Proof of concept for using banana waste based binders in sawdust briquetting: Comparative studies between raw and carbonized sawdust

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Abstract. A comparative study of carbonized versus raw sawdust briquettes production using a banana waste based binder was conducted. The binder was formulated from banana pseudo stem, pith, ripe banana, green banana in the ratio 2:2:1:1. Sawdust was pyrolyzed at temperature ranges of 300-350℃, 370-470℃ and 600-700℃. Briquettes were produced using a gravity aided press (GAP). The mechanical and combustion properties of the briquettes were compared to assess binder effectiveness on both feedstocks as well as the extent of improvement introduced by carbonization. Comparable shatter indices of 0.96 and 0.95 and densities of 425 kg/m3 and 685 kg/m3 for carbonized and raw sawdust-based briquettes respectively indicated that the binder performs well with both feedstocks. Proximate analysis indicated that carbonization increased the solid fuel quality through a 39%, 16% and 41% decrease in moisture content, volatile matter and ash content respectively, and a 35% increase in fixed carbon. Carbonized briquettes demonstrated shorter ignition time, a steadier burn rate, shorter time to boil and higher calorific value by factors of 53%, 47%, 32% and 15% respectively compared to raw sawdust briquettes. Conclusively, banana waste-based binders can be used with carbonized sawdust to produce higher fuel quality briquettes for grilling and space heating.

1 Introduction

Manicaland province in Zimbabwe enjoys a climate that promotes intensive agriculture and forestry activities [1]. However, value addition processes to timber and fruit products such as banana generate substantial quantities of wastes in the form of sawdust, bark [2], banana stem and banana fruits that are not fit for marketing [3]. Stockpiles of biomass waste left unattended to over time decompose naturally to generate methane which has 25 times global warming potential (GWP) than carbon dioxide [4]. Health related challenges associated with stockpiles of rotting banana fruits especially in landfills include

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groundwater contamination, air pollution, proliferation of pathogen vectors such as mosquitoes and tsetse flies [5]. Specific to sawdust stockpiles, human inhalation of sawdust fines blown by the wind cause respiratory tract diseases [6]. Additionally, the risk of veld fires is high in areas with sawdust stockpiles and these fires have much wider detrimental effects to the environment and the ecosystems [7]. Fortunately, these biomass residues can potentially be converted into the much needed energy resources through carbonization and densification techniques.

Sawdust densification to fuel briquettes using banana wastes as binders presents an opportunity for generating energy while cleaning the environment, increasing revenue streams for the waste owners and contributing to job creation. Fuel briquettes have numerous advantages and applications in both domestic and industrial settings [8]. Recently sawdust was successfully densified after torrefaction and the process included a preheating stage of the biomass to activate inherent binders such as lignin to effect strong particle bonding [9]. Torrefaction or pyrolysis is a necessary step that however requires heat expenditure to produce a high grade briquette that can be used indoors [10]. For outdoor use for example in steam boilers the sawdust can be densified without the carbonization pretreatment stage to improve the overall process energetics [11] In some cases, sawdust has been used in co-briquetting with other fuel sources such as coal [12], rice husks [13] and other sawdust-biomass mixtures [14]. Although, the briquetting of sawdust is a proven science, at low temperatures, the process requires addition of an external binder to facilitate strong particle bonding [15].

Most of the commercially available briquetting binders are either costly, reduce briquette calorific value or they compete with feedstocks for animals/humans [15], [16]. The latter drawback brings into the discussion the controversial food versus energy debate if for example we are to use carbohydrate based binders such as molasses [17], cassava [18] or corn starch [19] in briquettes production. To circumvent the aforementioned challenges, it is better to use binders from other agro-processing wastes which are underutilized such as banana wastes. These have been earlier reported to be readily available in the case study region of Manicaland. Banana harvesting wastes fall into different types such as the leaves, the pseudo-stem, fruit bunch stem and the banana fruits (ripe and unripe). These wastes have been used separately as feedstock or in combination with other feedstocks (co-briquetting) in different studies [20]. The banana wastes can be used as binders rather than feedstock especially in the case of abundant and alternative feedstocks such as sawdust [21]. Apparently, to the best of our knowledge, no publicly available scholarly work has previously investigated the use of combined banana wastes as binders for carbonized sawdust briquette production.

