Potential of densification of mango waste and effect of binders on produced briquettes

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Abstract: In Uganda, agro-processing of fruits produces large volumes of agricultural wastes, much of which are not utilized but disposed in the landfill. This study explored the possibility of producing biomass briquettes from mango waste (seed covers) that could be used for energy supply in small factories and for domestic cooking. Mangoes were selected because of their abundance throughout the country and its high fiber content which is a good property for a raw material for briquetting. Dried mango seed covers were crushed to particles of size 2 mm and bonded with three different binders; starch, starch-clay soil, and starch-red soil. The best mixing ratios for briquettes were; 4:1 (seed-cover: starch), 9:2:1 (seed cover: starch: clay soil), and 16:4:1 (seed-cover: starch: red soil). The formed briquettes were subjected to several standard methods to verify their suitability as fuels. The briquette properties tested were moisture content, volatile matter, ash content, fixed carbon content, calorific value, compressive strength, and gas emissions. Results showed that briquettes bonded with only starch had higher fuel properties ($p \leq 0.05$) with low: moisture content (11.9%), volatile matter (16.0%), ash content (2.8%) and emissions (0.178% CO, 0.0021% $(CH)_X$, 1.14% CO_2 and no NO_x); higher fixed carbon (69.3%), breaking strength (maximum force, 34 N and compressive stress, 273 N/mm^2) and calorific values (16,140 kJ/kg) compared to starch-red soil and starch-clay soil briquettes. But after a linear regression analysis, results further showed that maximum force (R^2 = 0.636) and ash content (R^2 = 0.520) were good indicators of energy content of a particular briquette. However, more research is needed on using other binder types rather than cassava starch which is considered as food.

Keywords: Agricultural wastes, binders, briquettes, briquette properties

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1 Introduction

In Uganda, energy use distribution is skewed to biomass use which supplies more than 90% of the country’s energy needs, with wood representing 70%, charcoal16% and crop residue at nearly4% (Hamish, 2012). Other energy sources include fossil fuels which account for 5% and hydroelectricity only 5% from two large dams and small hydro projects. About 95% of the Uganda’s population cannot access electricity because of the slow spreading of grid connections country wide (Kamese, 2004). In Uganda, biomass inform of wood fuels is still a major source of fuel to both rural and urban populations. Because of this, fuel being cheap and often free, it has contributed to its dominant use and easy accessibility by many people. The use of wood fuels is also extended to small scale industries like brick and tile production, agro-processing, and fish processing (Chaney, 2010).

Over the years, the over exploitation of forests to collect wood fuel have led to forest’s constant exhaustion,

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irregular rampant soil erosions, and non-uniform and unreliable rainfall distribution (Mani et al., 2006). In Africa, the search for fire wood is left to children and women who walk long distances hence reducing the time they put in agricultural production and other household activities. It results into low production, low incomes and household food insecurity (Kagere, 2012). Though some urban population that are above poverty line have access to fuels like kerosene, LPD gas, electricity, still these fuels are relatively expensive to be used as the only energy sources for cooking. Incidentally, fuels like kerosene, LPD gas when burnt, emit greenhouse gases which have contributed to global warming (Sugumaran and Seshadri, 2010).

Every year, agricultural wastes are collected in large volumes from homes, markets and processing industries to the landfills. This contributes to biochemical reactions which take place on landfill sites leading to formation of methane and leachate that pollute the atmosphere and ground water (Sugumaran and Seshadri, 2010). Some homes dry the waste in the back yards and later burnt inefficiently in the loose form causing air pollution. The habit of people throwing away wastes into water channels during rainy season has been the major cause of floods in some areas around Kampala. Most people have not realized that these agricultural wastes are potential huge source of energy giving materials derived from the animal and plant residues (Jekayinfa and Omisakin, 2005). Nevertheless, these agricultural residues have so many disadvantages, mostly attributed to low bulk densities but can be converted into high density fuel by briquetting. Therefore, wastes can be recycled into a renewable energy source by converting the biomass into high density fuel which is offered in acceptable form and at a reasonable price (Kaur et al., 2012).

