Determination of the optimal mass ratio for bagasse-banana leave briquettes for use in biomass-fired boilers

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Abstract*– Global warming, low energy security, rising energy prices, in addition to depletion of crude oil resources have prompted islands such as Jamaica to venture into alternative sources of energy. Currently, industries use heavy fuel oil (HFO) to power boilers and meet their energy needs. A major environmental concern is that the exhaust produced contains pollutants such as nitrogen dioxide and sulphur dioxide. These in addition to fossil fuel imports have highlighted the importance of having an energy source that is accessible locally, economically feasible, and has low or carbon neutral emissions when combusted. Biomass is a source of renewable energy and is available in Jamaica in sufficient quantity and in the form of agricultural waste. Sugar cane bagasse and banana leaves are major agricultural wastes and due to their prevalence, they are suitable for briquette production. For briquette manufacture, the study of key properties such as durability and higher heating value (HHV) are essential. This was accomplished by systematically analysing briquettes made with different mass ratios of bagasse and banana leaves with varying binder concentrations and particle sizes. From the analysis, the optimal mass ratio was found to be 1:1. Fundamentally, bagasse-banana leaf briquettes for biomass fired boiler applications should be produced with 50 % of bagasse and 50% banana leaves of 425 µm particle size with 0.01 g/cm^3 of starch solution.

Keywords—biomass, biofuels, pellets, boilers, renewable energy, energy security

I. INTRODUCTION

The increased level of global warming and depleting fossil fuel reserves has been slowly shifting the world to consider and implement renewable sources of energy. Utilizing the waste to generate energy, is a goal in the National Energy-from-Waste Policy 2010-2030. Goal 2 specifies that Jamaica's intention is to "build its energy-from-waste sector on the most appropriate technologies that are environmentally-friendly, producing a clean reliable renewable source of energy" [1]. Though various types of biomass have been widely studied to make briquettes, a composite briquette using banana and bagasse has not been undertaken. Production of this briquette will require the consideration of many factors, which include: component mass ratios, compaction pressure, the temperature of biomass, size of particles, binder concentration, and moisture content. Ultimately, it is expected that bagasse-banana leave briquettes will contribute to fuel diversification, reduction in petroleum dependency, and potential reduction of the gases that contribute to global warming [1].

Globally, there has been a united thrust towards cleaner sources of energy, which not only increases the energy mix of countries but is slated to decrease greenhouse emissions. To accomplish this goal, renewable energy sources which include solar, wind, geothermal, and biomass can be implemented. Readily available biomass can be utilized as fuel through the production of briquettes. This process involves the compression of solid material particles into defined solid shapes that are used for fuel.

Extensive studies have been done on the use of varied biomass sources and to determine their characteristics such as higher heating values (HHV), ash content, and durability [2]. In this research, specific emphasis will be placed on the production and subsequent determination of the optimal mass ratio of a biomass briquette (bio-briquette) composite from banana leaves and sugar cane bagasse. Ultimately, the vision is that bagasse-banana leave briquettes will contribute to fuel diversification, reduction in Jamaica's petroleum dependency, and potential reduction of the gases that contribute to global warming.

The potential of bagasse-banana bio-briquettes as an alternative to petroleum-based fuels would be beneficial to the country as a means of reducing energy costs. This is predominantly because both sources are readily available locally and essentially a more economical source of fuel as they are derivatives from agro-industrial processes.

The sugar and banana industries are two of the largest agro-industries and consequently produce a large quantity of waste. The Sugar Industry Authority approximates that the 2014/2015 crop year produced 1,278,800 tonnes of bagasse. This accounts for 91% of the sugarcane crop used in the refining process [3]. Additionally, bagasse cannot be stored for long periods due to high moisture content which typically ranges between 40%-55% [4]. Consequently, briquette provides an alternative in which it can be stored for longer periods, by reducing the moisture content to about 6%-8%. The Banana Board in Jamaica approximates that 1,028 hectares are used to grow bananas per year. The banana shrubs comprise mainly of the leaves and pseudostem. The pseudostem is unsuitable for briquette due to high moisture content and is not considered [5]. Both biomass sources contribute substantially to agro-waste and the use of this composite briquette can be used to aid Jamaica ascertaining Goal 2 of the National Energy-from-Waste Policy [1].

