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Production and experimental characterization of homogeneous and composite briquettes from fruit processing waste

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Abstract

Growth in agricultural produce processing continues to drive up energy consumption and contributes significantly to climate change. Fruits, in particular, are processed to enhance their market value and extend their shelf life; however, fruit processing generates substantial amounts of organic waste, creating a waste management challenge despite its potential as a renewable energy resource. This study focused on converting orange, mango, and jackfruit waste into briquettes using cassava starch, cornstarch, and clay as binders, all locally available. A manual lever press was employed for compaction to produce both homogeneous and composite briquettes. The briquettes were then evaluated for their physical, chemical, mechanical, and thermal properties at varying binder concentrations. Moisture content, volatile matter, fixed carbon, and ash content were analyzed using thermogravimetric analysis. Calorific values were determined using bomb calorimetry. Mechanical strength was assessed using compressive strength and drop strength tests, while thermal performance was evaluated through water boiling tests and burning rate measurements. Fixed carbon ranged from 22.87% to 62.06%, ash content from 6.55% to 57.20%, volatile matter from 15.71% to 39.41%, and moisture content from 4.21% to 13.66%. Calorific values ranged from 17.55 to 32.24 MJ/kg. Compressive strength varied from 0.125 to 0.471 N/mm^2, bulk density from 413.21 to 580.1 kg/m^3, and drop strength from 27.74% to 88.84%. The study confirms that jackfruit, orange, and mango waste are viable biomass feedstock for briquette production. Among the binders tested, cassava starch consistently yielded briquettes with superior mechanical and thermal properties, making it the binder of choice for optimizing performance in small-scale briquette production systems.

Key words: *Affordable and clean energy; Biomass; climate change; food processing; fossil fuel.*

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Introduction

The global energy landscape is characterized by a tension between rising energy demands and growing environmental concerns. Among economic sectors, buildings and industries dominate the world energy demand growth. Climate change has been linked to energy demand (Duan and Chen, 2018) because global energy production is still dominated by fossil fuels (Caetano *et al.,* 2017).

The food processing sub sector is a major element of the global industrial sector. According to the Food and Agriculture Organization, processed food sales account for 75% of global food sales. It is also estimated that only 30% of agricultural produce in developing countries undergoes industrial processing compared to 98% in developed countries (FAO, 2012). The agro processing industry, therefore, has a large potential for expansion in developing countries. The processing of agricultural produce generates enormous amounts of waste, which can be utilized to meet part, or all the energy needs of the respective processing industries (Hegde *et al.*, 2018).

The global food chain loses 1.3 billion tons of food as waste before consumption, annually (Zhu *et al.,* 2023). In 2018, fruit production accounted for 10% of the nine billion tons of global agricultural output (Grunwald, 2021). Up to 50% of fruit production is lost after harvest in developing countries, mostly due to inefficiencies in fruit processing, storage, and transportation (Zhu *et al.*, 2023). Additionally, nearly 50% of a citrus fruit, 45% of a mango fruit, and up to 70% of a jackfruit end up as waste during processing (Sagar *et al.,* 2018). Fruit waste is often disposed of in landfills (Campos *et al.*, 2020; Zhu *et al.*, 2023); however, new technologies have emerged which add value to the fruit waste through extraction of bioactive compounds (Lucarini *et al.,* 2021; Kandemir *et al.*, 2022), and energy production (Zanella *et al.*, 2016; Morales-Polo *et al.*, 2019) among others.

There are at least 38 small, medium, or large-scale fruit processing factories with certified products in the Ugandan market according to Uganda National Bureau of Standards (UNBS, 2020). Uganda's fruit processing industry is expanding as a direct result of the government's emphasis on widening the local industrial sector (NPA, 2012). Like other developing countries, Uganda's solid waste management systems have major shortcomings in waste segregation as well as insufficient capacity to handle the ever-growing waste generation (Abdulfatah *et al.*, 2019; Mugambe *et al.*, 2022). These inadequacies summon the need for value addition solutions to fruit waste from Uganda's fruit processing factories.

The objectives of this study were to develop briquettes from mango, orange, and jackfruit waste, generated from two fruit processing facilities in Uganda, and to determine the physical and chemical properties of the developed briquettes.

Bioenergy is energy obtained from biomass (Dahiya, 2015). Bioenergy is ultimately utilized through a combustion process; however, there are significant variations in the technologies used to convert biomass into biofuels. Okello *et al.* (2013) and Lee *et al.* (2019) concur that thermochemical conversion and biochemical conversion are the primary bioenergy conversion processes used to produce biofuels such as biogas, biochar, bio-diesel, bio-ethanol, and producer gas. Thermochemical processes entail direct combustion of biomass, pyrolysis, liquefaction, and gasification whereas biochemical processes comprise fermentation and anaerobic digestion (Chen *et al.*, 2015).

Biomass densification is a process in which the bulk density of biomass is increased. Biomass in its natural form has low bulk density and is irregularly shaped, which makes it difficult to utilize the biomass in modern energy applications. Densified biomass is easier and cheaper to handle, store, and transport (Okello *et al.,* 2013). Densified biomass also has less particulate emissions per unit volume and is better suited for use in industrial applications compared to loose biomass (Muazu *et al.*, 2017).

All forms of biomass can be densified, however, numerous studies have focused on the densification of agricultural, industrial, and municipal wastes as a means of waste management and an alternative to fuel wood. The production of briquettes from rice husks and coffee husks has been studied by Maninder *et al.* (2012), Lubwama and Yiga (2018) and Iftikhar *et al.* (2019). The densification of agricultural wastes such as mango leaves and banana leaves was explored by Maia *et al.* (2014) and Ycaza and Barre (2018), respectively whereas Onukak *et al.* (2017) produced briquettes from tannery solid waste and Sawadogo *et al.* (2018) produced briquettes from cashew industrial waste.
The most common forms of densified biomass are briquettes and pellets although cubes have been used in some applications (Muazu *et al.*, 2017). Biomass densification into briquettes and pellets usually involves drying, torrefaction or carbonization, size reduction, mixing with a binder(s), and compression or shaping.

Both torrefaction and carbonization are pathways to the thermal decomposition of biomass into charred material with better physical and chemical properties. Although both processes are conducted under non-oxygen conditions, torrefaction is done at temperatures between 200 °C and 300 °C and carbonization takes place at 600 °C. Both processes eliminate volatile matter and increase the energy density of the end-product (Ribeiro *et al.*, 2018; Barskov *et al.*, 2019).

Binders aid the bonding of charred biomass material during the densification process. Binders also improve the physical and chemical properties of the resultant briquettes. According to Sen *et al.* (2016), cited in Borowski *et al.* (2017), the addition of binders improves bulk density, compression strength, and impact resistance of briquettes. Muazu *et al.* (2017) denoted that starch, molasses, lignosulphonates, and sulphonate salts are the most common biomass binders used in briquette production.

Aransiola *et al.* (2019) demonstrated the production of high-quality briquettes from corncobs using cassava starch, corn starch, and gelatin independently. The effectiveness of cassava starch as a binder is further corroborated by Lubwama and Yiga (2018), Ycaza and Barre (2018), Sawadogo *et al.* (2018), and Onukak *et al.* (2017). Zanella *et al.* (2016) used corn starch whereas Iftikhar *et al.* (2019) used cow dung. Additionally, the possibilities of sustainable cassava and corn production in Uganda have been established by Roothaert and Magado (2011) and Smale *et al.* (2011).

Maia *et al.* (2014) produced stable briquettes from dried banana leaves without any binders. Similarly, Maninder *et al.* (2012) produced briquettes from rice husks, coffee husks, saw dust, ground nutshells and cotton stalks without binders. According to Asamoah *et al.* (2016), a discussion of how much binding material to add is guided by the binding properties of the raw material and the applied densification procedure. When a high-pressure briquette machine is used, there is a reduced need for a binder. Similarly, raw materials with higher binding properties require less binders at densification.