From the bioenergy literature, research has been conducted using different agricultural wastes and binders to produce briquettes having different heating values. Briquettes have been produced from saw dust of different wood species, wood ash, cow dung and starch (Emerhi, 2011); coconut husk and waste paper (Olorunnisola, 2007); rice husk, saw dust and waste paper (Chin et al., 2008); wheat straw, saw dust and waste paper (Demirbas and Sahin, 1998), etc. However, not much is known on briquette production using mango wastes generated from either agro-processing industries or homes.

Mangoes are among the common fruits that are consumed by many people and also used in juice production from their extractions in agro-processing industries in Uganda. And during their processing and raw consumption, seeds and peelings generated as waste are not utilized. They are disposed off and left to decompose or dried and burnt in a loose form which results into air pollution (Aina et al., 2009). However, the declining fuel wood and charcoal sources and rising prices of electricity, kerosene and LPG cooking gas calls for seeking alternative energy sources for both domestic and industrial use (Hamish, 2012). Therefore, this study attempted to find out whether these wastes have potential as an alternative source of fuel if densified and used as briquettes and also to assess the effect of binders on the properties of the briquettes produced. The physical and thermal fuel properties of briquettes were evaluated to determine their suitability for use.

2 Materials and methods

2.1 Source of waste and material preparation

Mango wastes were collected from Food Technology Business Incubation Center (FTBIC), Makerere University, Kampala, Uganda. Wastes were then transported to Makerere University Agricultural Research Institute Kabanyoro (MUARIK) in Wakiso district for further briquette production processes. The raw material was prepared from the wastes through series of steps, involving drying under solar dryer to moisture content of about 10% to 15% as proposed by (Mishra and Grover, 1996). The selected waste was mango seed covers which were separated from the mango pulp by crushing after drying to obtain the fibrous seed cover. The seed covers were milled to smaller particles that passed through a sieve of 2 mm. This was done to increase the surface area of the material which improves on the binding and strength of the binder-particle and inter-particle bonds.

2.2 Binder preparation and mix combinations

2.2.1 Starch binder

A paste was made from 153 g of cassava flour and

0.02 L of cold water maintained at 10 ℃ and thereafter poured into 0.08 L of boiling water at a temperature of 100 ℃. Continuous mixing was done to produce a good binder with more water and less sticky. In the final mixture making up the required binder, water was allowed to disperse without any clumps of flour, which took 10 min.

2.2.2 Clayey soil

A block of dry clayey was obtained and crushed into small clamps which were after soaked into water in a basin until all were dissolved to form soft clayey soil. The soft clayey helps to increase the binding strength properties within the selected material other than the dry clayey.

2.2.3 Red soil

The red soil was got from the anthill found in one of the gardens at MUARIK and was also dissolved in water. Such soil is reddish in colour and classified as RhodicFerrolsols according to FAO-UNESCO (1988). Taxonomically the soil is highly weathered and devoid of weathered mineral. Ants obtain the soil from a depth of about 30-70 cm with following horizontal description: Reddish brown 5 YR 4/4 moist, clay loam; weak coarse angular blocky; friable sticky, slightly plastic; few fine roots; many termite channels and fine to medium pores; diffuse boundary. The soil is deficient in soil organic matter and has low total N, pH, available P, K, and Ca. The aim of considering these soils is because they are capable of increasing the binding strength and the density of briquettes.

2.3 Mixing combinations

The applied binder mix combinations used were; 1) starch and clayey soil, 2) starch and red soil, 3) starch. Different ratios were used by weighing the raw material (crushed mango seed cover) and corresponding binders respectively using a digital weighing scale. The mixture of raw material and binder proportions used to produce the briquettes with desired qualities were summarized in Table 1.