The aim of the present study is therefore to investigate carbonized sawdust densification into fuel briquettes using a previously optimized binder for raw sawdust formulation consisting of the various banana harvesting wastes. The briquette characteristics of carbonized sawdust shall be compared to those of raw or uncarbonized sawdust.

2 Materials and methods

2.1 Materials

In this study banana wastes were collected and gathered from a local farmer in Burma Valley, Manicaland, Zimbabwe and sawdust was also collected from a saw milling company in Mutare, Paulington industrial area.

2.2 Experimental Method

The workflow for briquette production from sawdust and carbonized sawdust using banana wastes as binder is depicted in Figure 1. Briefly, sawdust was carbonized at 450oC in a custom fabricated pyrolysis reactor (Figure 1a). The pyrolysis reactor surface temperature was monitored using a temperature controller based on a thermocouple (DIGI-SENSE Model 20250-19). Sawdust was loaded into the pyrolysis chamber while dry firewood was loaded into the burning chamber of the reactor. The combustion chamber was ignited and regularly the amount of firewood in the burning chamber was increased or reduced in tandem with the thermometer readings from the pyrolysis chamber to keep this temperature in the region of 300-350 oC.

Initial tests to determine the minimum possible time for complete carbonization using this lower temperature range were done using 4 hrs, 5 hrs, 5hrs 30 mins then 6 hrs. Below 6 hrs, there was incomplete carbonization at to various extents (Figure 1a). Satisfactory carbonization was achieved at 6hrs and beyond (Figure 1b), therefore this batch time was applied uniformly across the temperature ranges.

Pyrolysis was then undertaken at other temperature ranges of 370-450 ºC and 600-700 ºC..

Fig. 1.. (a) Pyrolysis reactor and (b) briquetting equipment.

The carbonized sawdust was retrieved from the pyrolysis reactor after the 6 hr batch time and was quickly quenched with water to prevent oxidation and subsequent ashing. The mixture was then spread and dried for at least 48hrs before being subjected to briquette production.

Initial studies using a simple piston press had proved the technical viability of using banana waste forms as binders, with combinations of the banana stem pith and ripe banana (RB) waste; fruit-bunch-stem, green banana (GB). The binder formulation previously identified as the best with these wastes combined in the ratio 2:2:1:1 respectively was selected for use in the current study. Again in this study, a more rugged manual and gravity aided machine with a heavy load, delivering a force of 0.75kN was used (Figure 2b). The effective pressure on each of the 16 holes of `55mm diameter was 0.32Mpa. The height of each of the holes was 74mm. The briquettes were pressed for ~80.seconds and upon ejection from the machine. Briquettes from both raw and carbonized sawdust were produced using the same binder formulation. The sawdust-to-binder mixture 4:1 ratio by weight was used.

