 7 MPa	Carbonized	Cassava starch	100:7
Groundnut shells	≤ 7 MPa	Carbonized	Cassava starch	100:9
Groundnut shells	≤ 7 MPa	Carbonized	Wheat starch	100:3
Groundnut shells	≤ 7 MPa	Carbonized	Wheat starch	100:5
Groundnut shells	≤ 7 MPa	Carbonized	Wheat starch	100:7
Groundnut shells	≤ 7 MPa	Carbonized	Wheat starch	100:9
Bagasse	≤ 7 MPa	Carbonized	Cassava starch	100:3
Bagasse	≤ 7 MPa	Carbonized	Cassava starch	100:5
Bagasse	≤ 7 MPa	Carbonized	Cassava starch	100:7
Bagasse	≤ 7 MPa	Carbonized	Cassava starch	100:9
Bagasse	≤ 7 MPa	Carbonized	Wheat starch	100:3
Bagasse	≤ 7 MPa	Carbonized	Wheat starch	100:5
Bagasse	≤ 7 MPa	Carbonized	Wheat starch	100:7
Bagasse	≤ 7 MPa	Carbonized	Wheat starch	100:9
Bagasse and groundnut shells	≤ 7 MPa	Carbonized	Cassava starch: Wheat starch	50:50:2.5:2.5
Bagasse and groundnut shells	≤ 7 MPa	Carbonized	Cassava starch: Wheat starch	50:50:3.5:3.5
Groundnut shells	230 MPa	Non-carbonized	No binder	0
Groundnut shells	230 MPa	Non-carbonized	Wheat flour	4:1
Groundnut shells	230 MPa	Non-carbonized	Cassava flour	4.1