Table 1 Mixing ratios for the desired produced briquettes

Mixture	Proportions
Seed cover: Starch: Clayey soil	9:2:1
Seed Cover: Starch: Red soil	16:4:1
Seed cover: Starch	4:1

2.4 Briquette production process

Each mixture was filled in the mold and placed on to the pressing hydraulic machine for compaction. The maximum compaction pressure was 100 MPa read from the pressure gauge which was inserted at the pressing point of the machine. This helped in regulating the constant compaction pressure and prevention of oozing out of the binder. Twenty cylindrical briquettes with diameter of 4cm and height 2.5 cm (see Figure 1) were produced from mixing ratios of binders given in Table 1. They were then dried in solar dryer for three weeks at MUARIK.

a. Starch briquettes b. Starch-Clayey soil briquettes c. Starch- Red soil briquettes

Figure 1 Produced briquettes

2.5 Preparation of specimen for fuel properties tests

Samples of starch, starch-clay soil, and starch-red soil briquettes made from mixing ratios given in Table 1 were selected for grating and filing to get specimen with finer and smaller particles which were used in fuel properties determinations.

2.6 Determination of physical properties of briquettes

2.6.1 Density

Density was calculated from the ratio of the mass to the volume of the briquette. Mass was obtained by weighing the briquette on the digital weighing scale and volume using the formula of cylinder while subtracting off the volume of the hole within the briquette.

2.6.2 Compressive strength

It is the maximum crushing load a briquette can withstand before breaking or cracking. Compressive resistance was determined using diametrical compression test as performed by (Kaliyan and Morey, 2009), using a Universal Testing Machine-Tinius Olsen H50KT. The load was applied perpendicular to the axis of the briquettes. Maximum force (N) and compressive stress (N/mm^2) were recorded before breaking and cracking of the briquettes. Q_{wat} software plotted out the stress-strain curve on the monitor and then values imported into the Microsoft Excel™.

2.7 Determination of combustion properties of briquettes

Volatile matter was determined as per ASTM E897-88 (2004) standard procedures. Ash content was determined using ASTM E830-87(2004) standard procedures. Moisture content was determined using the gravimetrical oven method as performed in ASTM E1358-97(2013) standard procedures. Gross energy calorific value was determined as per ASTM E711-87(2004) procedures using the bomb calorimeter. The percentage fixed carbon was calculated using the equation in accordance with (Akowuah et al., 2013), where the sum of the percentages of moisture content, ash content and volatile matter was subtracted from 100%.

To carry emission tests out, briquettes were packed on the domestic clay stoves and ignited (Figure 2). The gas analyzer was set to the available room gases before reading off the emitted gases from the screen in accordance with (Yuhazri et al., 2012). After sometime, concentrations of emitted gases were recorded during the burning and without burning of briquettes. A gas analyzer read concentration of carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x) and unburnt hydrogen carbons ($(CH)_X$).

a. Starch-Red soil briquettes b. Starch-Clayey briquettes c. Starch briquettes

Figure 2 Testing emissions from, A) Starch-Red soil briquettes, B) Starch-Clayey briquettes and C) Starch briquettes

2.8 Experimental design and statistical analysis

The experiment was set up as a completely randomized experimental design with three treatments (starch, starch-clay, starch-red soil) replicated three times. Data was then analyzed for differences among treatment means based on fuel properties (moisture content, volatile matter, ash content, fixed carbon content, calorific value, and compressive strength) using SAS statistical software (SAS Institute, Cary, NC, USA). A one-way analysis of variance (ANOVA) was performed and treatment means separated using Waller-Duncan K-ratio Test to test for significance differences ($p \leq 0.05$) in the properties exhibited by the different briquettes. The obtained significant fuel properties were further analyzed to find out which factor highly influence the briquettes' calorific values by setting up a linear regression model using Excel (Microsoft Corp., 2007) and an R-squared (R^2) factor was used.

2 Results

The physical and combustions properties of the briquettes produced from mango seed covers were limited to density, compressive strength, percentage moisture content, percentage volatile matter, percentage ash content, percentage fixed carbon and the calorific value. Table 2 is showing the mean values of physical and combustion properties of the briquettes.

