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TOWARDS THE PROMOTION OF FUEL BRIQUETTES USING MUNICIPAL SOLID WASTE AND RESIDUAL BIOMASS IN BURUNDI

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Abstract

The issue of domestic energy is still a major concern in developing countries. A sound knowledge of fuel characteristics is a major asset for their acceptability and their distribution. Samples of briquettes made partially with Municipal Solid Waste (MSW) were collected in several companies with unknown characterization. This study intended first to characterize them for physical and chemical properties. Subsequently, energy content of the briquettes and the energy price are presented and compared to those of charcoal and peat, which is typically used by the local population as fuel. To classify the different briquettes according to their quality in terms of rate as well as their level in fire resistance, cooking tests and heating curves have been made. The calorific value of the studied briquettes varied from 12.3 to 18.6 MJ/kg compared to 32.5 MJ/kg for charcoal and 14.7 MJ/kg for peat. Consequently, their value as viable substitutes for charcoal or peat is apparent. However, some samples burn very quickly and do not provide prolonged heating while other samples have a slow rate of combustion and release little energy. Finally, the briquettes using MSW have a low price between $0.16 and $0.19/kg compared to the price of $0.53/kg for charcoal and $0.20/kg for peat. The promotion of these briquettes as a valuable substitution fuel is proved and contribute to sustainable development by reusing MSW and avoiding deforestation.

Key words: Biofuel briquette, Burundi, Municipal Solid Waste (MSW)

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1. Introduction

The population of developing countries has been grown at an average annual rate of 2.6% over the last thirty years (UNFPA-CEA, 2016). However, rapid population growth has serious negative economic effects, because with rates of more than 2% per year, development can be hindered (UNFPA-CEA, 2016). Highly rapid population growth affects energy needs, putting pressure on the expansion of agricultural and residential spaces, and consequently on forest resources that are already in deficit (Oliveira et al., 2007; Ministère de l'Énergie et des Mines, 2012). For illustration of Burundi, one of the developing countries in central Africa, more than 90% of the population of cities and almost 100% of secondary urban centers use charcoal or firewood as a source of energy mainly for cooking food (Ministère de l'Énergie et des Mines, 2012). Thus, in Burundi, natural resources are generally declining due to two factors: the strong pressure and demographic density pushing for the search of new agricultural lands and a considerable deficit (in a ratio of 1: 3) between the annual supply and demand of wood energy. Deforestation has caused repetitive drought and agricultural problems (Ministère de l'Énergie et des Mines, 2012). As reported by Gan and McCarl (2007), it should be noted that forest conservation in one country can influence the degree of conservation or deforestation in other countries due to a lack of global coordination and so offsetting environmental gains. On this point of view, agricultural solutions need to be combined with conservation policies to reduce deforestation (Desbureaux and Damania, 2018).

In addition, in developing countries, including Burundi, rapid urban population growth and changing lifestyles have resulted in increased rates of waste generation to which stakeholders and local communities were not prepared to cope with (Koledzi, 2012; Mizero et al., 2015; Nyankson et al., 2015). Indeed, human activities generate waste responsible for harmful effects and human health hazards by pollution of soil, air and water (Neupane and Neupane, 2013; Patil and Kamble, 2017). Solid waste production follows population growth and socio-economic development (Tabet, 2001). The particularity of solid waste lies in their occupation of space in mass and volume (Ciambrone, 1997; Mizero et al., 2015; Rana et al., 2017). Waste may be used as secondary raw material by its recycling like a partial binder material alone or in briquetting of rice and wheat straw (Demirbaş and Sahin, 1998; Zeng et al., 2007; Horne et al., 2009). The impacts associated with the use of fuels made from household and agro-food waste are environmentally friendly, reduce deforestation and its complications, ensure a healthy environment, and are consistent with natural resource conservation policies (Zeng et al., 2007; Emerhi, 2011; Lewison et al., 2019). The thermogravimetric model, which is used for evaluating the pyrolysis and gasification yields of the fermentable fraction of household waste, has shown that pyrolysis and gasification thermal treatment routes are not feasible to provide household energy in Burundi's capital, Bujumbura, only after prior drying (Kapepula et al., 2016).

In a recent study in Burundi (Mizero et al., 2015), it was mentioned that several companies had started producing briquettes from municipal solid waste mixed with other types of waste as binders or to improve energy performance. Moreover, the study of the quality and costs of the fuel briquettes from agricultural and forest biomass has been performed abroad (Bhattacharya et al., 1985; Hamelinck et al., 2005; Stolarki et al., 2013), but not sufficiently in Burundi. Therefore, two hypotheses can be put forward: (a) biofuel briquettes made at Bujumbura do not have the same physicochemical characteristics because the constituent raw materials are different; (b) the calorific value of biofuels can be used as a criterion in comparing the real cost of the briquettes.

