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Impact of material composition and food waste decomposition on characteristics of fuel briquettes

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A R T I C L E I N F O

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A B S T R A C T

This study investigated the potential of using locally available municipal solid wastes (MSW) (such as food wastes from restaurants, charcoal dust, coconut husk and shell, and sawdust) as feedstock to produce non-carbonized fuel briquettes. A low-cost briquetting machine sourced from Alfaster Industries in Kenya served to demonstrate the concept. Using decomposed food waste resulted in briquettes with higher bulk density (+4%), greater net calorific value (+18%) and lower burning rate (-24%), compared to the use of regular food waste. There was no significant difference in ash content from the two briquette types. The results also indicate that decomposing food waste and mixing it with tree-based raw materials such as coconut waste, charcoal waste or sawdust improves the quality of briquettes, and enhances the temperatures achieved during combustion. This recycling solution has the potential to serve multiple benefits in MSW management for sustainable cities while reducing rural land degradation and deforestation.

Abbreviations

SSA	Sub-Saharan Africa
MSW	Municipal solid wastes
FW	Food waste
FRI	Food Research Institute
CSIR	Council for Scientific and Industrial Research
2FI	Two-factor interaction

Introduction

In sub-Saharan Africa (SSA), use of wood fuel is rising due to population growth and emerging urbanization trends. Typically, a one percent rise in urbanization has been linked to a 14% rise in charcoal consumption (Chandra, 2021; World bank, 2009). Such trends raise concern since unsustainable production and inefficient utilization of wood fuel often result in land degradation, deforestation, as well as other adverse effects on the environment (Chandra, 2021).

In Ghana, 96% of rural and 67% of urban populations rely on wood and/or charcoal (Olatunji et al., 2021; Wiedinmyer et al., 2017). The national average for biomass consumption per capita is 100 kg, i.e., equivalent in volume for 2019 to 3 million and 4.2 million metric tons of charcoal and firewood, respectively (Energy Commission Ghana, 2019). These high levels of fuel consumption in the country are partly due to the fact that charcoal and wood are the main sources of energy for domestic cooking as well as for small food and industrial enterprises such as fish smoking, local brewing, pottery making, cooking oil extraction, street food and grills (Gebrezgabher and Amewu, 2016; Olatunji et al., 2021). To reduce demand for wood or charcoal, waste-based substitutes in the form of briquettes are frequently explored globally.

The production of briquettes involves compressing waste biomass material into a uniform solid unit for use in similar ways as firewood or charcoal. Briquette making from biomass materials could make a substantial contribution to the economic advancement of developing countries by helping to meet energy and safe environmental demands of urban and industrial sectors (Olatunji et al., 2021). Non-carbonized briquettes are produced from dry solid residues and are mostly meant to substitute wood. They offer the advantage of igniting easily,

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compared to the carbonized briquettes (Feng et al., 2020; Krajnc, 2015). However, the disadvantage is that they do not last long because of their soft texture. They also produce higher fine particulate matter than carbonized briquettes which may become a concern for human health if used indoors (Njenga, 2013a; Olatunji et al., 2021). Besides, carbonized briquettes which are also classified as charcoal briquettes are produced through densification of carbonized (or pyrolyzed) materials or following carbonization of densified briquettes, to substitute charcoal (Bonsu et al., 2020).

Asamoah et al. (2016) documented the operating procedures and requirements for producing different types of briquettes. Although three types of machines (i.e., screw press, piston press and hydraulic press) have been used for briquette production, each has own advantages and disadvantages. Selection of briquette production equipment should be based on materials to process and the expected quality and users of the products. Binders such as cassava starch, molasses, red soil, and clay are required when processing briquettes at low (i.e., close to ambient) temperature in briquetting machines with low pressing ability, or when the feedstock includes large amounts of carbonized materials, which lack plasticity, due to their lignin content below 5% (Kizito et al., 2022; Guo et al., 2020; Srivastava et al., 2014). The amount of binder required depends on the binding properties of both the waste mix and of the binder (Guo et al., 2020). Usually, it needs to be kept at a minimum for cost reasons (Asamoah et al., 2016). Ultimately, the responses in terms of briquette quality will vary with the biomass characteristics, e.g., whether they are carbonized or not, the densification method and strength and the chemical composition, including if binders are added.