Table 2 Mean values of physical and combustion properties of mango seed cover briquettes

Briquette types^z	Physical parameters				Combustion parameters			
	Density, kg/m^3 ×10^3	Maximum Force, N	Compressive stress, N/mm^2	Moisture content, %	Volatile matter, %	Ash content, %	Fixed carbon, %	Calorific value, kJ/kg ×10^3
Starch-Clayey soil	1.66b	183.7b	22.9a	11.9a	22.9a	10.2b	66.9b	15.918a
Starch-Red soil	1.559b	160.7b	16.7a	11.0a	20.6b	10.9a	68.5b	15.100a
Starch	1.464a	272.6a	34.0a	11.9a	16.0c	2.8c	81.2a	16.140a

Note: z, Elements with same letter within columns are not significantly different ($p \le 0.05$).

3.1 Physical properties of briquettes

3.1.1 Density

The average densities for briquettes from different binder combinations are shown in Table 2. The densities exceeded the range of 1,100 kg/m^3 for briquettes made from charcoal saw dust by (Akowuah et al.,2012), produced by use of a screw press briquetting machine at a die pressure range of 100 to 200 MPa with no additives and starch as binders. This implies that our briquettes are denser and have a longer burning time when used for drying and heating or cooking. However, there was a difference ($p \le 0.05$) between the density of starch briquettes compared to starch-clayey and starch-red briquettes because of the addition of the bulky densities of such soils to the material with starch during the mixture compaction, thus have much influence on briquette density variations whose bulky densities were added onto the total density of briquettes (Olorunnisola, 2007).

3.1.2 Compressive strength

The maximum force and compressive stress of starch briquettes were higher than briquettes produced from other binding materials (*starch and clayey soil, starch and red soil*) in Table 2. There was a difference ($p \le 0.05$) between the maximum force on starch briquettes compared to other briquettes because of variations in the strength of bonds between the material and binder and within the particles. The use of other binders like red and clayey soils has particles which tried to co-exist between the inter-particle bonds as well as binder-material bonds. Other reasons of weaker bonds probably was because the soil particles tried to block the inflow of binders mainly starch into the material particles. Since the breaking strength increases with increasing compacting pressure (Kers et al., 2010), this explains that all the voids within the material were all filled by the starch. Additionally, the compressive stress was not different ($p \le 0.05$), probably because the constant applied compressive forces were acting upon the same cross sectional areas of the briquettes. Briquettes (*starch -clayey soil, starch-red soil*) with low breaking strength were weak which caused them to crumble faster during burning and easily break during their transportation to the potential end users. Also such briquettes burn at a shortest time and less heat is generated in the process. High compressive stress and maximum force of starch briquettes, indicates more volume displacement which is good for packaging, storage and transportation and above all, it is an indication of good quality briquettes because of the strong inter-particle bonds (Kaliyan and Morey, 2009).

3.2 Combustion properties of briquettes

3.2.1 Moisture content

There was higher moisture content in briquettes made using starch and starch-clayey binders compared to those produced with starch binder (Table 2). But, there was no difference ($p \le 0.05$) between moisture content of all briquettes because the material was dried to the recommended levels which did not exceed 10% and this was also pointed out by (Olorunnisola, 2007) and (Mishra and Grover, 1996). And also at 18% moisture content level and below, the material does not contain free water but water is chemically bonded within the material (bound water), thus properties will not be influenced by moisture content so long as it is less than 18% as shown in Table 2 (Olorunnisola, 2007). Another factor was that all the briquettes were dried under the same conditions (same solar dryer, drying temperatures and drying times). The mean percentages of moisture content were slightly higher by 0.09% in starch-clay briquettes compared to starch-red soil briquettes, because a binder additive like clayey is less porous than red soil and do not easily loose water to the atmosphere at drying temperatures. Moisture content determines the briquette quality and burning characteristics of briquettes. When the moisture content is low, the briquettes will easily be ignited, no slaggness during burning will occur and higher calorific values are expected from the fuel. Moisture content levels help in planning of proper handling of the briquettes when stored and during transportation to the access points by the consumers. This prevents the deviation from the required moisture range of about 10% to 15% according to (Mishra and Grover, 1996) due to hygroscopic properties of the material being handled. This range identified by Mishra and Grover (1996), results into a denser, more stable and more durable briquettes. With high moisture content in the briquette, much of the heat will be used to vaporize the surplus water and sometimes briquettes tear into pieces with low burning rate and less heat is generated with too much smoke emitted (Akowuah et al., 2012).