The purposes of this study are : (1) to compare properties of fuel briquettes produced from different companies (Burundi Bioenergy (BB), Belgian Technical Cooperation (BTC), Burundi Quality Stoves (BQS) and Onatour, (2) to evaluate their energetic content and performances by heating tests and (3) to evaluate the ratio cost/energy of the briquettes. This study aims to promote the use of briquettes made from municipal solid waste and biomass in order to contribute to waste management for better sanitation and energy recovery from waste, as well as arrest deforestation and increase the production of low cost fuel in Burundi.

2. Material and methods

2.1. Study area

The study had been conducted in Bujumbura, the economic capital of Burundi, one of the countries in the Great Lakes region of central Africa (Figure 1). It has been assumed that the material used to manufacture the briquettes is localized in the same neighbourhood.

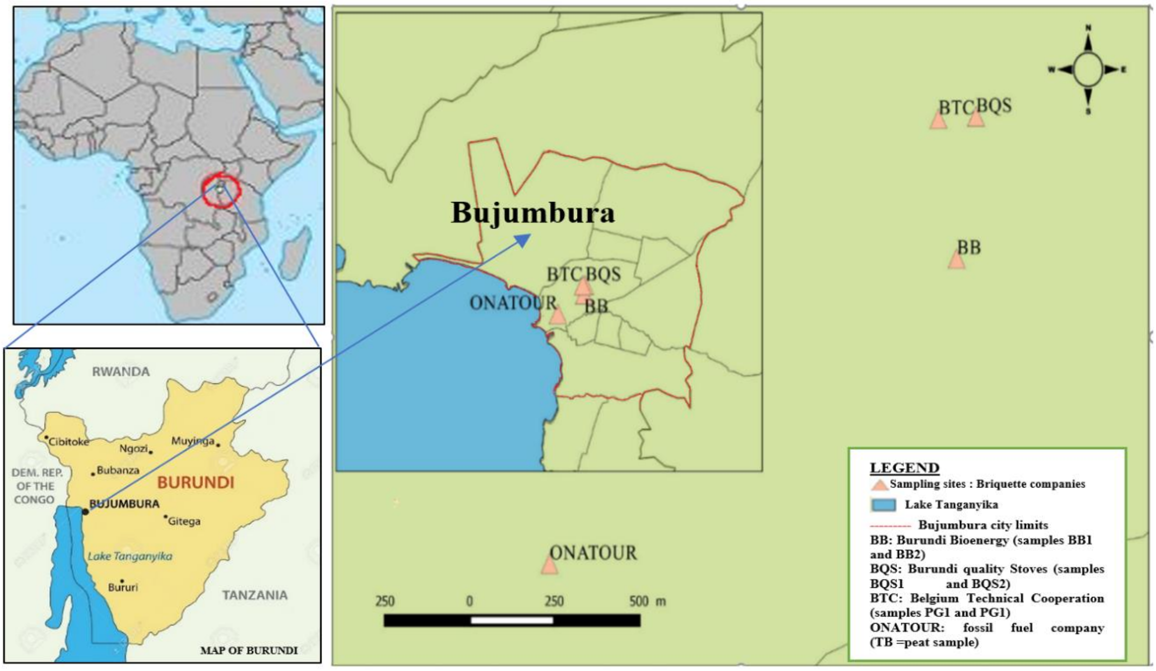


Figure 1: Sampling sites of fuel briquettes (Bujumbura city)

2.2. Samples

Seven samples of combustible briquettes used for this comparative study were collected during 2015, produced from the local companies. The names of companies and the briquettes code are provided in parenthesis:

i) Burundi Bioenergy (BB) is a Burundian company that deals with the energy recovery of household waste and residual biomass. We took two samples named BB1 and BB2 for the two types of briquettes manufactured.

ii) Belgian Technical Cooperation (BTC) was also involved in Burundi in the recycling of household waste through its "PAVAGE project" which was involved in the manufacture of two varieties of combustible briquettes with codes PG1 and PG2.

iii) Burundi Quality Stoves (BQS) is also a company that valorises agro-industrial waste in the manufacture of several varieties of biofuels.

iv) ONATOUR is a public company that extracts, packages and sells peat, a natural fossil fuel that exists in abundance in the Burundian subsoil; the peat sample is coded TB. The different samples with their primary composition are listed in Table 1.

Table 1: Description and Composition of Briquette Samples (BB1=Burundi Bioenergy sample type 1, BB2 = Burundi Bioenergy sample type 2; PG1= Pavage Gris sample 1; PG1= Pavage Gris sample type 2; BQS1 = Burundi Quality Stoves sample type 1, BQS2 = Burundi Quality Stoves sample type 2 and TB = peat sample).