Materials and Methods

Study Area

This study was conducted in Uganda, with fruit waste sourced from two processing facilities: Jakana Foods Limited in Kampala (Central Uganda) and Soroti Fruits Limited in Soroti (Eastern Uganda). Kampala is the capital city, with a tropical climate and high fruit consumption / processing rates. Soroti lies in a major fruit – growing region, particularly for citrus and mangoes. These two sites were selected because they are representative of Uganda's expanding fruit processing sector and provide substantial amounts of waste material suitable for briquette production.

Materials

Jackfruit waste was obtained from Jakana Foods Limited in Kampala, Uganda while mango and orange fruit waste were obtained from Soroti Fruits Limited in Soroti, Uganda. Upon collection, the waste was immediately used in the briquette development process. Cornstarch, cassava starch, and clay were used as binders since they are readily available in Uganda. The binders were obtained from the Ugandan local market.

Briquette Development Procedure

All the fruit waste was sun dried for ten days and then carbonized in a steel drum. The char was pounded into particles less than 2 mm using a wooden mortar and pestle. The pounding helped to increase the char's surface area for bonding with the binding materials. Crushed char from homogeneous waste materials was mixed with multiple binding materials and water. To investigate the best mixing ratios that yielded good physical and chemical properties, the following char to binder ratios were used; 95:5, 90:10, and 85:15, by mass. These permutations were based on methods used in similar studies by Katimbo *et al.* (2014), Zanella *et al.* (2016) and Sawadogo *et al.* (2018).

Char with composite waste materials was made using orange and mango fruit waste ratios of 70:30, 50:50, and 30:70, respectively, by mass. Similarly, char with jackfruit waste and mango fruit waste ratios of 70:30, 50:50, and 30:70, respectively, was used. These permutations were consistent with Lubwama and Yiga (2018). The varying ratios were also necessary to understand the influence of each fruit waste variety on the properties of the composite briquettes. Before being added to the char, all starch binders were gelatinized using water heated above 80℃, the binder to water ratio was 1:10. Each sample of the char mixed with a clay binder or a gelatinized starch binder was placed into a mold and manually compressed with a lever press, to briquettes of dimensions 6 cm wide and 10 cm high (Figure 1).

Figure 1:
Developed Briquette Samples

Physical and Chemical Properties

An Eltra thermostep thermogravimetric analyzer, software version TGA1.4.3.2a3, with an accuracy of ±0.0001 g, was used to determine the volatile matter, ash content, moisture content, and fixed carbon for each developed briquette sample. Each sample weighed approximately 1.1g. Temperature was gradually increased from room temperature to 105 °C at a rate of 5 °C per minute to determine moisture content in a nitrogen environment using the weight lost in the process. To determine volatile matter content, the temperature was further increased at the same rate to 915 °C and sustained for 7 minutes in the nitrogen environment. Weight loss was similarly used to determine volatile matter content. The temperature was then reduced to 750 °C and oxygen gas was introduced to achieve complete combustion to determine the ash content. Fixed carbon content was deduced from the values of moisture content, volatile matter content, and ash content.

The calorific values for each briquette sample were determined using an IKA C 2000 oxygen bomb calorimeter with an accuracy of ±0.01°C. Samples from the developed briquettes were completely burnt in an oxygen environment.

Bulk density was examined in accordance with Lubwama *et al.* (2020). The bulk density was computed as a ratio of the briquettes' mass to volume. The briquettes' volume was obtained using the standard equation for the volume of a cylinder since the briquettes were cylindrical. The briquettes' dimensions were obtained using a vernier caliper. Compressive strength was measured using a Testometric FS300 CT machine with a ±0.001 N/mm^2 accuracy.

Ultimate Analysis

The composition of Carbon, Hydrogen, Oxygen, Nitrogen, and Sulphur was computed using results from thermogravimetric analysis. Elemental composition was achieved using Equations 1, 2, 3, and 4 (Saffe *et al.*, 2019).

$$C = (0.635 \times FC) + (0.460 \times VM) - (0.095 \times ASH) \quad (1)$$

$$H = (0.059 \times FC) + (0.060 \times VM) + (0.010 \times ASH) \quad (2)$$

$$O = (0.340 \times FC) + (0.469 \times VM) - (0.023 \times ASH) \quad (3)$$

$$NS = 100 - C - H - O \quad (4)$$

Where FC, VM, and ASH are the percentages of fixed carbon, volatile matter, and ash content on a dry basis. NS represents Nitrogen and Sulfur.

Mechanical Properties

Drop strength was examined in accordance with Lubwama *et al.* (2020). A drop test was conducted by elevating the developed briquette samples to a 2-meter height and dropping them onto a metallic plate. The drop strength was computed as a ratio of the mass of the briquette after being dropped to the mass of the briquette before being dropped.

Thermal Properties

A water boiling test was carried out to assess the cooking efficiency of the developed briquettes by determining the time taken by a known quantity of the briquettes to boil a known volume of water. Burning rate analysis was derived from the time-based data about weight and temperature of the samples, captured during thermogravimetric analysis in 2.3 above.

The water boiling test protocol, version 4.2.3 (PCIA, 2014) was used and tests were conducted for both cold start high power and hot start high power phases. An Envirofit supersaver cookstove was used for these tests. 5 liters of water were placed in a 7-liter cylindrical flat bottomed aluminum pot and brought to boil using the developed briquettes in the Envirofit cookstove. The time taken for the water to reach the boiling point was recorded. The cold start high power phase commenced with the cookstove at room temperature whereas the hot start high power phase commenced after the cold start phase, with a hot cookstove.

Data Analysis

A total of 81 briquette samples were produced and evaluated to ensure robustness of results. Instead of performing replicate measurements on a few samples, a larger number of unique briquette samples was analyzed to capture variability across different binder types and mixing ratios. Proximate analysis was derived directly from the weight loss steps recorded during thermogravimetric analysis. Moisture content was calculated from the mass lost when samples were heated to 105 C in nitrogen. Volatile matter was obtained from the additional mass lost as the temperature increased to 915 C in nitrogen. Ash content was determined from the residue remaining after complete combustion at 750 C in an oxygen atmosphere. Elemental composition was estimated using equations 1 – 4. Calorific values were obtained from bomb calorimeter readings. Mechanical and thermal property data were summarized using averages and ranges across the different sample categories. Relationships among calorific value, fixed carbon, ash content, and binder concentration were further examined through correlation analysis.

Results

Table 1 presents the physical properties of the developed briquettes. Fixed carbon content ranged from 22.87% to 62.06%, ash content from 6.55% to 57.20%, volatile matter from 15.71% to 39.41%, and moisture content from 4.21% to 13.66%. The highest fixed carbon content was observed in briquettes predominantly composed of mango waste, while jackfruit-based briquettes recorded the lowest. Briquettes bound with clay exhibited higher ash concentrations and lower moisture content compared to those bound with cornstarch and cassava starch. The average values for fixed carbon, ash content, volatile matter, and moisture were 49.23%, 15.99%, 26.71%, and 8.07%, respectively.

The average volatile matter content across all 81 samples was 26.71%. When categorized by binder type, the average volatile matter content was 21.68% for clay, 28.63% for cornstarch, and 29.84% for cassava starch. The average calorific values for single biomass briquettes made from jackfruit, mango, and orange were 20.36 MJ/kg, 27.5 MJ/kg, and 23.37 MJ/kg, respectively. At binder concentrations of 5%, 10%, and 15%, the average calorific values were 24.41 MJ/kg, 23.93 MJ/kg, and 23.47 MJ/kg.