The production of biomass briquettes has been reported to occur at research, pilot and industrial scales. Usually, woody, and herbaceous biomass such as sawdust is preferred. Common emerging feedstock includes agrowaste such as bamboo, husks, kernel, maize cob, straws, coconut waste, and various agro-processing wastes, including cashew processing waste which is typically a mixture of shell, press cake and nut shell, tuber peels, but materials such as faecal sludge (FS) and municipal solid waste (MSW) are also gaining interest (Kizito et al., 2022; Akolgo et al., 2021; Bonsu et al., 2020; Feng et al., 2020; Guo et al., 2020; Ifa et al., 2020; Magnago et al., 2020; Osei et al., 2020; Odotei et al., 2019; Sawadogo et al., 2018).

The abundance of MSW in Ghana represents a potential opportunity for fuel briquette production. Usually, MSW are generated from households (55–80%), followed by commercial or market areas (10–30%) and include a large fraction of food waste (FW) (biodegradable organics represent 68% in mass of the MSW). In Ghana, the generation of MSW, which has disparities based on socio-economic factors, reaches 0.86 kg/person/day in largest city, Accra, but averages 0.47–0.51 kg/person/day in smaller urban areas (Miezah et al., 2015). Collecting and disposing of MSW in landfills or open dumps is a labour-intensive and ineffective process, though it consumes 50 to 70% of municipal budgets (Lissah et al., 2021). The consequences of the poor sanitation costs Ghana about 1.6% of the country's Gross Domestic Product (Water and Sanitation Program, 2012).

Production of briquettes using MSW is not yet widespread compared to the use of other materials. Afsal et al. (2020) tested the use of vegetable market waste in combination with sawdust in briquette production at a waste mass ratio of 25, 50, 75, and 100%. The binding material they used was bentonite clay. They found that the adding of sawdust to the feedstock mixture improved briquette combustion characteristics by increasing the calorific value by up to 12% and volatile matter content by up to 16%, compared to briquettes from vegetable market waste only. Compared with firewood, coal, and conventional sawdust briquettes, vegetable market waste + sawdust briquettes appeared to be of acceptable quality (Afsal et al., 2020). In addition, Kizito et al. (2022) produced briquettes using a mixture of FS and various individual FW fractions (e.g., pineapple peels, charcoal fines, and bean husks) at a mass ratio of 50% FS:50% biomass. In their process, fermented red soil acted as the binder.

In general, the MSW briquettes are meant for domestic use, but some formulations which integrate plastics are solely meant to substitute conventional coal in industrial combustion processes due to the potential for emissions of toxic flue gases (Gug et al., 2015). For example, Tumuluru et al. (2021) tested the briquetting of a MSW mixture comprised of 30% plastic, 60% paper and non-corrugated cardboard, and 10% textile material. Their main conclusion was that the resulting briquette product had characteristics and physico-chemical properties like conventional woody and herbaceous biomass.

To process agrowaste residues, which could have up to 50% to 80% in moisture content, materials are usually left to dry on the farmers' fields or under sheds, which is the most economical approach (Okot et al., 2019; Srivastava et al., 2014). In most cases involving the use of vegetable urban waste or processed agrowaste, under shed and sun-drying are used to remove the excess water and attain the desirable moisture content (Tumuluru et al., 2021; Afsal et al., 2020; Ifa et al., 2020; Srivastava et al., 2014). This necessary drying step might constrain the process, given the length of time it requires to be completed, and consequently the land footprint. Alternatively, using a mechanical drying process, e.g., a press and/or a heated dryer, is energy and capital-intensive, and only recommended for processing during rainy season, when sun-drying is barely possible, or as a strategy to reduce the footprint of the drying process or to speed-up the processing rate (Tumuluru et al., 2021; Ifa et al., 2020; Gug et al., 2015). Finally, in the case of wet briquetting processes, an additional drying step is required after the briquettes have been formed.

There is seasonal variation in the generation of FW. To reduce the impact of this on the quality of manufactured briquettes and ensure briquettes with standard characteristics are produced throughout the year, mixtures of raw materials are preferred. This helps to minimise the variability of individual feedstock characteristics and availability on the process (Okot et al., 2019). Another challenge with the process can be linked to the degree of biodegradation of the raw residue, which would affect its physico-chemical characteristics, but this parameter has not yet been investigated.