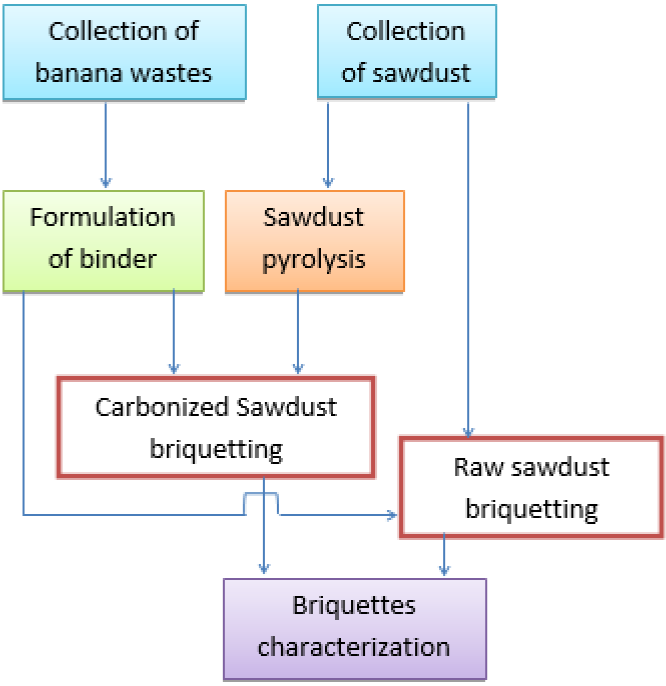

Fig. 2. Block flow diagram of sawdust briquetting using banana waste binder

The resultant briquettes were placed on a flat surface and left to air dry in a closed room with adequate air ventilation 2 weeks before characterizing them for the other thermal and mechanical properties.

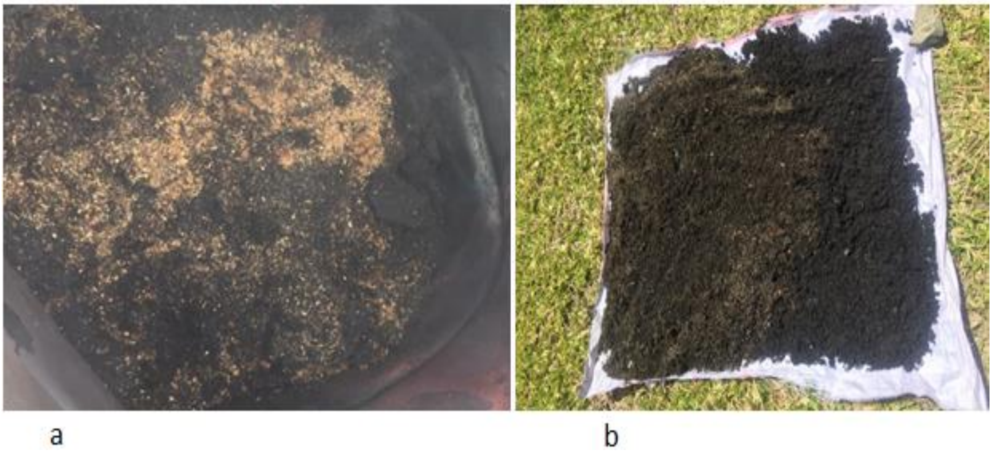

Fig 3. (a) Less than 80% of sawdust converted at 4hrs and 5hrs batch times. (b) Close to 100% conversion at 6hrs batch time

2.3 Briquettes Characterization

2.3.1 Proximate Analysis

Proximate analysis of the briquettes was conducted according to standard procedures for Moisture Content (MC) [22], Volatile Matter (VM) [23], Fixed Carbon (FC) [24] and Bulk density [25].

2.3.2 Calorific value

The briquette heating values were determined at ZimLabs using the standard methods [26].

2.3.3 Shatter index

Each briquette was dropped once from a height of 2m onto a concrete floor and the largest remaining piece was weighed [27]. The cohesiveness of the briquettes colloquially known as the shatter index, F, was then determined by means of the equation 1.

$$F = [M_f(g)] / [M_i(g)] \tag{1}$$

Where Mi is the initial weight of a briquette (g) and Mf is the weight of the largest piece after dropping (g).

2.3.4 Water Boiling Tests

In this test 50ml of water was measured in a beaker and poured into a metal can. A briquette sample was weighed, sprinkled with kerosene (15ml) then ignited. The kerosene was allowed to burn off. The water containing metal can was placed on the tripod stand positioned over the burning briquette. From this set up, the ignition time, burning rate and time taken to reach boiling temperature was recorded for the specific briquette.