The highest calorific value recorded was 32.24 MJ/kg in a sample with 95% mango char and 5% clay binder. The lowest, 17.55 MJ/kg, was recorded in a sample with 85% jackfruit char and 15% clay binder. The overall average calorific value was 23.94 MJ/kg. Like fixed carbon content, briquettes made from jackfruit waste had the lowest calorific values, whereas those made from mango waste had the highest. Compressive strength ranged from 0.125 N/mm^2 to 0.471 N/mm^2, with cassava starch-bound briquettes showing the highest strength and clay-bound briquettes the lowest.

Table 2 presents the results for elemental composition, bulk density, and drop strength of the developed briquettes. Bulk density ranged from 413.21 kg/m^3 for briquette sample M3J7CA5 to 580.1 kg/m^3 for sample M5J5CL15, with an average bulk density of 474.7 kg/m^3. Drop strength ranged from 27.74% for sample OCL5 to 88.84% for sample OCA10, with an average drop strength of 51%. In terms of elemental composition, carbon content ranged from 16.32% in sample O7M3CL5 to 49.6% in sample MCO10. Hydrogen content ranged from 2.86% in sample O7M3CL5 to 5.15% in sample MCO15. Oxygen content varied from 13.83% in sample O7M3CL5 to 32.98% in sample O5M5CA15. Sulphur and nitrogen content together ranged from 13.06% in sample MCO15 to 66.98% in sample O7M3CL5. The average elemental composition across all samples was 42.03% carbon, 4.67% hydrogen, 28.9% oxygen, and 24.41% for the combined nitrogen and sulphur content.

Table 3 shows the water boiling test results. The shortest boiling time during the cold start phase was 33 minutes, from briquette samples O7M3CO5, O7M3CO15, and O3M7CO15. The longest boiling time during the cold start phase was 70 minutes, from briquette sample O3M7CL15. The shortest boiling time during the host start phase was 23 minutes, from briquette sample O3M7CO5. The longest boiling time during the hot start phase was 68 minutes, from briquette samples M7J3CA15 and O3M7CA15

Figures 2 to 4 represent plots of the burning rates against time. The burning rate had an initial trough followed by a rapid rise in burning until 35 minutes into the combustion. This was followed by a gentle deceleration in the burning rates up to 100 minutes of combustion before a second acceleration. The highest burning rate was 0.0082 g/min in the

124th minute and the largest changes in burning rates were registered between 100 and 135 minutes.

Figure 2:

Burning rate Curve for single fruit waste samples

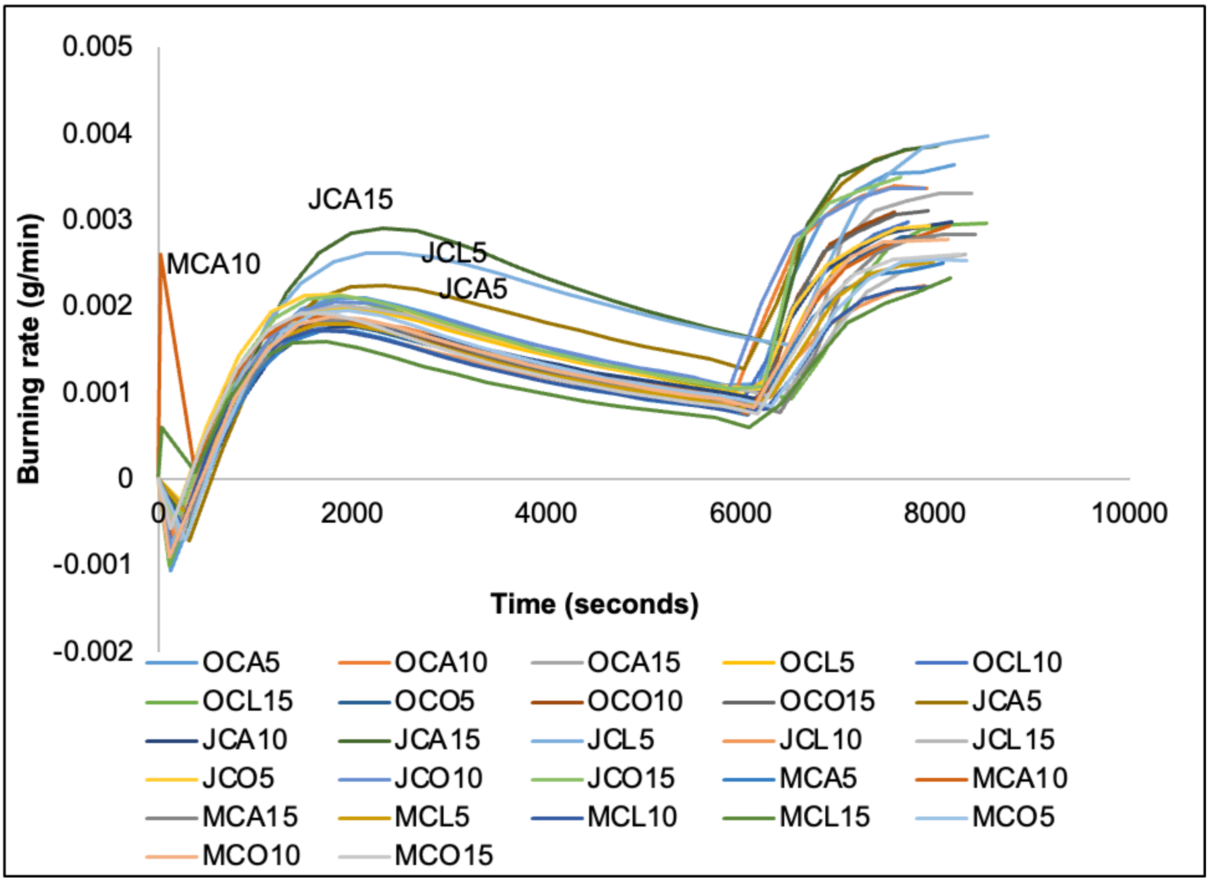

Figure 3

Burning rate Curve for Orange - Mango fruit waste briquettes

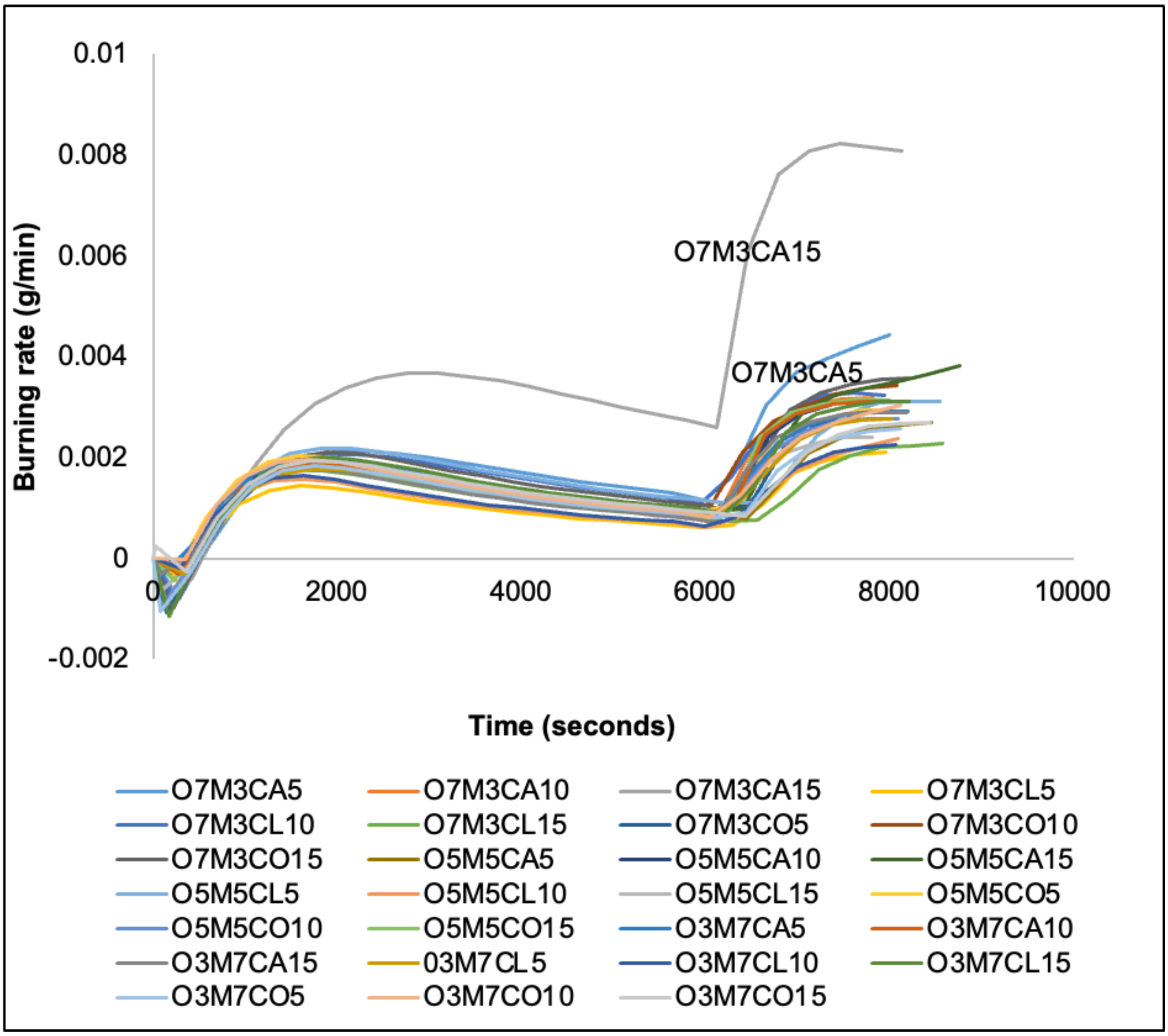

Figure 4

Burning rate Curve for Mango-Jackfruit waste briquettes

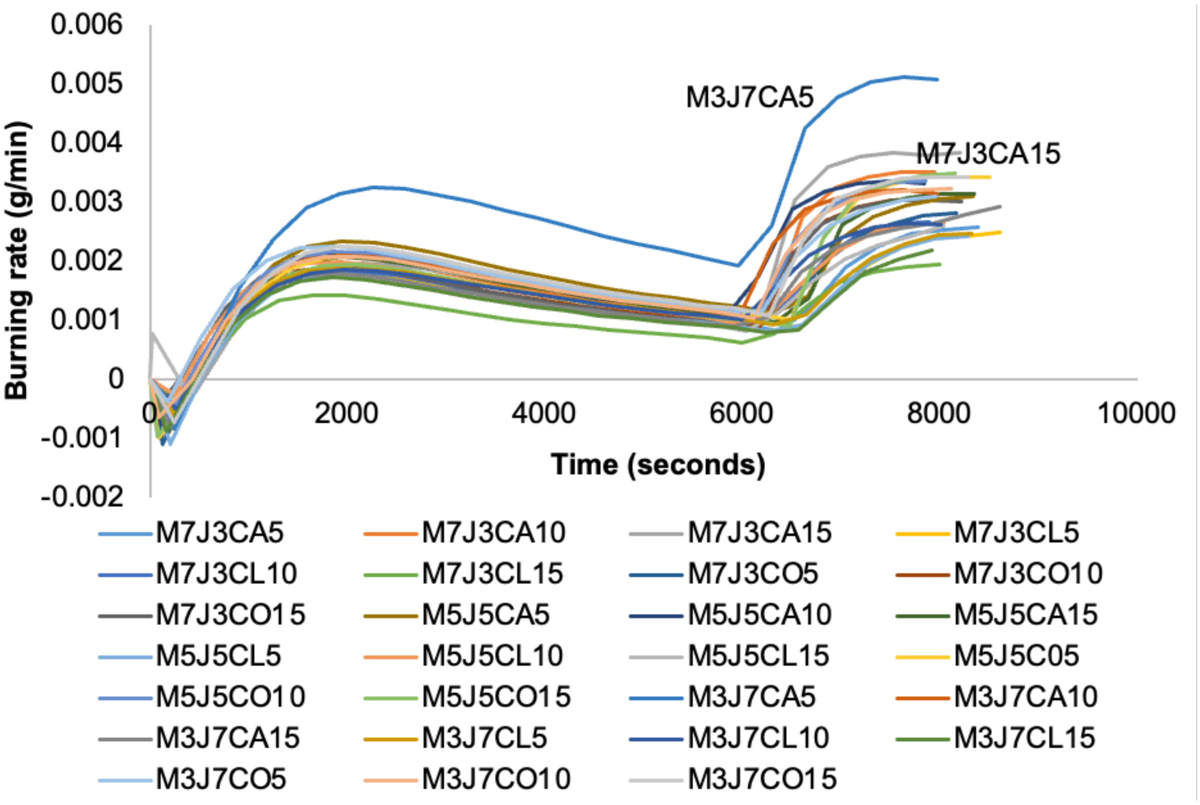

Table 1

Compressive Strength and Results of Thermogr

No.	Sample Id	Sample composition	% Moisture	% Volatile matter	% Ash	% Fixed carbon	Calorific value (MJ/kg)	Comp. Strength (N/mm^2)
1	OCA5	O:CA - 19:1	8.27	30.62	12.74	48.36	23.75	0.302
2	OCA10	O:CA - 9:1	8.15	30.95	10.88	50.02	24.29	0.389
3	OCA15	O:CA - 17:3	8.31	34.96	10.41	46.32	24.58	0.471
4	OCL5	O:CL - 19:1	8.43	24.94	12.42	54.21	22.05	0.131
5	OCL10	O:CL - 9:1	7.51	27.16	16.21	49.12	21.77	0.167
6	OCL15	O:CL - 17:3	5.62	17.62	26.42	50.34	21.95	0.166
7	OCO5	O:CO - 19:1	7.50	26.34	12.55	53.62	25.47	0.265
8	OCO10	O:CO - 9:1	8.03	30.64	11.77	49.56	23.51	0.293
9	OCO15	O:CO - 17:3	8.01	32.05	11.13	48.80	22.95	0.298
10	JCA5	J:CA - 19:1	8.38	25.94	21.45	44.24	20.62	0.299
11	JCA10	J:CA - 9:1	8.67	28.07	20.18	43.08	20.33	0.381
12	JCA15	J:CA - 17:3	13.66	30.93	17.66	37.74	18.08	0.398
13	JCL5	J:CL - 19:1	8.84	21.96	22.90	46.30	20.59	0.127
14	JCL10	J:CL - 9:1	7.70	21.88	32.70	37.72	18.08	0.129
15	JCL15	J:CL - 17:3	7.20	19.45	38.09	35.26	17.55	0.125
16	JCO5	J:CO - 19:1	9.22	26.86	22.46	41.46	23.06	0.279
17	JCO10	J:CO - 9:1	9.01	29.01	19.68	42.30	22.94	0.322
18	JCO15	J:CO - 17:3	9.11	33.68	18.75	38.46	21.99	0.363
19	MCA5	M:CA - 19:1	7.47	23.62	7.58	61.33	26.36	0.295
20	MCA10	M:CA - 9:1	7.33	29.03	7.19	56.46	27.02	0.381
21	MCA15	M:CA - 17:3	8.06	29.26	6.55	56.13	27.17	0.397
22	MCL5	M:CL - 19:1	7.34	23.23	8.34	61.09	32.24	0.180
23	MCL10	M:CL - 9:1	6.93	20.72	14.81	57.54	28.91	0.209
24	MCL15	M:CL - 17:3	6.09	23.50	23.12	47.29	27.50	0.291
25	MCO5	M:CO - 19:1	8.06	23.24	6.64	62.06	27.98	0.284
26	MCO10	M:CO - 9:1	7.41	24.24	6.78	61.56	25.36	0.304
27	MCO15	M:CO - 17:3	7.35	25.00	6.78	60.88	24.92	0.319
28	O7M3CA5	O:M:CA - 133:57:10	7.60	32.29	10.81	49.29	25.24	0.289
29	O7M3CA10	O:M:CA - 63:27:10	8.04	32.06	10.13	49.77	25.56	0.387
30	O7M3CA15	O:M:CA - 119:51:30	9.56	30.19	14.87	45.37	24.13	0.408
31	O5M5CA5	O:M:CA - 95:95:10	8.06	28.14	10.71	53.09	24.21	0.295
32	O5M5CA10	O:M:CA – 45:45:10	7.97	29.07	10.24	52.72	23.39	0.345
33	O5M5CA15	O:M:CA – 85:85:30	8.33	39.41	9.02	43.24	22.74	0.371
34	O3M7CA5	O:M:CA – 57:133:10	7.82	25.07	9.63	57.48	27.11	0.300
35	O3M7CA10	O:M:CA – 27:63:10	8.05	30.95	8.83	52.16	24.79	0.369