Sample	Origin	Raw materials used
BB1	Burundi Bioenergy	wood chips : 90%; rice bran : 5%; corn straw: 4%; cassava flour: 1%
BB2	Burundi Bioenergy	decomposed household garbage: 90% ; Wood chips: 6%; Rice husk: 4%
PG1	BTC	Wood charcoal residues: 90% ; Cassava flour: 6%; Clay: 4%
PG2	BTC	Wood charcoal residues: 90% ; Dry clay: 10%
BQS1	BQS	Coffee hull: 60% ; Wood chips: 20% ; Cow dung: 20%
BQS2	BQS	Coffee hull: 35% ; Wood chips: 25% ; Rice husk: 20%; Cow dung: 20%
TB	ONATOUR	Peat: fossil fuel

2.3. Methodology

The characterization of samples fuel was carried out in the laboratory of chemistry and environmental analysis (LCAE) of the faculty of science at the University of Burundi. The physicochemical properties of the briquettes under study were determined in the furnace Naberterm type, by the evaluation of the loss on ignition at temperatures 105°C, 550°C and 850°C respectively corresponding to the humidity levels (W), the volatile organic matters content (VOM) and fixed carbon (C_F) and finally ash (A) (Boucher et al., 2002; Jung, 2007).
By determining the higher calorific value (CV_H) with a constant volume in calorimetric bomb type JK7-3058, the temperature variations had been noticed on a precision Beckmann thermometer. The CV_H was found from the initial to final relative temperatures, with the aid of the equivalent water value of the calorimeter. The protocol for determining the CV_H and the calculation of the lower calorific value (CV_L) follows the standard NF ISO 1928 (Boucher et al., 2002). CV_H takes into account the heat released by the condensation of water vapor so that $CV_L = CV_H - Lv$ where Lv is the latent heat of vaporization of water.
The kitchen tests on combustion of the samples were conducted on the basis of the combustibility test method whose parameters were evaluated: the weight loss rate, the total burning time, the increase in the temperature of heated water, measured with a Pt-Rh thermocouple, and the progress of the vertical flame (Emerhi, 2011; Onuegbu et al., 2011). Having achieved the combustion of 0.5kg of each briquette, their burning rates are calculated; which makes it possible to compare them with each other. We then obtain for each biofuel its rate of consumption by fire. It is given by the following expression:

$$v(g/h) = \frac{m(g)}{t_c(h)}$$ (Onuegbu et al., 2011);

Where v is the rate of consumption in g/h, m is the mass of sample in g and t_c the total time of combustion in hours.

It is worthwhile to note that descriptive statistics had been done by SPSS 22. Moreover, Pearson correlation between physicochemical parameters had been evaluated, using the matrix correlation. Based on the selling price registered from each selected company and their calorific values, market value for the energy content of each type of briquettes was determined in $/1000 kcal. The comparison of the results of all parameters in this study allowed us to predict their performances.

3. Results and discussion

3.1. Characterization of briquette samples

As the studied briquettes are made from different types of biomass (Table 1), it is necessary to characterize each briquette by determining their physicochemical composition and to compare them with eucalyptus charcoal. The characterization was conducted in an oven and a furnace for physicochemical parameters and an adiabatic calorimeter for the calorific content (CV_H). The findings from characterization of seven briquette samples with comparison to Eucalyptus Charcoal are presented in Table 2. The measured parameters are: volatile organic matter (VOM), ash content (A) and fixed carbon content (C_F) using analytical balance on the dry matter basis, while moisture (W) was carried from raw samples. The Eucalyptus Charcoal had been taken as a fuel reference (Mizero et al., 2015) due to its current use by the Burundian urban population. It was important to compare its calorific value with the studied fuel briquettes.

Table 2: Parameters value (Mean ± SD) for the seven types of briquettes (see table 1 for abbreviations)

Briquette	%W	%DM	% VOM	%C_F	%A	CV_H(MJ/kg)
BB1	9.34±0.67	90.66±0.67	77.66±0.63	20.22±0.62	2.12±0.01	17.88±0.30
BB2	9.61±0.66	90.39±0.66	37.05±0.84	22.70±0.92	40.25±1.03	12.29±0.54
PG1	7.59±0.25	92.41±0.25	20.89±1.8	57.17±1.73	21.94±0.59	18.63±0.89
PG2	5.96±0.88	94.04±0.88	18.83±1.59	45.30±0.88	35.87±1.10	17.9±0.30
BQS1	8.14±0.78	91.86±0.78	56.77±1.14	18.07±1.40	25.16±1.38	12.91±0.68
BQS2	7.72±1.08	92.28±1.08	55.14±1.51	17.62±0.72	27.24±2.09	13.94±0.22
TB	25.81±4.50	74.19±4.50	46.28±0.64	33.04±0.36	20.68±0.70	15.27±0.39
CBE *	5.28**	94.72**	30.63**	67.87**	1.5**	33.56***

(*) CBE : Eucalyptus Charcoal (**) Eucalyptus charcoal (Dusabe, 2014) (***)Eucalyptus charcoal (Mizero et al., 2015)

The results presented in Table 2 show that the briquettes under study are of a different composition, considering their physicochemical parameters (W, DM, VOM, C_F, A) and their energetic content. This confirms the observations made above in relation to the difference of raw materials used to produce them.