The use of biomass to make briquettes has become increasingly popular in developing countries as a means of producing cost-effective energy [1]. Agro-wastes, branches, and leaves from forest floors are generally used for this purpose. Biomass feedstocks such as bagasse can be further compacted by continuous presses or batch presses to increase durability and consequently make them more suitable for storage and transport. The durability/strength of these briquettes depends on interlocking, valence, and Van der Waal forces between particles which are greatly affected by compaction pressures [6]. At high pressures of approximately 15 bar and above, the natural components within the material become activated and subsequently act as binders. Moreover, lever presses cannot be used for high compacting pressures therefore the impact of binders, particle sizes, and biomass temperature becomes more significant on the strength or durability of the briquette [6].

Various studies have been done to determine the properties of banana and bagasse bio-briquettes separately such as their HHV, combustion characteristics, and durability through the use of different binders. According to Maia et al, the HHV for banana leaf and bagasse was to be 17.7 MJ/kg and 16.0 MJ/kg [7]. This information was corroborated by Goulbourne & Gabbidon, as the values were determined to be 17.4 MJ/kg and 16.5 MJ/kg respectively [8]. They further observed that the durability of banana leaf bio-briquettes had the highest value at small particle sizes; that is less than 425 µm (≤425 µm) while observing that bagasse had low durability at the same particle size. Particle size shape is a key factor with regards to densification and biomass material of 6-8 mm size with 10-20% powdery component gives the best results [6]. As a result, it is essential to crushing larger particles to obtain particle size that has an adequate amount of sufficiently small particles. Particle size within this range results in improved packing and allows particles to be closer and consequently, attraction forces can have a greater effect. Saptoadi indicates that smaller briquette sizes are preferred because they promote better combustion characteristics by increasing the combustion rate due to higher surface area [9].

The temperature of the biomass mixture before briquette manufacture can affect briquette density, crushing strength, and moisture stability. Heat allows the starch in the mixture to gelatinize and to form a sticky consistency which enables greater bonding. High-pressure steam hydrolyzes the hemicellulose and lignin portions of biomass into lower molecular carbohydrates, lignin products, sugar polymers, and other derivatives [6]. These products, when subjected to heat and pressure, act as adhesive binders, and provide a bonding effect "in situ". The addition of heat also relaxes the inherent fibers in biomass and softens its structure, thereby reducing their resistance to deformation which in turn results in a decreased specific power consumption and a corresponding increase in production rate. However, the temperature should not be increased beyond the decomposition temperature of biomass which is approximately 300 °C.

At low compaction pressures, the effect of the binder and higher temperatures will become more significant. At elevated temperatures of about 60-80 °C, the starch will gelatinize, and will aid in binding the particles and ultimately increase the durability. Small particle sizes will facilitate closer packing of particles and increase particle interlocking and durability. Maia et al also observed that sulfur and nitrogen contents present in the biomass are generally low, resulting in low pollutant gas emissions, such as SO_2 and NO_2 during the combustion process[7] .

II. MATERIAL AND METHODS

The bagasse was collected from the Worthy Park sugar estate, St. Catherine, and the dried banana leaves were collected from various bananas farms in South Eastern St. Ann. The cassava starch used as the binder was obtained from the Rural Agricultural Development Authority (RADA) outlet.

A. Preparation of Raw Materials

The bagasse and banana leaves were air-dried for 3 days to reduce the moisture content. The moisture content of the air-dried materials was recorded. The size of the dried banana leaf was manually reduced by removing the leaf blade from the midrib and then grating before shredding. Size reduction was then separately carried out using an industrial blender. Each fiber sample was sieved and packaged according to >425 µm and ≤425 µm particle sizes, respectively.