3.2.2 Volatile matter

There was variation in volatile matter of briquettes produced as observed in Table 2. There was a difference ($p \leq 0.05$) between volatile matter of the starch, starch-clayey and starch-red soil briquettes which was expected, because clayey and red soils are known to have insignificant quantity of organic matter but with predominant inorganic particles. Therefore, high proportion of volatile matter was a result of high proportion of organic matter in the material (Olorunnisola, 2007). However, the values of volatile matter were higher than those obtained by other researchers like; (Akowuah et al., 2012); (Emerhi, 2011); (Olorunnisola, 2007), which explains that the material and binders which were selected are better for briquetting. Briquettes had relatively high volatile matter which is an indication of easy ignition, fast burning and proportionate increase in flame length. Some biomass generally contains high volatile matter of around 70% and 80% with low char content (Akowuah et al., 2012). This makes mango seed covers bonded with starch having lowest volatile matter to be highly reactive giving a faster combustion rate during the devolatisation phase than other briquettes. Briquettes(starch and starch-red soil)with much lower volatile matter have an incomplete combustion which contributes to release of significant amount of smoke and toxic gases (Akowuah et al., 2012) which is supported by the emission results in Figure3.

3.2.3 Ash content

Briquettes from starch had very low ash content, followed by starch-clayey briquettes and lastly starch-red soil as shown in Table 2. The cause of difference ($p \leq 0.05$) between ash content of all briquettes was a result of the added proportions of clayey and red soil which have particles within their bonded structures which easily turn into ash after combustion. This was also observed by Olorunnisola (2007). Briquettes bonded with only starch without clayey and red soils released less ash content thus improving their quality. In terms of saving on handling and disposal costs after the briquettes have been used for various economic purposes, which is an added advantage (Olorunnisola, 2007). Ash is the non-combustible component of biomass and it influences ($p \leq 0.05$) on the heat transfer to the surface of the fuel as well as the diffusion of oxygen to the fuel surface during char combustion. High ash content results into dust emissions which lead to air pollution and affects the combustion volume and efficiency. The higher the fuel's ash content, the lower its calorific value since it influences the burning rate due to minimization of the heat transfer to fuel's interior parts and diffusion of oxygen to the briquette surface during char combustion (Chaney, 2010). Hence, briquettes made from starch are most suitable for cooking and showed higher calorific values ($p \leq 0.05$), which believed that ash in this case was the dependent factor.

3.2.4 Fixed carbon

The percentage fixed carbon of briquettes from starch was higher than starch-red soil and starch-clayey soil as presented in Table 2. However, there was a difference ($p \leq 0.05$) between starch briquettes compared to others because clayey and red soils in their compaction state, they are believed scientifically for having low fixed carbon thus prolonging the cooking time of briquettes due to their low heat release (*bake-oven effect*) (Olorunnisola, 2007). The fixed carbon of the briquette is a percentage of carbon (solid fuel) available for char combustion after volatile matter is distilled off or lost to the atmosphere. Therefore, fixed carbon gives a rough estimate of the heating value of fuel and acts as the main heat generator during burning (Akowuah et al., 2012). When only starch was used as the binder, gave a high percentage of fixed carbon suggesting the reasons as to why high calorific values were exhibited by these briquettes. Fixed carbon positively correlated with carbon monoxide, with less fixed carbon contained in the briquettes gave less carbon monoxide. And this is strongly supported by the emission results presented in Figure 3 from all briquettes. The low fixed carbon in starch-clayey briquettes indicates prolonged cooking time but with low heat released, because of the effect of added clayey which tends to reduce the calories of the briquettes by causing the fuel-saving effect (Olorunnisola, 2007).