It is worth noting that high humidity proportionally reduces the calorific value of a fuel. The values of moisture content (%W) were in the order of 5%-10%, except for peat at 25% (Table 2). Moreover, PG1 and PG2 briquette samples showed have a lower value (7.59% and 5.96% respectively) compared to the other samples. This explained their higher calorific values compared to the other briquette samples. The different values of VOM, C_F and A obtained experimentally for briquette samples are discussed separately through sections 3.1.1. and 3.1.2.

3.1.1. Volatile organic matter (VOM), fixed carbon (C_F) and ash (A) contents

The experiment showed a high rate of volatile matters for the BB1 briquette (77.66%), followed by the BQS1 (56.77%) and BQS2 (55.14%) briquettes (Figure 2). These high levels of VOM are explained by the fact that these briquettes are made mainly of non-carbonized raw material, such as coffee hull; wood chips; cow dung (Table 1). For this reason, they will release more fumes in proportion to their volatile organic matter content. Considering their contents VOM, they were comparable to those studied by Oladeji (2010): respectively 67.98% for rice husk briquette and 86.53% for corncob briquette.

The ash content of the samples varied from 2.12 ± 0.01 to 40.25 ± 1.03% (Figure 2). The respective samples BB2 and PG2 displayed high levels of ash (40.25 ± 1.03 and 35.87 ± 1.10, respectively). For this purpose, the PG2 briquette was manufactured using clay as the sole binder. Although this clay has no energy value, once used, it progressively extended the heating while ensuring the structure of the fuel. The BB2 sample, whose composition seemed to be close to BB1, had a high ash content due to the method of composting and recovery of this compost: quantities of earth and sand were mixed with the organic matter, which negatively impacted the energy value of the fuel.

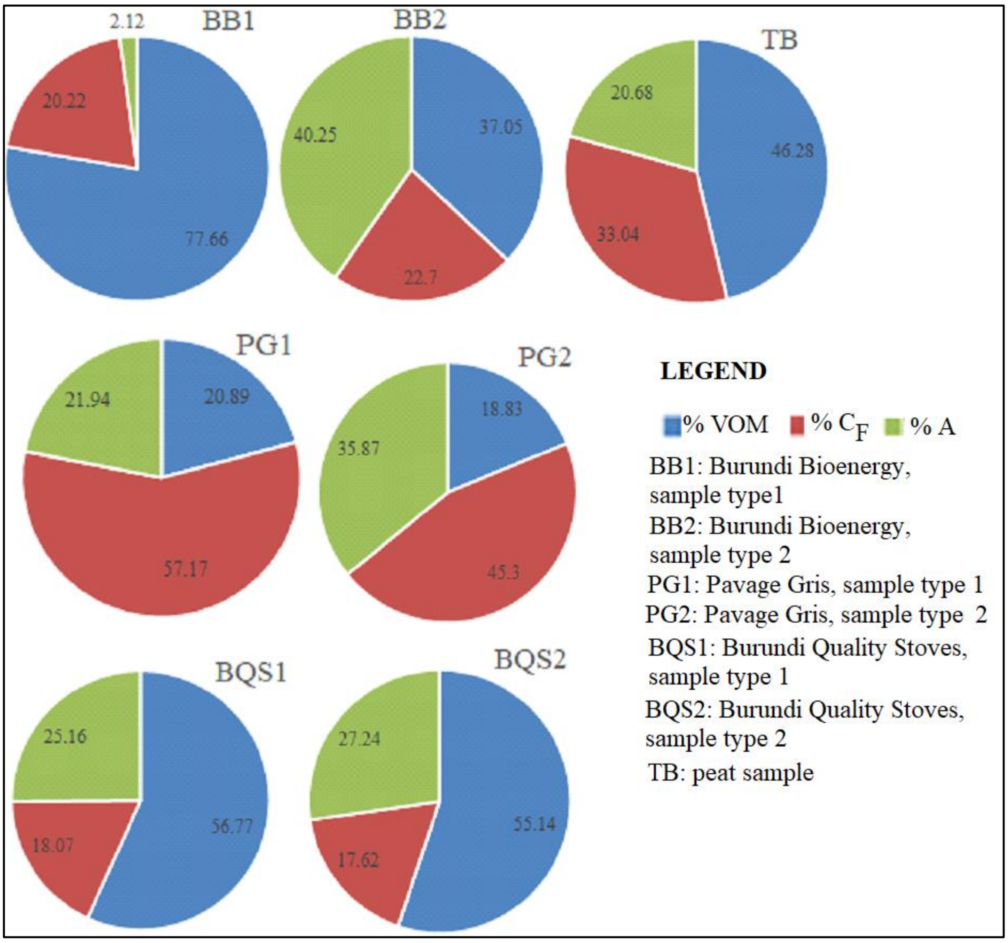


Figure 2: Percentage of VOM, C_F and A of the briquettes

The fixed carbon content was from 17.62 ± 0.72% to 57.17 ± 1.73%. The PG1 briquette took the 1st place with a content of 57.17 ± 1.73% (Table 1). This high content, close to that of charcoal (67.87%), was explained by the fact that this briquette was made of coal dust and cassava flour as binder which may also carbonize. Ours findings showed that the fixed carbon contents of our samples were higher than those found by Oladeji (2010) for briquettes from rice husk (13.4%) and corncob (12.07%). Moreover, these fixed carbon contents were higher, compared to those found by Raju et al. (2014) and reported in Table 3, for which the largest value was 19.42% (Table 3). The same observation can be emitted for the higher volatile organic matter content and the lower moisture content, except for the TB sample.