B. Production of Briquettes

The cassava starch was blended to ensure homogeneity. The stock solution was prepared by measuring 50g of the blended cassava in 1000mL volumetric flask in addition to distilled water to ensure the volume of 1000 mL and stoppered shaken for homogeneity and to ensure a concentration of 0.05gcm^{-3}. This procedure was repeated to produce binder concentrations of 0.03 gcm^{-3} and 0.01gcm^{-3}.

Table 1: Mass ratio of ground bagasse to the banana leaf that was tested at various particle sizes

Particle Size (µm)	Bagasse Mass Ratio	Banana leaf Mass Ratio
>425	0	1
	0.25	0.75
	0.5	0.5
	0.75	0.25

	1	0
≤425	0	1
	0.25	0.75
	0.5	0.5
	0.75	0.25
	1	0

20 g of banana leaf and bagasse was used for each ratio combination. 200ml of 0.05g cm^{-1} binder concentration was added to the bagasse-banana leaf mixture in a 600 ml beaker and stirred. The beaker with contents was heated to approximately 60-70 °C using a gravity oven. 40 g of the bagasse-banana mixture (with binder) was placed on a nylon material and placed in the mold cavity of the lever press. This was compressed for 10 minutes using a 9.07 kg weight. After compression, the briquette was removed and left to air dry for one day to remove excess moisture. Four (4) briquette samples were obtained for each ratio combination. After air drying, the briquettes were placed in the gravity oven at 120ºC for one (1) hour to further reduce the remaining moisture. The aforementioned steps were repeated using 0.03 gcm^{-3} and 0.01 gcm^{-3}binder concentrations respectively.

C. Briquette Tests

The briquettes were analyzed based on the selected responding variables, namely, density, durability, moisture content, ash content, HHV.

Table 2: Summary of the manipulated and responding variables used in the research

Manipulated variables	Values	Responding
Bagasse: Banana leaf mass composition	0-1	HHV, durability, moisture content, ash content
Particle size (μm)	>425, ≤425	HHV, durability, moisture content, ash content, density
Starch concentration (g/cm^3)	0.01-0.05	HHV, durability, ash content

The average density of each set of briquettes was calculated by randomly weighing the briquette on an electric balance and measuring the dimension (length, width, height) using a Vernier caliper. The following equation was used to determine the density.

$$Density\ (g/cm^3) = \frac{Mass}{Volume} = \frac{Mass}{length * width * height}$$

To measure the durability, the initial mass of a briquette was recorded before placing it in the bottle containing 10 marbles. The bottle was inverted 75 times, after which the final mass was recorded. This was done in triplicate and the percentage durability was determined using the formula below.

$$Durability\ (\%) = \frac{Mass\ before\ -\ Mass\ after}{Mass\ before} * 100$$

Proximate analysis was done to determine the average moisture content of each set of briquettes. The moisture content of 3 randomly selected briquettes from each set was measured using a Denver Instrument ® moisture analyzer set at 110°C. The value was recorded when the moisture reading was stabilized.

Proximate analysis was done to measure the ash content of each set using ASTM E1750 method using a briquette that was randomly chosen from each set. The mass of the briquette and crucible used were measured separately before the briquette being placed within the crucible. Both were placed into a furnace at 600°C for 4 hours. The total mass of the ash and crucible was measured after being removed and cooled. The ash content was determined using the following equation:

$$Ash\ content\ (\%) = \frac{Total\ mass\ after\ being\ removed - Mass\ of\ crucible}{Mass\ of\ briquette}$$

HHV for 9 bagasse-banana leaf briquettes with durability above 90% was obtained using an adiabatic bomb calorimeter.

III. RESULTS

A total of 120 briquettes were made for analysis. The bagasse-banana leaf briquettes were divided into 30 sets each of which contained 4 samples.