No.	Sample Id	Sample composition	% Moisture	% Volatile matter	% Ash	% Fixed carbon	Calorific value (MJ/kg)	Comp. Strength (N/mm^2)
36	O3M7CA15	O:M:CA – 51:119:30	7.27	29.56	8.56	54.62	26.14	0.406
37	O7M3CO5	O:M:CO - 133:57:10	8.27	28.76	10.85	52.13	26.54	0.236
38	O7M3CO10	O:M:CO - 63:27:10	7.71	30.06	10.27	51.96	26.35	0.297
39	O7M3CO15	O:M:CO - 119:51:30	8.63	30.71	10.04	50.62	25.41	0.310
40	O5M5CO5	O:M:CO - 95:95:10	8.11	26.54	19.87	45.48	26.27	0.251
41	O5M5CO10	O:M:CO – 45:45:10	8.25	25.63	9.25	56.86	28.23	0.266
42	O5M5CO15	O:M:CO – 85:85:30	7.83	32.19	9.49	50.49	26.58	0.289
43	O3M7CO5	O:M:CO – 57:133:10	8.22	26.44	9.64	55.70	29.67	0.270
44	O3M7CO10	O:M:CO – 27:63:10	7.57	29.62	8.79	54.02	28.77	0.294
45	O3M7CO15	O:M:CO – 51:119:30	8.29	26.95	8.39	56.37	31.52	0.304
46	O7M3CL5	O:M:CL - 133:57:10	4.21	15.71	57.20	22.87	24.53	0.175
47	O7M3CL10	O:M:CL - 63:27:10	6.95	21.34	26.47	45.24	23.09	0.181
48	O7M3CL15	O:M:CL - 119:51:30	6.51	20.68	27.88	44.94	22.17	0.188
49	O5M5CL5	O:M:CL - 95:95:10	7.72	22.55	24.06	45.66	22.04	0.154
50	O5M5CL10	O:M:CL – 45:45:10	6.18	25.14	27.30	41.38	20.93	0.161
51	O5M5CL15	O:M:CL – 85:85:30	6.36	21.05	24.96	47.62	21.59	0.148
52	O3M7CL5	O:M:CL – 57:133:10	6.73	22.26	11.18	59.83	23.01	0.155
53	O3M7CL10	O:M:CL – 27:63:10	6.09	21.97	21.26	50.68	22.88	0.186
54	O3M7CL15	O:M:CL – 51:119:30	4.83	16.57	46.73	31.87	20.85	0.194
55	M7J3CA5	M:J:CA - 133:57:10	8.36	25.99	10.82	54.83	27.28	0.274
56	M7J3CA10	M:J:CA - 63:27:10	8.35	30.62	10.77	50.26	25.48	0.338
57	M7J3CA15	M:J:CA - 119:51:30	8.67	33.93	11.28	46.12	23.54	0.392
58	M5J5CA5	M:J:CA - 95:95:10	10.58	28.65	14.35	46.41	24.77	0.289
59	M5J5CA10	M:J:CA – 45:45:10	9.33	29.73	12.76	48.17	25.97	0.355
60	M5J5CA15	M:J:CA – 85:85:30	9.44	30.46	13.05	47.06	25.16	0.376
61	M3J7CA5	M:J:CA – 57:133:10	11.17	29.68	16.81	42.33	20.83	0.308
62	M3J7CA10	M:J:CA – 27:63:10	9.88	28.44	15.90	45.78	22.69	0.382
63	M3J7CA15	M:J:CA – 51:119:30	8.78	27.93	14.55	48.74	24.33	0.407
64	M7J3CO5	M:J:CO - 133:57:10	9.81	26.76	9.65	53.77	24.47	0.247
65	M7J3CO10	M:J:CO - 63:27:10	8.49	29.55	10.99	50.97	24.28	0.241
66	M7J3CO15	M:J:CO - 119:51:30	8.10	28.73	10.40	52.78	23.33	0.258
67	M5J5CO5	M:J:CO - 95:95:10	9.11	31.25	12.90	46.74	23.93	0.252
68	M5J5CO10	M:J:CO – 45:45:10	8.96	27.64	12.78	50.62	24.87	0.273
69	M5J5CO15	M:J:CO – 85:85:30	8.40	33.92	11.89	45.78	24.53	0.275
70	M3J7CO5	M:J:CO – 57:133:10	9.31	26.67	16.97	47.04	23.10	0.284
71	M3J7CO10	M:J:CO – 27:63:10	9.45	29.13	15.88	45.54	22.12	0.288
72	M3J7CO15	M:J:CO – 51:119:30	10.13	31.28	14.24	44.34	21.56	0.295
73	M7J3CL5	M:J:CL - 133:57:10	7.47	22.84	10.14	59.54	20.47	0.191
74	M7J3CL10	M:J:CL - 63:27:10	7.29	21.62	12.91	58.18	21.66	0.174
75	M7J3CL15	M:J:CL - 119:51:30	6.10	19.11	37.26	37.53	20.84	0.184

No.	Sample Id	Sample composition	% Moisture	% Volatile matter	% Ash	% Fixed carbon	Calorific value (MJ/kg)	Comp. Strength (N/mm²)
76	M5J5CL5	M:J:CL - 95:95:10	7.54	22.81	13.54	56.12	22.41	0.178
77	M5J5CL10	M:J:CL – 45:45:10	8.03	21.82	14.11	56.04	21.85	0.178
78	M5J5CL15	M:J:CL – 85:85:30	8.03	25.98	19.30	46.69	21.22	0.198
79	M3J7CL5	M:J:CL – 57:133:10	8.57	22.39	14.61	54.43	21.14	0.162
80	M3J7CL10	M:J:CL – 27:63:10	8.38	21.13	19.29	51.20	20.99	0.177
81	M3J7CL15	M:J:CL – 51:119:30	6.82	19.88	35.68	37.62	21.42	0.201

Note. The table shows the results of thermogravimetric analysis of various samples. The samples have been assigned letters as follows; O – orange, M – Mango, J – Jackfruit, CA – cassava, CO – corn, CL - clay