Table 3: The proximate analysis for fuel briquettes (Adopted from Raju et al., 2014)

Name of the sample	Moisture content (%)	Ash content (%)	Volatile matter (%)	Fixed carbon (%)
Sawdust	17.71	10.3	54.59	19.42
Badam leaves	18.20	15.8	47.3	18.7
Cocopeat	18.65	9.8	53.55	18.1

3.1.2. Low Calorific Value (CV_L) of briquettes

The calorific values were determined in an adiabatic calorimeter PARR model 1341, equipped with a calorimetric bomb model JK7-3058. Results of analysis showed that low calorific value CV_L varied from 12.72 to 18.46 MJ/kg (Table 4). During combustion, the moisture is removed in the form of water vapour (H_2O), as well as the water that forms from the constituent hydrogen of the fuel. Due to the lack of technical equipment to carry out the elemental analysis, we deduce the low calorific value the CV_L. We are satisfied with its estimate by deducting only the latent heat of vaporization of water from the CV_H sample: we thus obtain the low calorific value CV_L presented in table 4.

Table 4: High calorific value CV_H and Low calorific value CV_L (abbreviations: see Table 1)

Samples	CV_H(MJ/kg)	CV_L(MJ/kg)
BB1	17.88	17.66
BB2	12.29	12.06
PG1	18.63	18.46
PG2	17.9	17.75
BQS1	12.91	12. 72
BQS2	13.94	13.76
TB	15.27	14.67
CBE	33.56	32.44

Our results for calorific values (12.72 to 18.46 MJ/kg) are lower than those found by Hassan et al. (2017), for briquettes produced from carbonized *Martynia annua* woody shells and wood charcoal, whom low calorific value CV_L were between 5479.31 ± 4.14 cal/g and 6815.12±0.53 cal/g (equivalent to 22.93-28.51 MJ/kg).

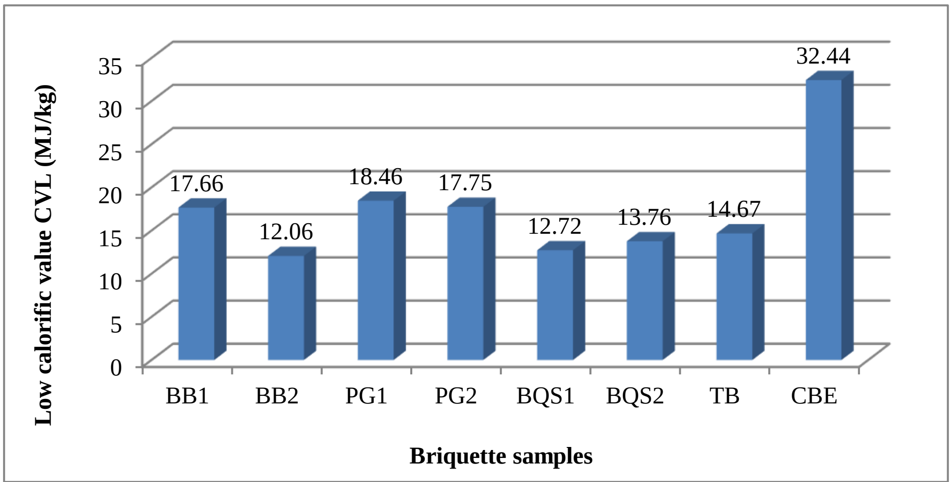


Figure 3: Low calorific value (CV_L) of briquettes samples

From the outset, we noticed that our briquettes have a CV_L more or less equal to half of the eucalyptus charcoal (Figure 3). A higher value of CV_L was observed for the PG1 (17.76 MJ/kg) and PG2 (18.46 MJ/kg) samples than for the other studied biofuels (BB1, BB2, BQS1, BQS2). These results showed that the samples under study had a calorific value of the same order of magnitude as those studied by different researchers (Njenga et al., 2009, Oladeji, 2010; Stolarski et al., 2013). Compared with eucalyptus charcoal, which releases 32.44 MJ/kg (Table 4), the briquettes studied in this work were poor to medium fuels. However, their value as substitutes for charcoal and firewood is undeniable. The types of briquettes, such as BB2, BQS1 and BQS2, whose heating value was relatively low (12.06 MJ/kg, 12.72 MJ/kg and 13.76 MJ/kg respectively), needs to be improved in order to increase performance and their acceptability.