Table 3: Average moisture content of biomass before air drying

Biomass	Bagasse	Banana leaf
Average moisture content (%)	31.5	4.2

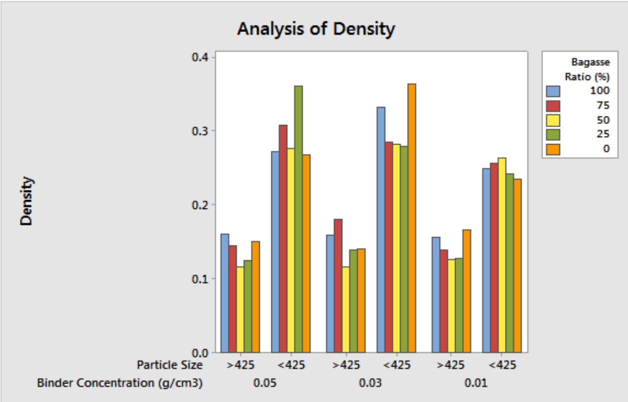

Figure 2: Bar graph showing the average density of the bagasse-banana leaf briquettes at varying mass ratio, particle sizes and binder concentration using Minitab 17

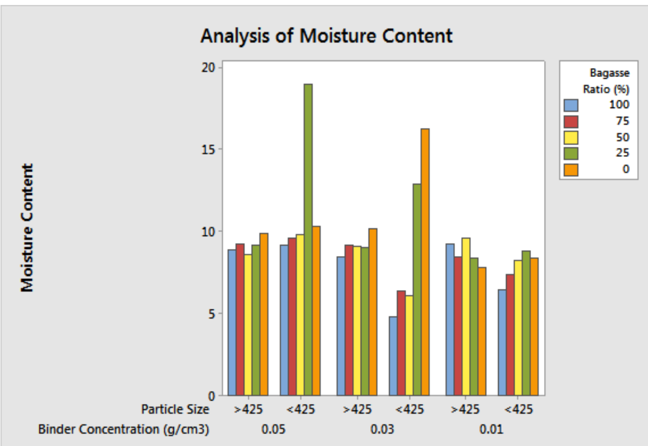

Figure 3: Bar graph showing moisture content of the bagasse-banana leave briquettes at varying mass ratio, particle sizes and binder concentration using Minitab 17

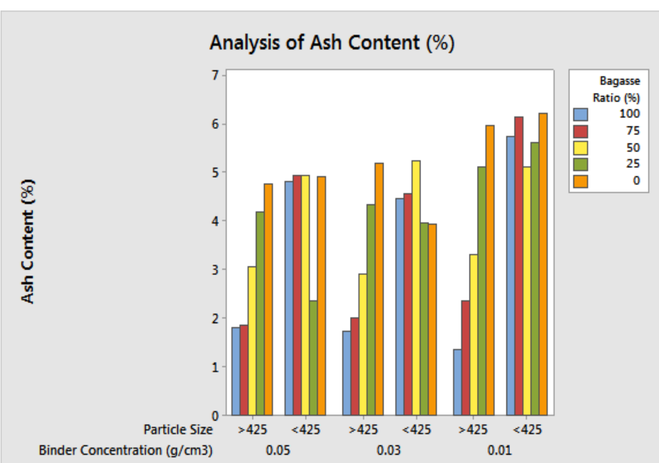

Figure 4: Bar graph showing ash content of the bagasse-banana leave briquettes at varying mass ratio, particle sizes and binder concentration using Minitab 17

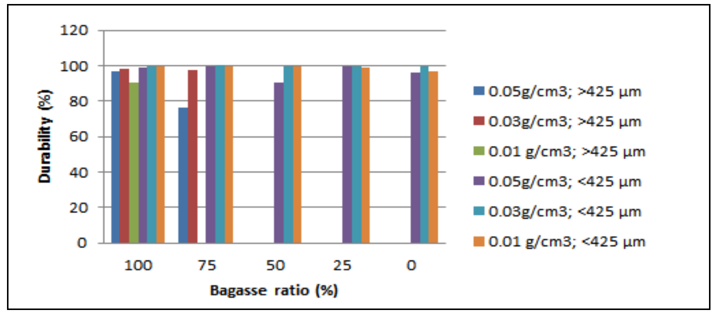

Figure 5: Bar graph showing the durability of the bagasse-banana leave briquettes at varying mass ratio, particle sizes and binder concentration using Microsoft Excel