The briquette burning rate was calculated using equation 2:

$$B_R = [Q_1 - Q_2] / T \tag{2}$$

Where:

B_R = Burning rate, g/min

Q_1 = Initial briquette weight (g)

Q_2 = Final briquette weight after burning (g)

T = Total burning time (min)

3 Results and Discussion

3.1 Effect of the final pyrolysis temperature on the yield and distribution of products

Figure 3.1 shows the distribution of bio char at temperatures 300-350℃, 370-470℃ and 600-700℃. The yields of bio char was determined by weighing the products. It was observed that the yield of bio char decreased as the temperature range was increased from 300-350 ℃ to 400-450℃. It was even much lesser for 600-700oC. This is supported by researchers such as Babinszki et al., [27], who discovered that higher yields of biochar are obtained at lower temperature ranges.

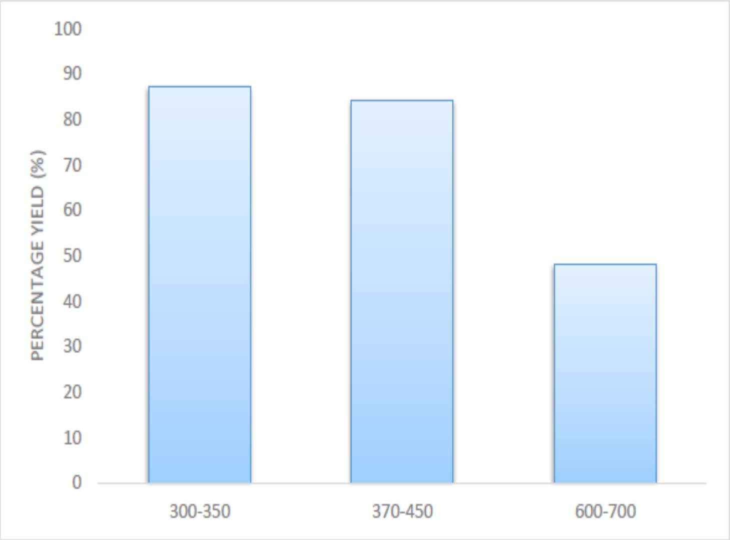

Figure 4. Biochar yields at various temperature ranges

3.2 Calorific value for briquettes

The char obtained at 300-350 ºC and 370-450 ºC had better value propositions for commercial production. Their results on conducting calorific value tests are shown in Table 1.

Table 1: Calorific value results

Charcoal briquette sample	**Calorific value/ MJ/kg**
Obtained at 300-350 ºC	28.78
Obtained at 370- 450 ºC	28.25

Evidently, the calorific value (CV) of charcoal obtained at a lower pyrolysis temperature is higher than the CV at a higher temperature range. This is also confirmed by Babinszki et al. [27].

3.3 Comparison of various mechanical and burning properties of biochar against sawdust briquette produced from same briquetting machine

Having determined that the best charcoal briquette was that one obtained from char produced at 300-350 oC, this charcoal briquette's other mechanical and burning properties were compared to those of raw sawdust briquettes. The briquettes characterization results accrued from this study are reported in Table 2.

Table 2. Briquette characterization results

Test Parameter	**Test Details**	**Raw Sawdust**	**Carbonised**	**% Change***
Ignition time	Time taken by briquette to self-sustain burning/seconds	86	40.00	53.0
Time taken for water to boil (minutes)	50ml of water (glowing state)	33	25.00	32.0
Burning rate (g/min)	Mass of fuel consumed (g) / total time taken (min)	0.912	0.484	47.0
Shatter index	Weight of briquette after dropping / weight of briquette before dropping	0.95	0.96	1.1
Relative/bulk density (kg/m^3)	Density of briquette	685	425	23.0
Proximate analysis	Moisture content (MC), Volatile matter (VM), Ash, Fixed carbon (FC)	MC-7.23; VM-34.12; Ash-13.42; FC-43.91	MC-4.43; VM-28.50; Ash 7.86; FC-59.21	MC – 39.0 VM – 16.0 Ash – 41.0 FC – 35.0
Calorific value	High heating value of fuel (MJ/kg)	24.56	28.78	15.0