3.2. Comparison of cooking tests of combustible briquettes

3.2.1. Kitchen tests

Various parameters of interest were measured to detect the possible differences of behavior between samples during the cooking: time of ignition (t_{ignit}), total time of combustion ($t_{tot.comb}$), time of boiling of the heated water (t_{boil}), volume of evaporated water and rate of combustion (Q_{water} and v_{comb}).

Table 5: Cooking tests with 0.5 kg of briquette samples (abbreviations: see Table 1)

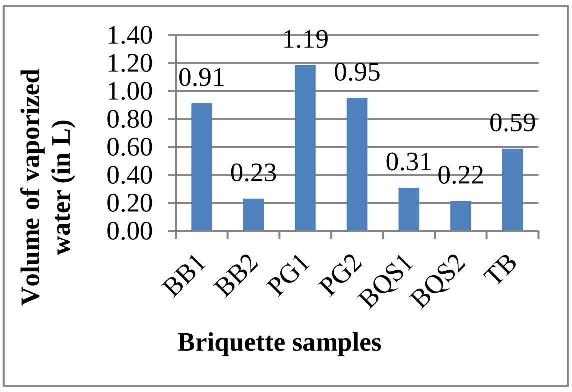
Sample's code	Origin	CV_H (MJ/kg)	Lv (MJ)	CV_L (MJ/kg)	$t_{totof\ comb}$	$t_{ignition}$ (min)	t_{boil} (min)	$Q_{water\ vap(L)}$	v_{comb} (g /h)
BB1	BB	17.88	0.215	17.66	86	4.4	75.0	0.913	348
BB2	BB	12.29	0.222	12.06	117	7.2	68.0	0.232	256
PG1	CTB	18.63	0.175	18.458	130	5.7	107.3	1.186	230
PG2	CTB	17.90	0.137	17.75	114	8.0	92.7	0.951	263
BQS1	BQS	12.91	0.188	12.72	104	8.8	48.7	0.31	288
BQS2	BQS	13.94	0.178	13.76	125	10.2	43.3	0.215	240
TB	ONATOUR	15.27	0.595	14.67	159	10.1	118.0	0.589	188
CBE	On market	33.56	0.115	32.44	90	9	74	>1.5	333

Total time of combustion ($t_{tot.comb}$) showed that the fuel briquettes did burn to ashes (Table 5) for a period ranging from 86 min (BB1) to 130 min (PG1). The combustion time was more than comparative studies of burning rates and water boiling time of wood charcoal and briquette (Hassen et al., 2017) which ranged from 73.5 to 95 min (close to 90 min, duration of Eucalyptus charcoal CBE). So, this result showed that these briquettes from municipal solid waste and residual biomass could more ensure prolonged heating of food than Eucalyptus charcoal.

It is important to note that in developing countries, charcoal wood is often obtained after deforestation, which has a negative impact on forest reserves (Malimbwi et al., 2000). On the other hand, the briquettes under study were made from waste (secondary raw materials) and can serve as one element in a circular economy. The promotion of these briquettes in Burundi would be innovative and environmentally friendly.

3.2.2. Rate of combustion (v_{comb}) and variation of the amount of water during heating (Q_{water})

By burning 0.5 kg of fuel briquettes in a fireplace on which we placed a pan containing a given quantity of water (1.5 L), the release of heat brings the water to boil and then vaporized. At the end of the test, it was possible to determine the quantity of water vaporized for each type of fuel (Q_{water}). For the 7 briquette samples submitted to this study, the findings showed the difference in their behavior during their combustion (Figure 4a and 4b).



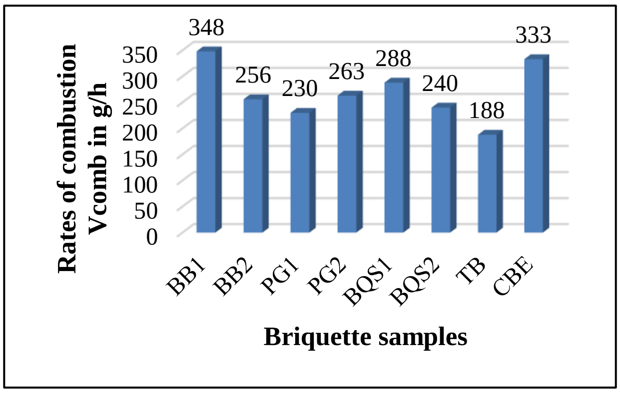


Figure 4a: Volume of vaporized water (L) **Figure 4b: Rates of combustion in g/h**

For 0.5 kg of briquette samples, kitchen tests showed that the amount of water vaporized varied from 0.22 to 1.19 L of water (Figure 4a), while that evaporated by charcoal exceeding 1.5 L.