Table 2

Elemental Composition, Bulk Density, and Drop Strength

No.	Sample Id	Sample composition	Bulk density (kg/m3)	Carbon %	Hydrogen %	Oxygen %	Sulphur and Nitrogen %	Drop strength
1	OCA5	O:CA - 19:1	517.75	43.59	4.82	30.51	21.08	60.11%
2	OCA10	O:CA - 9:1	535.47	44.96	4.92	31.27	18.85	88.84%
3	OCA15	O:CA - 17:3	479.19	44.51	4.93	31.90	18.65	82.55%
4	OCL5	O:CL - 19:1	414.41	44.72	4.82	29.84	20.62	27.74%
5	OCL10	O:CL - 9:1	514.70	42.14	4.69	29.06	24.10	31.55%
6	OCL15	O:CL - 17:3	494.59	37.56	4.29	24.77	33.38	28.67%
7	OCO5	O:CO - 19:1	427.26	44.97	4.87	30.29	19.86	41.56%
8	OCO10	O:CO - 9:1	477.36	44.45	4.88	30.95	19.72	48.77%
9	OCO15	O:CO - 17:3	413.91	44.67	4.91	31.37	19.04	57.12%
10	JCA5	J:CA - 19:1	452.51	37.98	4.38	26.71	30.92	58.85%
11	JCA10	J:CA - 9:1	467.14	38.35	4.43	27.35	29.87	70.94%
12	JCA15	J:CA - 17:3	479.46	36.52	4.26	26.93	32.29	78.11%
13	JCL5	J:CL - 19:1	519.45	37.33	4.28	25.52	32.88	28.97%
14	JCL10	J:CL - 9:1	480.93	30.91	3.87	22.34	42.89	30.52%
15	JCL15	J:CL - 17:3	507.17	27.72	3.63	20.23	48.42	29.61%
16	JCO5	J:CO - 19:1	519.24	36.55	4.28	26.18	32.99	47.15%
17	JCO10	J:CO - 9:1	468.82	38.33	4.43	27.53	29.70	66.69%
18	JCO15	J:CO - 17:3	472.41	38.13	4.48	28.44	28.95	75.51%
19	MCA5	M:CA - 19:1	470.67	49.09	5.11	31.75	14.05	54.14%
20	MCA10	M:CA - 9:1	498.26	48.52	5.14	32.64	13.69	71.88%
21	MCA15	M:CA - 17:3	492.18	48.48	5.13	32.66	13.73	75.23%
22	MCL5	M:CL - 19:1	470.46	48.68	5.08	31.47	14.77	33.13%

No.	Sample Id	Sample composition	Bulk density (kg/m3)	Carbon %	Hydrogen %	Oxygen %	Sulphur and Nitrogen %	Drop strength
23	MCL10	M:CL - 9:1	427.73	44.67	4.79	28.94	21.61	35.78%
24	MCL15	M:CL - 17:3	482.88	38.64	4.43	26.57	30.36	50.22%
25	MCO5	M:CO - 19:1	516.68	49.47	5.12	31.85	13.56	51.23%
26	MCO10	M:CO - 9:1	430.33	49.60	5.15	32.14	13.10	63.58%
27	MCO15	M:CO - 17:3	518.58	49.51	5.16	32.27	13.06	65.22%
28	O7M3CA5	O:M:CA - 133:57:10	449.74	45.13	4.95	31.66	18.26	48.41%
29	O7M3CA10	O:M:CA - 63:27:10	480.67	45.39	4.96	31.73	17.92	71.19%
30	O7M3CA15	O:M:CA - 119:51:30	424.60	41.29	4.64	29.24	24.83	76.55%
31	O5M5CA5	O:M:CA - 95:95:10	434.47	45.64	4.93	31.00	18.43	51.12%
32	O5M5CA10	O:M:CA – 45:45:10	445.48	45.88	4.96	31.32	17.84	65.58%
33	O5M5CA15	O:M:CA – 85:85:30	459.76	44.73	5.01	32.98	17.28	69.18%
34	O3M7CA5	O:M:CA – 57:133:10	443.83	47.12	4.99	31.08	16.81	59.59%
35	O3M7CA10	O:M:CA – 27:63:10	485.44	46.52	5.02	32.05	16.41	68.84%
36	O3M7CA15	O:M:CA – 51:119:30	498.67	47.46	5.08	32.24	15.22	77.44%
37	O7M3CO5	O:M:CO - 133:57:10	457.10	45.30	4.91	30.96	18.83	38.93%
38	O7M3CO10	O:M:CO - 63:27:10	439.48	45.84	4.97	31.53	17.66	53.89%
39	O7M3CO15	O:M:CO - 119:51:30	476.31	45.31	4.93	31.38	18.38	60.41%
40	O5M5CO5	O:M:CO - 95:95:10	418.80	39.20	4.47	27.45	28.87	40.11%
41	O5M5CO10	O:M:CO – 45:45:10	511.39	47.02	4.99	31.14	16.86	41.66%
42	O5M5CO15	O:M:CO – 85:85:30	457.64	45.97	5.01	32.05	16.98	49.58%
43	O3M7CO5	O:M:CO – 57:133:10	460.59	46.62	4.97	31.12	17.30	43.89%
44	O3M7CO10	O:M:CO – 27:63:10	479.57	47.09	5.05	32.06	15.79	52.19%
45	O3M7CO15	O:M:CO – 51:119:30	469.36	47.40	5.03	31.61	15.96	64.45%
46	O7M3CL5	O:M:CL - 133:57:10	477.56	16.32	2.86	13.83	66.98	31.21%
47	O7M3CL10	O:M:CL - 63:27:10	463.38	36.03	4.21	24.78	34.98	32.45%
48	O7M3CL15	O:M:CL - 119:51:30	479.27	35.40	4.17	24.33	36.10	33.69%
49	O5M5CL5	O:M:CL - 95:95:10	426.59	37.08	4.29	25.55	33.08	29.54%
50	O5M5CL10	O:M:CL – 45:45:10	472.84	35.25	4.22	25.23	35.30	27.98%
51	O5M5CL15	O:M:CL – 85:85:30	550.3	37.55	4.32	25.49	32.63	29.33%
52	O3M7CL5	O:M:CL – 57:133:10	485.48	47.17	4.98	30.52	17.33	28.88%
53	O3M7CL10	O:M:CL – 27:63:10	420.71	40.27	4.52	27.05	28.16	34.41%
54	O3M7CL15	O:M:CL – 51:119:30	501.23	23.42	3.34	17.53	55.70	35.96%
55	M7J3CA5	M:J:CA - 133:57:10	466.25	45.75	4.90	30.58	18.77	42.29%
56	M7J3CA10	M:J:CA - 63:27:10	461.31	44.98	4.91	31.20	18.91	64.34%
57	M7J3CA15	M:J:CA - 119:51:30	462.81	43.82	4.87	31.33	19.98	74.12%
58	M5J5CA5	M:J:CA - 95:95:10	435.46	41.29	4.60	28.89	25.22	49.96%
59	M5J5CA10	M:J:CA – 45:45:10	482.59	43.05	4.75	30.03	22.16	69.92%
60	M5J5CA15	M:J:CA – 85:85:30	419.31	42.65	4.73	29.98	22.63	70.81%
61	M3J7CA5	M:J:CA – 57:133:10	413.21	38.94	4.45	27.93	28.69	64.69%
62	M3J7CA10	M:J:CA – 27:63:10	512.79	40.64	4.57	28.54	26.25	73.57%