3.2.5 Calorific values

According to Table 2, heating values for starch, starch-clayey and starch-red soil briquettes reduced in that sequence as listed respectively. They also compare well with most biomass energies, for examples; groundnut shell briquette- 12,600 kJ/kg (Kaliyan and Morey, 2009); cowpea- 14,372.93 kJ/kg and soybeans- 12,953 kJ/kg (Enweremadu et al. 2004); rice husk- 13,389 kJ/kg and Corncob briquettes- 20,890 kJ/kg (Kaliyan and Morey, 2009). However, there was no difference ($p \leq 0.05$) between the calorific values of briquettes. Because all the binders used (starch, clayey and red soils) are known to have the ability to release as much heat as possible as also observed by different scientists like (Emerhi, 2011) and (Olorunnisola, 2007). The type of binders used is one of the important factors which should be considered during briquetting with aim of enough heat released. Different researchers have observed that clayey and red soils have bake oven effect and fuel-saving effect with contribution to heat released from the briquettes. And since the aim of briquetting the agricultural residues, is to produce a good and efficient high giving energy fuel source that can support combustion, use of the material-starch ratio is one of the best mixture to be considered when briquetting mango seed covers. During combustion, starch briquettes exhibited better flame length and ignition qualities with desired energy values which are good to produce the required heat to be used in processing industries and households. The structure of the briquettes with the hole in the center also contributes to the combustion properties of the briquettes since it helps in the circulation of air for continuous burning.

3.2.6 Emission concentrations

High carbon dioxide and carbon monoxide concentrations were emitted from starch-red soil briquettes, followed by starch briquettes and starch-clayey briquettes (Figure 3). Since fixed carbon is the main component of the formation of carbon monoxide, with less fixed carbon contained in the briquettes, low carbon monoxide is expected. Volatile matter is also important for conditioning the reaction of conversion of carbon monoxide to carbon dioxide because the combustion of volatile matter results into higher heat than solid phases which involve only conduction of heat transfer by briquettes volume (Abqari et al., 2009). The increase in temperature supports the formation of carbon dioxide which then reduces the carbon monoxide emission during the subsequent burning of briquettes. The high increase for carbon monoxide in starch-red soil and starch briquettes reflects the dominance of char burning compared to flaming combustion (Edwards et al., 2004). A good quality briquette is one that contains small amount of CO, $CO_{2,}$ NO_x gases released during combustion. Because such gases cause air pollution and have effects to human health and thus hazardous to people involved in cooking.

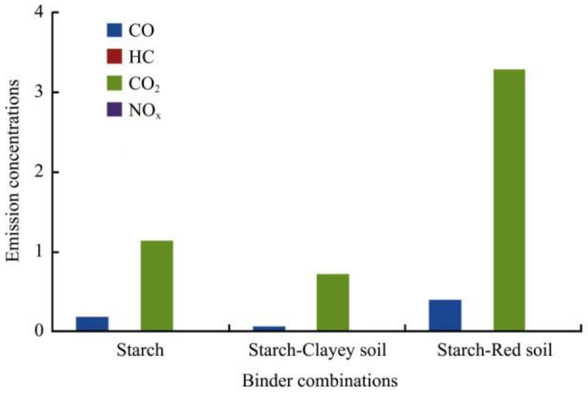

Figure 3 Variations of emissions from combustion of produced briquettes

3.3 Determining the degree of influence of significant fuel properties on the calorific values of briquettes

In order to come up with a comparison and relationship between the calorific value with the rest of fuel properties that could be explained statistically, a linear regression analysis model (Figure 4) was selected and used for analysis. The R-squared coefficient was used to determine a better estimate for the degree of influence of the properties on calorific values of briquettes, where calorific value was the dependent factor and properties such as maximum force, volatile matter, ash content and fixed carbon as the independent factors. The obtained R^2 values for each factor where; maximum force-R^2=0.64 (*positive correlation*), volatile matter-R^2=0.15 (*negative correlation*), ash content- R^2=0.52 (*negative correlation*) and fixed carbon-R^2=0.34 (*positive correlation*). Maximum force and ash content had higher R^2 values which explain that these properties have much effect on the calorific values of briquettes. Also looking at the correlations of each factor, further explains that when maximum force is increased, the more heat values given out and the more ash content increases, the heat values reduces. Therefore, these two factors are the most important variables which should be considered during the aim of efficient energy supply from mango seed cover briquettes.