The burning rate (v_{comb}) of the samples ranged from 188 to 288 g/h (Figure 4b); that of charcoal is 333 g/h (Figure 4b). Our findings were almost the same as those found by Hassan et al. (2017) for briquettes produced from carbonized *Martynia annua* woody shells and wood charcoal: 3.68 g/min to 4.76 g/min (equivalent with 220 g/h to 285 g/h). The PG1 and PG2 briquettes sprayed higher amounts of water (Figure 4a). This is explained by the fact that these two samples contain more fixed carbon (more energetic fraction). The PG1 briquette had a better performance because, in addition to coal dust and clay, it contains cassava flour playing a dual role (structural and energetic) in the briquette.

It was also noted that, apart from peat (TB) which is a fossil fuel, PG1 briquette burned at a low speed (230 g/h) compared to other biofuels, while extracting more steam. This showed that the burning time, more or less long, characterizes the slow or fast way the energy contained in a fuel is extracted during heating. Eucalyptus charcoal

(CBE) and BB1 briquette burned very quickly (Figure 4b), but have a different energy content (Table 4). This can therefore be indicative of a high level of porosity and volatile content.

The values of the different parameters from Table 2 and 5 have been used to obtain the correlation matrix shown in Table 6. This table had been made by bivariate analysis of each parameters, using SPSS 22. As one would expect, we find a highly significant ($p < 0.01$) correlation between the amount of water vaporized and the lower calorific value. The amount of water vaporized is well correlated with the fixed carbon content of the samples ($p < 0.01$), while volatile organic matter is inversely correlated with the fixed carbon. We think that this was indicative of how to improve the quality of the biofuels studied in order to increase their calorific value by increasing the fixed carbon content on adding materials that have been previously carbonized. At this point, we observed that biofuel briquettes made at Bujumbura did not have the same physicochemical characteristics because the constituent raw materials were different and then the hypothesis (a) was confirmed.

Table 6: Correlation matrix among physico-chemical parameters of the briquettes

Parameters	CVL	%C_F	%A	%VOM	Q_{water}	V_{comb}	%W
CVL	1						
%C_F	0.707	1					
%A	-0.452	0.135	1				
%VOM	-0.255	-0.814*	-0.686	1			
Q_{water}	0.966**	0.798*	-0.399	-0.352	1		
V_{comb}	0.174	-0.411	-0.455	0.569	0.111	1	
%W	-0.181	-0.035	-0.199	0.142	-0.110	-0.555	1

** : The correlation is significant at the 0.01 level

* : The correlation is significant at the 0.05 level

3.2.3. Combustion monitoring curves

The energy content of our briquettes can be evaluated by exploiting the temperature variation curves of the heated water.

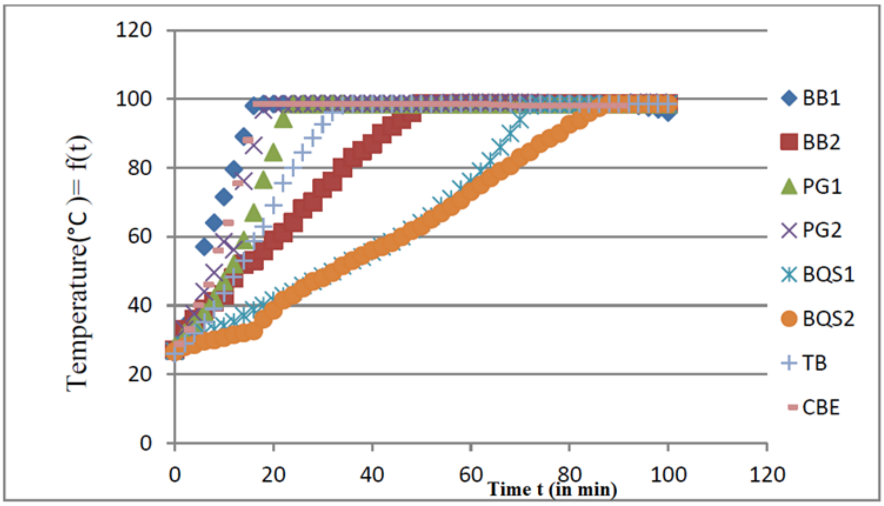


Figure 5: Variation of the water temperature as a function of the combustion time (t=time of briquette burning, T=f(t) in °C: temperature of water heated by 0.5 kg of briquettes)

The briquette samples BB1, PG2 and PG1 had approximately the same rate of combustion (0.5kg) and ensured the boiling of water (100°C) during 40-80 minutes (Figure 5); this time was slightly higher than that found by Hassan et al. (2017) from 12 to 15 minutes, during the combustion of 225 g to 275 g of briquettes. Their curves representing the temperature variation evolved linearly. This was explained by the fact that these samples had a high content of fixed carbon (20% -57%) and organic volatile matter (19%-78%) which released more energy during combustion (Table 2). They caught fire easily and provided rapid heating.