No.	Sample Id	Sample composition	Bulk density (kg/m3)	Carbon %	Hydrogen %	Oxygen %	Sulphur and Nitrogen %	Drop strength
63	M3J7CA15	M:J:CA – 51:119:30	491.78	42.42	4.70	29.34	23.55	85.12%
64	M7J3CO5	M:J:CO - 133:57:10	498.95	45.54	4.87	30.61	18.97	42.11%
65	M7J3CO10	M:J:CO - 63:27:10	479.11	44.92	4.89	30.94	19.26	38.22%
66	M7J3CO15	M:J:CO - 119:51:30	486.70	45.74	4.94	31.18	18.14	45.17%
67	M5J5CO5	M:J:CO - 95:95:10	513.33	42.83	4.76	30.25	22.16	39.94%
68	M5J5CO10	M:J:CO – 45:45:10	441.55	43.64	4.77	29.88	21.70	45.87%
69	M5J5CO15	M:J:CO – 85:85:30	467.51	43.55	4.86	31.20	20.39	43.89%
70	M3J7CO5	M:J:CO – 57:133:10	420.26	40.53	4.55	28.11	26.81	46.63%
71	M3J7CO10	M:J:CO – 27:63:10	512.95	40.81	4.59	28.78	25.82	48.22%
72	M3J7CO15	M:J:CO – 51:119:30	478.90	41.20	4.64	29.42	24.75	53.33%
73	M7J3CL5	M:J:CL - 133:57:10	449.75	47.35	4.98	30.72	16.94	35.68%
74	M7J3CL10	M:J:CL - 63:27:10	423.68	45.67	4.86	29.63	19.85	30.88%
75	M7J3CL15	M:J:CL - 119:51:30	502.84	29.08	3.73	20.87	46.32	37.76%
76	M5J5CL5	M:J:CL - 95:95:10	514.59	44.84	4.81	29.46	20.88	34.11%
77	M5J5CL10	M:J:CL – 45:45:10	486.66	44.28	4.76	28.96	22.00	39.66%
78	M5J5CL15	M:J:CL – 85:85:30	580.1	39.77	4.51	27.62	28.11	38.81%
79	M3J7CL5	M:J:CL – 57:133:10	520.79	43.47	4.70	28.67	23.16	29.52%
80	M3J7CL10	M:J:CL – 27:63:10	519.64	40.40	4.48	26.87	28.25	38.25%
81	M3J7CL15	M:J:CL – 51:119:30	487.82	29.65	3.77	21.30	45.29	39.92%

Note. To ease representation, the samples have been assigned letters as follows; O – orange, M – Mango, J – Jackfruit, CA – cassava, CO – corn, CL - clay

Discussion

Physical and Chemical Properties

The volatile matter content in starch bound briquettes was similar to the results of Borowski *et al.* (2017) who also used starch binders. On the other hand, Sunardi *et al.* (2019) used a starch binder but obtained lower volatile matter content values ranging from 21.28% to 21.35% whereas results from Zanella *et al.* (2016) ranged from 48.5% to 69.3% using cornstarch.

According to Katimbo *et al.* (2014) and Falemara *et al.* (2018), briquettes with a high volatile matter content are easier to ignite than briquettes with a low volatile matter content. On the contrary, Falemara *et al.* (2018) denoted that high volatile matter content implies high emissions during combustion. This inference can be derived from the chemical composition of volatile matter. It entails long and short chain aromatic hydrocarbons and some sulfur (Ozbayoglu, 2018), which are converted into vapor when heated (Sunardi *et al.*, 2019). Volatile matter content in briquettes decreases with an increase in temperature at the carbonization stage (Faizal, 2017).

The average ash content of 15.99% was significantly higher than the results by Falemara *et al.* (2018) and Sawadogo *et al.* (2018) whose average ash content values were 4.4% and 5.8%, respectively. The ash content of this study was lower than the results of Ikelle *et al.* (2014) and Thliza *et al.* (2020) whose average ash content values were 33.675% and 19.88%, respectively. Onchieku *et al.* (2012) also obtained an average ash content of 44.2% using clay as a binder.

The clay briquettes in this study had higher average ash content, 23.66%, compared to briquettes bound by cornstarch and cassava starch whose average ash content values were 12.18% and 12.14%, respectively. Furthermore, the ash content generally increased with the overall clay concentration in the briquettes. The disparity originates from the difference in ash content between the individual binders. Clay on its own has a high ash content of 90.1% (Onchieku *et al.*, 2012) whereas the ash content in cassava ranges from 0.32% to 2.06% (Ojo et al, 2017; Nilusha *et al.*, 2021). The ash content in corn ranges from 1.1% to 2.95% (Sule *et al.*, 2014).

Ash represents the incomburstible inorganic remnants in a fuel, these often include silicon, aluminum, sodium, vanadium, and nickel . Ash holds no heating value and lowers the burning efficiency of a fuel. This is corroborated by Chukwuneke *et al.* (2020) whose study showed that a mahogany sawdust briquette yielded 45.7% burning efficiency compared to 34.7% efficiency of a rice husk briquette. The difference in burning efficiencies was synonymous to the differing ash content values of mahogany and rice husks at 1.3% and 14%, respectively.

The average fixed carbon of 49.23% in this study was higher than Sunardi *et al.* (2019) at 31.98%, and Zanella *et al.* (2016) at 31.514% who used maize cobs and orange bagasse, respectively as the primary biomass. On the other hand, Borowski et al. (2017) and Sawadogo *et al.* (2018) achieved higher fixed carbon content values of 64.55% and 60.68% respectively, using cashew waste and wood, respectively as the primary biomass. Like ash content, fixed carbon is an intrinsic characteristic of biomass. Carbonization reduces volatile matter and increases both ash content and fixed carbon content. According to Faizal (2017), both fixed carbon and ash content increase with the carbonization temperature.

The average calorific values for cassava starch, cornstarch, and clay briquettes were 24.28 MJ/kg, 25.17 MJ/kg, and 22.36 MJ/kg, respectively. The results were similar to the calorific values in studies by Faizal (2017), Sunardi *et al.* (2019), and Lubwama *et al.* (2020) but less than the values obtained by Falemara *et al.* (2018). In their study, Falemara *et al.* (2018) posulated that calorific value has a postive correlation with the density of the unprocessed biomass after obtaining a higher calorific value for briquettes from wood residue (34.4 MJ/kg) compared to briquettes from groundnut shells (32.12 MJ/kg) and corn cobs (32.98 MJ/kg).

The average calorific values obtained for single biomass briquettes of jackfruit, mango, and orange in this study were 20.36 MJ/kg, 27.5 MJ/kg, and 23.37 MJ/kg, respectively. The bulk densities of jackfruit seeds, mango seeds, and orange peels are 460 kg/m^3 (Divekar and Barge, 2021), 390 kg/m^3 (Okpala and Gibson-Umeh, 2013), and 300 kg/m^3 (Vitale *et al.*, 2021) respectively. These results represent a negative correlation of -0.35, in contrast with Falemara *et al.* (2018). While assessing the calorific values and bulk densities of different species of bamboo, the results from Sette *et al.* (2016) also indicated a negative correlation of -0.36. Furthermore, Ycaza and Barre (2018) obtained higher calorific values for briquettes from coconut shells and mango leaves compared to wood briquettes.

A positive correlation of 0.55 exists between fixed carbon and calorific value in this study, in agreement with Onchieku *et al.* (2012), La *et al.* (2020), and Lubwama *et al.* (2020). An inverse relationship was observed between calorific value and ash content, with a -0.52 coefficient of correlation, the relationship was also denoted by Sunardi *et al.* (2019). The average calorific values at binder concentrations of 5%, 10%, and 15% were 24.41 MJ/kg, 23.93 MJ/kg, and 23.47 MJ/kg. This inverse relationship between binder concentration and calorific value was similarly observed by Zanella *et al.* (2016).