The objective of this study was to investigate the use of various locally available waste materials to produce briquettes which can substitute wood or charcoal for cooking needs. After optimizing the briquette production process, especially the water requirement and the concentration of cassava starch added as a binder in a pre-gelatinized form, we studied the effect of FW on the briquette quality. In Ghana, the use of briquettes is new and unregulated. Gebrezgabher and Amewu reported that potential users of briquettes identified key qualitative criteria they would consider in selecting a type of fuel (Gebrezgabher and Amewu, 2016). These include, in addition to the price, how long the fuel lasts and its heating value. Hence, the quality parameters considered in our study included the burning characteristics of the briquettes produced, using criteria such as the net calorific value, the temperature in flame and the ash content. We also analysed the ash generation and in some instances its composition, to assess potential for their recycling in agriculture to enrich the treated soils in minerals. Finally, the bulk density of the briquettes produced were assessed, given the impact of this parameter on transport and handling costs.

Materials and methods

Collection and pre-treatment of materials or feedstock

For our briquette production trial, four waste types amongst MSW were selected through a rapid feasibility study due to their availability; charcoal dust, sawdust, coconut (fibre, shells, husks) and mixed uncooked FW (Nikiema et al., 2016). The proximate analyses of the feedstock are presented in Table 1. The ultimate analyses for sawdust and coconut husk/shell are in the supplemental file (Table 1).

Charcoal dust was obtained from charcoal sellers and users in Accra, Ghana. The charcoal dust is the residue from the abrasion of charcoal

Table 1
Proximate analysis of process feedstock.

	Waste Materials		Moisture content[b] (%)	Dry ash content (%)	Dry fixed carbon (%)	Dry volatile matter (%)	Density (kg/m^3)	Calorific value (kJ/g)
This study[a]	Charcoal fines		5.4 ± 3.7	42.6 ± 4.8	49.8 ± 2.9	7.6 ± 5.5	531 ± 47	18.9 ± 3.5
	Coconut fibre		32.6 ± 3.9	6.1 ± 2.5	17.8 ± 3.9	77.8 ± 4.5	202	18.3 ± 2.3
	Coconut husk		31.8 ± 3.7	1.9 ± 2.5	26.7 ± 1.2	71.4 ± 1.4	955 ± 79	18.5 ± 4.7
	Coconut shell		22.1 ± 10.2	0.4 ± 0.2	26.6 ± 9.2	73.0 ± 9.1	1003 ± 213	20.0 ± 2.2
	Sawdust		12.2 ± 1.5	2.3 ± 0.8	9.4 ± 2.8	88.3 ± 3.6	170 ± 78	17.6 ± 1.2
	FW		70.6 ± 5.2	6.5 ± 3.3	14.2	79.3	1220 ± 23	18.5 ± 4.7
Literature review[d]	Sold Charcoal		8.9 ± 1.4	8.3 ± 1.4	77.6 ± 1.3	14.1 ± 2.1	529 ± 114	25.0 ± 4.3
	Firewood		16–20	0.2–6	10–20	80–90	472–716[c]	7–16
	Fuel	Value	6–14	< 4	9–25	50–90	500–1300	10–35
	Briquette	Generality	Low, for better combustion	Low to avoid slagging	As high as possible	Low, to minimise gas emissions	High, for compactness and easy transportation	As high as possible
		How it is affected by process.	High	Low	Moderate	Moderate	High	Low
		How it is affected by raw biomass.	High	High	High	High	Moderate	High

[a] Values reported are the mean ± standard deviation of each waste tested.

[b] The moisture content of raw materials is given before pre-processing.

[c] Depends on moisture content of wood and on shape. Here values are given for roundwood type. Values given are at 15% moisture content.

[d] FAO, 1985; Reyes et al., 1992; Krajnc, 2015; Asamoah et al., 2016.

during handling and transportation. It is treated as waste as it does not have a direct market value to charcoal sellers or users. As a preliminary step, charcoal dust was sieved with a grid sieve having openings of 0.5 mm. The coarse residue (<30% in mass) was further ground manually with a mortar and pestle to produce finer charcoal and then combined with the sieved material. Both the sieved and the fine ground residue were mixed to make the briquette.