Peat (TB) and BB2 briquette had approximately the same average rate of combustion (35-50 minutes) (Figure 4, Table 2). These properties of the BB2 sample, which is made from fermentable municipal solid waste, highlighted the possibility of energy recovery from waste in developing countries (Schulz, 1979). Finally, BQS1 and BQS2 samples had poor combustion rates (Figure 5) and needed to be improved. Their curves of temperature (Figure 5) were almost sigmoidal. They burnt very badly, emitting a lot of smoke for a considerable time to reach the boiling point.

3.3. Ratio cost/energy evaluation for the briquettes

The selling prices registered from each selected company in this study for each package of briquettes (50 kg) are presented in table 8. It is clear that the prices of the briquettes hereafter reported are fixed on weight basis regardless of their qualities. From our physicochemical characterization we can deduct the price of the briquettes considering their energy content (cost/1000 kcal) and thus classify them in relation to Eucalyptus charcoal (Table 8).

Table 7: Prices of fuel briquettes on the market at Bujumbura

Briquette	Provider	Price/50kg ($)	Price/1kg ($)
PG1	BTC	8.13	0.16
PG2	BTC	8.13	0.16
BQS2	BQS	8.13	0.16
BQS1	BQS	8.13	0.16
BB1	Burundi Bioenergy	9.48	0.19
BB2	Burundi Bioenergy	9.48	0.19
TB	ONATOUR	9.87	0.20
CBE	City market	27.09	0.54

Concerning the price by weight, charcoal (CBE) remained the most expensive at a price of $0.54/kg while briquettes have a price ranging from $0.16 to $0.20/kg (Table 7). These prices of briquettes were in the same range of prices but slightly higher than those found by Stolarski et al. (2013) which varied from $73.8 to $152/t.

From an energy cost perspective, the cost for an energy of 1000 kcal issued from charcoal (CBE) was the most expensive at a price of $0.070/1000 kcal (Table 8). The price for the other briquettes ranged from $0.037 to $0.054/1000 kcal. Thus, CBE was more energy-efficient and had a higher heating rate than other biofuels but it is the most expensive. Furthermore, charcoal had a high rate of combustion, meaning a larger quantity of charcoal than the quantity of other studied biofuel briquettes was needed to cook the same amount of food. Therefore, CBE sample was the last one in the ranking among all others (8^{th} in Table 8).

Table 8: Ratio cost/energy of fuel briquettes on the market at Bujumbura

Briquette	CV_L MJ/kg	Cost in $ (/1000kcal)	Ranking
PG1	18.45	0.037	1
PG2	17.75	0.038	2
BB1	17.66	0.045	3
BQS2	13.76	0.049	4
BQS1	12.72	0.054	5
TB	14.67	0.056	6
BB2	12.06	0.066	7
CBE	32.5	0.070	8

In summary, briquettes could be classified in order of purchase prices (by weight), as follow: PG1, PG2, BB1, BQS2, BQS1, TB and finally BB2 (Table 8). Comparing the cost per 1000 kcal of each fuel, charcoal CBE was therefore at the last position (8th). However, BB1, BQS1 and BQS2 briquettes had a price respectively of \$9.48, \$8.13 and \$8.13 per bag (50 kg) in relation to their energy content, respectively 17.6 MJ/kg, 12.7 MJ/kg and 13.7 MJ/kg. Results showed that these prices (per bag or per kg) of briquettes were about the third of the price of charcoal (CBE) while having a half to a third of their energy contents. After this, we observe that the calorific value of biofuels can be used as a criterion in comparing the real cost of the briquettes. Then the hypothesis (b) is well confirmed.

4. Conclusion

The briquettes studied were made of different raw materials collected in Bujumbura. Their physicochemical analysis and the cooking tests showed that they are medium to poor fuels. Pearson's correlation matrix showed that there was a significant correlation ($p < 0.05$) between the fixed carbon content of the briquette samples and the quantity of water vaporized in cooking. Despite the negative correlation between VOM and fixed carbon, their value as substitutes for charcoal and firewood is undeniable. Some of them (PG1 and PG2) had high performances such as low speed of combustion and high fire resistance. The cost/energy ratio of the briquettes is interesting for the briquettes, referring to the charcoal which is very expensive. So, biofuel briquettes would be more efficient overall than charcoal and could then be used by households as valuable substitution fuels. Nevertheless, their improvement remains necessary in order to enhance their performance.

The issue of domestic energy is still a major concern in developing countries such as Burundi, where the majority of the population exclusively uses firewood, charcoal and agricultural residues, which has consequences on deforestation. In addition, the use of DSM and biomass as raw material for manufacture of these briquettes would therefore allow the reduction in volume of MSW on landfills (circular economy). Then the promotion of briquettes from MSW would be a contribution to forest conservation with a positive impact in the fight against drought and climate change. Further research may focus on the improvement of the calorific value of briquettes made from waste and biomass residues and the evaluation of their content in heavy metals.

Conflicts of interest

There are no conflicts to declare.

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