* These are changes in parameter values attributed to carbonization

The briquette thermal and mechanical properties of carbonized sawdust are superior when compared to those of raw sawdust, except for the bulk density which is low for carbonized versus raw sawdust. This is so possibly because carbonized sawdust briquette has a higher mean value of fixed carbon and lower volatile matter content than the latter [28]. Higher briquette density is normally associated with strongly bonded particles and this infers durability of the briquette [29]. Possibly the formulated binder sticks better to the raw sawdust surfaces than the pyrolysed biomass surfaces. The density variation may also be partly attributed to slightly poor binding caused by lignin degradation during carbonization process. Lignin contributes to better biomass binding hence higher density of the briquette [28]. Despite this small density difference between the two briquettes, the shatter index of the two briquettes are almost equal indicating almost similar durability of the two briquettes on impact related handling. The short ignition time, burning rate and time for water to burn infers that the carbonized briquettes have more energetic constituents and lesser impurities, leading to unhindered burning in terms of the flame and also heat. The lower density of carbonized briquettes most likely contributed to the faster burn rate as lighter substances tend to quickly burn out due to the fewer particles present per unit volume [31], [32]. The calorific value of carbonized sawdust briquettes was higher than that of raw sawdust as a direct consequence of the increased C/O and C/H ratio of pyrolysed biomass. Furthermore, this may be attributed to the decrease in density which results in increased porosity. An increase in porosity enhances the penetration of oxidants and discharge of combustion products during combustion [18]. The higher pressure in the gravity aided machine press resulting in a denser product 685-863kg/m3compared to 380kg/m3 that is normally achieved in the hand piston press.

Similar studies were conducted by Rotich [33], where pyrolysis took 25-30 hours to complete for 50 kg of sawdust using 50 kg of fuel compared to a fuel to raw-material ration of 4:1 for this research. In the case of Rotich [33], he used the fuel to kickstart the carbonization reaction and then used some of the heat generated during the pyrolysis of sawdust to further carbonize the rest of the sawdust. The researcher obtained high heating values (HHVs) of 22-23 MJ/kg and 28 MJ/kg for torrid and fully carbonised sawdust respectively, where the latter results are comparable to those obtained in this study. The briquettes' HHVs and density values also agree with results from other research work that covered the carbonisation of loose biomass and subsequent briquetting, particularly Zubairu & Gana [34] and Ofori & Akoto [35].

4 Conclusions and Recommendations

The significant improvements in ignition time and burning rates of carbonized sawdust briquettes versus raw saw dust coupled with near equal mechanical properties justify the effort of pyrolysis prior to briquetting. This study provides the proof of concept for using banana waste based binder in briquetting pyrolysed sawdust. It was observed that conversion increased with longer residence times and the ideal time was 6hours using a fuel-to-raw material ratio of 4:1. There is scope to explore a lower fuel-to-raw material ratio if the process is to be sustainable. Low-to-moderate temperatures achieved higher yields with little variation in calorific value, compared to high temperatures. Carbonized briquettes demonstrated shorter ignition time, a steadier burn rate, shorter time to boil and higher calorific value by factors of 53%, 47%, 32% and 15% respectively compared to raw sawdust briquettes. Future work must investigate if other briquette properties such as compressive strength, water absorption resistance and chemical degradation are affected when this newly discovered binder formulation is applied on different briquette feedstocks. In conclusion, carbonized sawdust and binders derived from banana waste can be combined to create briquettes of superior fuel quality that can be utilized for grilling and space heating.

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