The average bulk density was 474.7 kg/m^3. The bulk density results were similar to the range of 476 kg/m^3 to 578 kg/m^3 reported by Lubwama *et al.* (2020). The results were lower than 820 kg/m^3 to 870 kg/m^3 reported by Ikubanni *et al.* (2019), 1,023.4 kg/m^3 reported by Ycaza and Barre (2018), and and 594 kg/m^3 to 629 kg/m^3 reported by Zanella *et al.*(2016). A briquette's density represents the compactness of particles within a given volume. Briquettes with a high bulk density have more particles within a small volume and this improves their burning duration (Katimbo *et al.*, 2014). The low compaction ratio from the manual lever press used in this study is responsible for the low bulk density results compared to other studies. Ikubanni *et al.* (2019) used a motorized piston press and Zanella *et al.* (2016) used a hydraulic press.

Ultimate Analysis

Carbon and hydrogen results were similar to values reported by Ikubanni *et al.* (2019); however, Ikubanni *et al.* (2019) had higher oxygen composition of 32.82% to 35.67%. The average carbon and hydrogen compostion was similar to 44.6% to 50.1% and 5.1% to 5.6%, respectively, reported by Ajimotokan *et al.* (2019). Sulphur and nitrogen composition was higher than Zanella *et al.* (2016) and Adu-Poku *et al.* (2022). The high sulphur and nitrogen values are undesirable because they correlate with high emissions of harmful gases. Calorific value of briquettes increases with the composition of carbon and hydrogen (Senila *et al.*, 2022). According to Maulina *et al.* (2021), calorific value decreases with the ratio of hydrogen to carbon.

Mechanical Properties

The average compressive strength for all 81 samples in this study was 0.271 N/mm^2. The value was lower than 0.38 N/mm^2, the acceptable compressive strength in the industry, which was recommended by Richards (1990), cited in Prasityousil and Muenjina (2013) and Kpalo *et al.* (2020). The low compressive strength value implies a high susceptibility to damage during transportation. According to Mitchual *et al.* (2013), compressive strength of briquettes depends on particle size, biomass density, and compaction pressure. This finding was further corroborated by Ajimotokan *et al.* (2019).

Zepeda-Cepeda *et al.* (2021) deduced that compressive strength increases with a reduction in particle sizes; however, the findings of Bello and Onilude (2020) showed that the significance of the effect of particle size on briquette quality becomes less pronounced at high compaction pressures. According to Muazu and Stegemann (2015), the higher the compaction pressure, the higher the compressive strength. The application of a manual lever press to compact briquettes in this study is a likely cause of the low compressive strength. This is evidenced in a study by Onchieku (2018) where a manual lever press registered a 1.18 compaction ratio compared to a 2.4 compaction ratio by an electric screw extruder.

The average compressive strength for cassava starch briquettes was 0.356 N/mm^2 whereas the average compressive strength for corn starch briquettes was 0.284 N/mm^2. Briquettes from the two starch binders had comparably higher compressive strength than clay based briquettes, in similarity with Katimbo *et al.* (2014). The superiority of cassava starch as a binder in comparison with corn starch is consistent with the findings of Aransiola *et al.* (2019). According to BeMiller and Whistler (2009), cited in Ek *et al.* (2020), the granule size of cassava starch is between 4 and 35 µm. In comparison, the granule size of corn starch ranges from 1 to 20 µm (Singh *et al.*, 2016). The larger the starch granule size, the easier it is to gelatinize the starch; therefore, cassava starch holds a lower gelatinization temperature than corn starch (Abdullah *et al.*, 2016). Additionally, the paste viscosity of cassava starch is higher than that for corn starch (Ek *et al.*, 2020).

This study also showed that briquettes with higher binder concentration generally exhibited higher compressive strength regardless of the binder type, in consistence with Aransiola *et al.* (2019) and Zepeda-Cepeda *et al.* (2021).

The average drop strength was 51%. The average drop strength was lower than values reported by Ikubanni *et al.* (2019), Lubwama *et al.* (2020), and Poku *et al.* (2022). The variation in results stems from the compaction methods used. According to Adu-Poku *et al.* (2022), drop strength increases with the compaction pressure applied in briquette development. The results also showed that drop strength increased with the binder concentration, this was synonymous with Rajaseenivasan *et al.* (2016). The addition of a binder improves adhesion among a briquette's particles and consequently reduces shattering on impact. High drop strength implies better handling and resistance to damage during transportation and storage (Zanella *et al.*, 2016).

Thermal Properties

The time to boil was similar to results reported by Igboanugo *et al.* (2015) and Medina *et al.* (2016). Briquettes with starch binders had shorter time to boil compared to briquettes with the clay binder. Low ash content and high calorific values in the starch briquettes enabled the dissipation of more heat. Furthermore, the starch binders had high volatile matter content which quickened the ignition process (Lubwama *et al.*, 2020). The time to boil during the cold start phase was generally longer than the time to boil during the hot start phase because part of the heat released by the briquettes during the cold start phase was used to heat up the cookstove. This finding was also reported by Kivumbi *et al.* (2021).

The first trough in the burning rate curves represents a weight increase due to moisture at the onset of thermal decompostion. The burning rates were generally lower than rates reported by Lubwama *et al.* (2020) despite having similar ash content and volatile matter compostion. Variations in binder concentration and char ratios did not influence the burning rates. According to Gani and Naruse (2007), burning rate increases with the cellulose composition in biomass.

Mango fruit waste has 30% cellulose composition (Wongkaew *et al.*, 2021). The cellulose composition in orange and jackfruit waste is 22% (Ayala *et al.*, 2021) and 27.75% (Sundarraj and Ranganathan, 2017), respectively. In their study, Lubwama *et al.* (2020) used rice husks, coffee husks, and groundnut shells. Their cellulose composition is 35 - 40% (Gao *et al.*, 2018), 35% (Collazo-Bigliardi *et al.*, 2018), and 38.3% (Patidar et al, 2020), respectively. The variation in cellulose composition explains the difference between the burning rates of the two studies.

Conclusion

The briquette development process used cassava starch, cornstarch, and clay as binders, and a manual lever press for compaction. Physical and chemical properties were examined for both homogeneous and composite briquettes at varying binder concentrations. Moisture content, volatile matter, fixed carbon, and ash content were examined using thermogravimetric analysis. Calorific values of the developed briquettes were determined with bomb calorimetry. Mechanical integrity was examined through drop strength, bulk density, and compressive strength.

Thermogravimetric analysis showed that the developed briquettes had good physical properties. The 26.71% average volatile matter content indicated that the briquettes were easy to ignite, and they released low emissions during combustion. Briquettes, which entailed mango fruit waste char had higher fixed carbon and subsequently registered higher calorific values. Briquettes with starch binders had lower ash content compared to briquettes with the clay binder. The highest rate of change in the burning rate was registered between the 100th and the 135th minutes. The lowest and highest percentage weight losses at the highest combustion temperature were 56% and 78%, respectively.

Although briquettes with the cassava starch binder had higher compressive strength compared with cornstarch and clay binders, the 0.271 N/mm^2 average compressive strength for all developed briquettes was lower than 0.38 N/mm^2, the acceptable compressive strength in the industry. The low mechanical integrity was further confirmed by a 51% average drop strength which means that the developed briquettes are susceptible to damage during transportation and storage. The low mechanical integrity in this study highlighted the shortcomings of using a manual lever press as a compaction method. Water boiling test results reechoed the optimum calorific value and volatile matter content results from briquettes which had starch binders.

Briquette development with other compaction methods should be explored in further studies to improve the mechanical integrity. More binder options should also be researched and tested with the fruit waste varieties of this study, preferably binders not associated with food. Further research should explore linkages between briquettes' thermal stability and the briquette production process.

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Data Availability

Datasets related to this paper are hosted by Mendeley Data at https://dx.doi.org/10.21227/fh8m-er23 (Semazzi *et al.*, 2023).

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