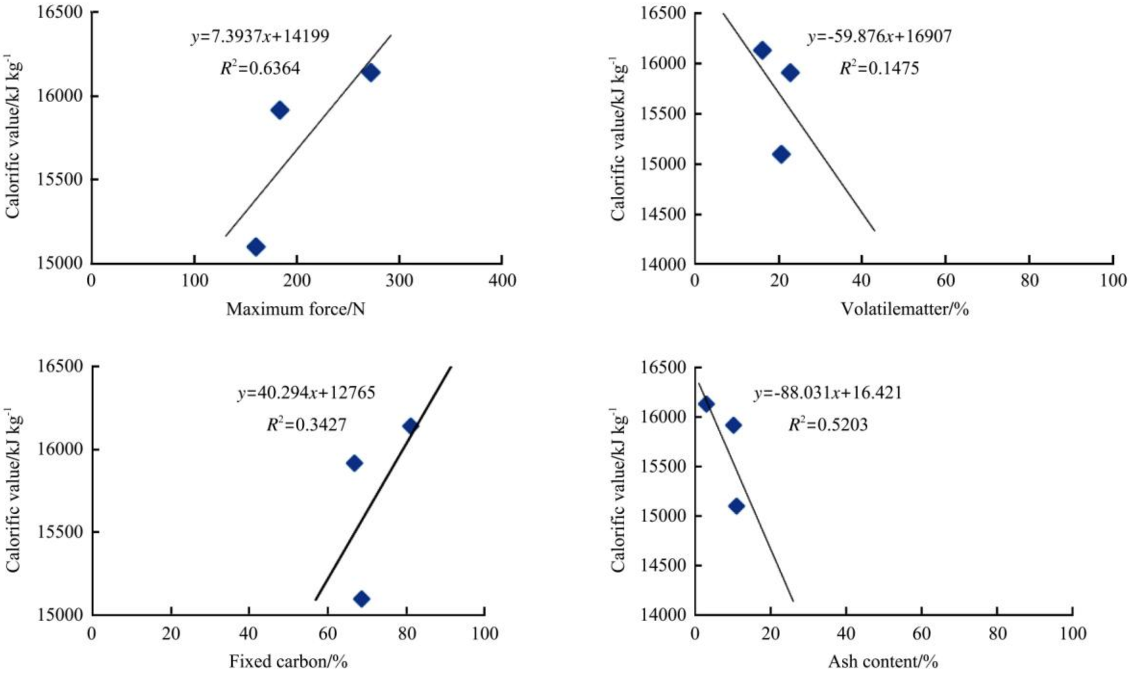

Figure 4 Linear regression analyses for the significant fuel properties and calorific value

4 Conclusions

The following conclusions can be drawn from this research:

- Mango wastes such as seed covers are potential raw material for briquette production
- The quality of briquettes produced from the seed covers are highly influenced by the binder types used
- To have high heat released which is enough for drying, heating and cooking, the material should be bonded with starch. Starch briquettes also have more benefits linked to less release of carbon, ash and emissions which have effects to the atmosphere
- The particle size of the material plays an important role during material preparation for briquetting. and 2 mm particle size forms a fibrous(powder-like) product essentially suitable for material densification
- Ash content and maximum breaking force are the best indicators and determinants for the heat values produced by these briquettes
- With this alternative of clean energy use of briquettes, there will be reduction on the number of trees cut per year for firewood thus mitigating the occurrences of climate changes. The amount of starch flour required to produce one hundred (100) briquettes is approximately 0.5 kg of flour. This can be obtained from ¾ of the whole piece of

cassava finger. Although some starch can be obtained from cassava wastes, there is a need to quantify the impact on household food security if cassava flour is to be used a binder in briquette production. Thus, more research is needed to explore other binders than cassava starch.

Furthermore, survey on cost analysis and adoption of this technology has to be carried out to show the acceptability and future market potential for mango waste briquettes among households and processing industries.

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