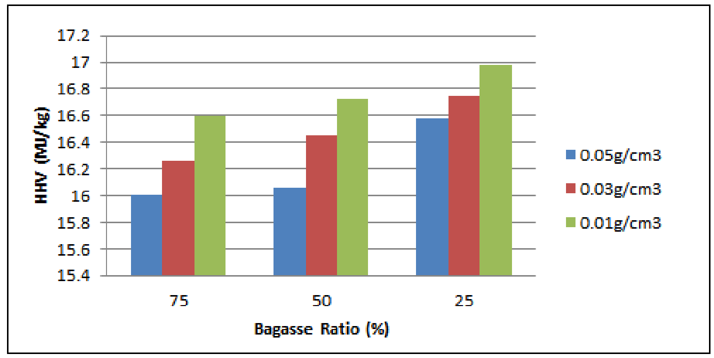

Figure 6: Bar graph showing HHV of the bagasse-banana leave briquettes at ≤425 µm particle size, varying mass ratio and binder concentration

IV. Discussion and Conclusion

A total of 120 briquettes were made for analysis. The bagasse-banana leaf briquettes were divided into 30 sets each of which contained 4 samples.

From Figure 3, briquettes of 25% and 50% bagasse at ≤425 µm particle size using a 0.03 g/cm^3 binder concentration, contained moisture levels within the acceptable range of 6-8%. Briquettes within this range are strong and free of cracks [6]. The higher readings for the bagasse-banana leaf briquettes at ≤425 µm, 25% bagasse, 0.05g/cm^3 cassava binder concentration; ≤425 µm, 25% bagasse, 0.03g/cm^3 and ≤425 µm, 0% bagasse, 0.03 g/cm^3, was due to the slow evaporation of the water within the briquettes due to humid weather. Additionally, there was no correlation observed between the biomass ratios to the moisture content.

The ash content was observed to rise steadily with an increase in the mass ratio of the banana leaf at each binder concentration using >425 µm particle sizes. According to literature, banana leaves have a higher ash content percentage than bagasse at 7.5% [10]. Additionally, it was noted that the smaller particle sizes had higher ash content.

The fluctuation in density of each category resulted from the inconsistency of the solid to liquid ratio of the 40 g of the bagasse-banana leaf (with binder) mixture that was compressed to make the briquettes. Higher density values of briquettes within the same particle size range was due to the mixture consisting of more solid than liquid. However, the particle size of ≤425 μm showed higher density values than >425 μm for the respective binder concentration. This is due to the difference resulted from an increase in the attraction forces between particles for smaller particles.

From the experiments conducted, the bagasse-banana leaf briquettes made from ≤425 μm particle sizes with 0.01 g/cm^3 cassava starch binder concentration and 0.25: 0.75 bagasse to banana leaf ratio produced the highest calorific value. However, bagasse-banana leaf briquettes made from particle sizes ≤425 μm, with 0.01 g/cm^3 cassava starch binder concentration and 1:1 bagasse to banana leaf ratio, had lower ash and moisture content, higher durability, and density. Through the utilization of the abundant agro-waste accumulated in both sugar cane and the banana industry, Jamaica will be able to reduce its carbon footprint, enable better energy security and be in a better position for a sustainable future.

A major limitation in the completion of this study was the use of cassava starch, as it is a staple and to avert the food versus fuel conflict, other binders such as the bitter cassava, clay, or cow dung can be considered. Another recommendation for future work could involve the production of briquettes made using high-pressure presses such as a screw press, to reduce the quantity of binder used and to increase the durability of larger particle size. Lastly, test the emission gases produced from the burning of the briquettes should be monitored to compare with emissions produced from the combustion of petroleum-based fuels.

ACKNOWLEDGMENT

We are thankful to Professor Aples, Dr. T. Sinclair, Murna Plummer, Berlyn Christie, Odian Barrett, Brandeice Barrett and the engineers of Wigton Windfarm

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