Sawdust from hard wood was collected from a local sawmill. Coconut waste was sourced from a dedicated dumping site in a public area in Accra, Ghana. Its initial moisture was up to 45%. It was air-dried for 7 to 10 days, until the coconut pieces looked deep brown in colour and with moisture of about 10%, and then was shredded to facilitate grinding. The ground coconut waste became a mixture of fibrous material (coarse) and a peat, obtained from the husk and shell parts, respectively. It was used for making the briquette.

Pre-sorted mixed FW was collected from local restaurants. Additional sorting was done on the production site by using rakes and hand picking to remove impurities. The FW had initial moisture content of about 75% which needed to be reduced for proper storage. Two methods were used for this purpose. First, the FW was mixed with a shovel and spread on a concrete shaded platform for air-drying. The FW was then manually turned after every two days. In the second method, the FW was allowed to decompose, which allowed comparisons between decomposed and fresh (non-decomposed) FW. To decompose the FW, the material was stacked in heaps of 200 kg, turned twice a week, and watered to maintain a moisture content of about 60% to 70%, for 30 days. During this 'composting' phase, the temperature in the heap ranged between 44 °C and 60 °C. After 30 days, the waste was spread to air-dry under a shed. In both cases, the drying time was 12 days. Subsequently, moisture contents of 7% to 11% and 10% to 13% were maintained for the non-decomposed and decomposed wastes, respectively. The pre-treated FW was then ground and used for briquette production.

Cassava starch, which is known to be a good binding agent (Njenga et al., 2016; Nikiema et al., 2014) was included in the waste mixture to enhance briquette's strength. Cassava starch was obtained from the Food Research Institute (FRI) of the Council for Scientific and Industrial Research (CSIR) of Ghana. Before use, the required amount of starch was dissolved in 200 ml of water at room temperature. Thereafter, 800 ml of boiling water was added for pre-gelatinization of the starch to occur. The mixture was later combined with the wastes at the required quantities for briquette moulding.

Briquette production

Table 1 summarizes key general quality requirements for briquette. Good quality and an efficient fuel briquette depends on low levels of moisture content (6–14%), volatile matter (50–90%) and ash content (< 4%) together with a high fixed carbon content (9–25%). The bulk density of briquettes gives an indication of transportation requirement per unit of energy and hence higher density is preferred. Durability of briquettes is also a key characteristic to consider, especially if they are to be transported, to reduce losses from breakages into fine particles. How these parameters are affected by raw materials or briquetting process is also mentioned in Table 1. The main characteristics of waste materials presented in Table 1 confirm their suitability for briquette production. However, charcoal dust had higher ash content than expected due to contamination with soil.

Fig. 1 illustrates the briquette production process. A low-cost automated screw briquette-making machine with a production capacity of up to 1000 kg/day was obtained from Alfaster Industries, in Kenya costing about US$1700 (Supplemental file - Fig. 1). This modest machine made by local artisans is designed for production at ambient temperature. Though some specifications lack, it works under low pressure and as such production of carbonized and non-carbonized briquettes with a diameter of 43 mm each requires use of a binding agent. Literature review by Asamoah et al., 2016 carried out to inform this work showed that artisanal or modest machines produce good quality briquettes.

First, we weighed the materials according to the desired mix ratios to form 3000 g of dried wastes mixtures. Then, we added pre-gelatinized starch and water and manually mixed the materials thoroughly. The mixing ratios of raw materials and binders are presented later under the results section. Finally, we placed the mixture in the pan of the briquette machine and started the machine. We collected the briquettes in plates and sun-dried them for a duration of 5–7 days, depending on the waste material mix and weather, to attain moisture content of 10% or less (Supplemental file - Fig. 2). This is in line with other trials, such as the one led by Sawadogo et al., 2018 who required up to 2 weeks drying at ambient temperature (30 °C). Logically, a shorter time is required when drying temperatures are higher. Similarly, Bonsu et al., 2020 sun-dried their carbonized palm kernel shells briquettes also produced in Ghana for 7 days.

Characterization of briquettes

The parameters analysed include moisture content, water absorbed,

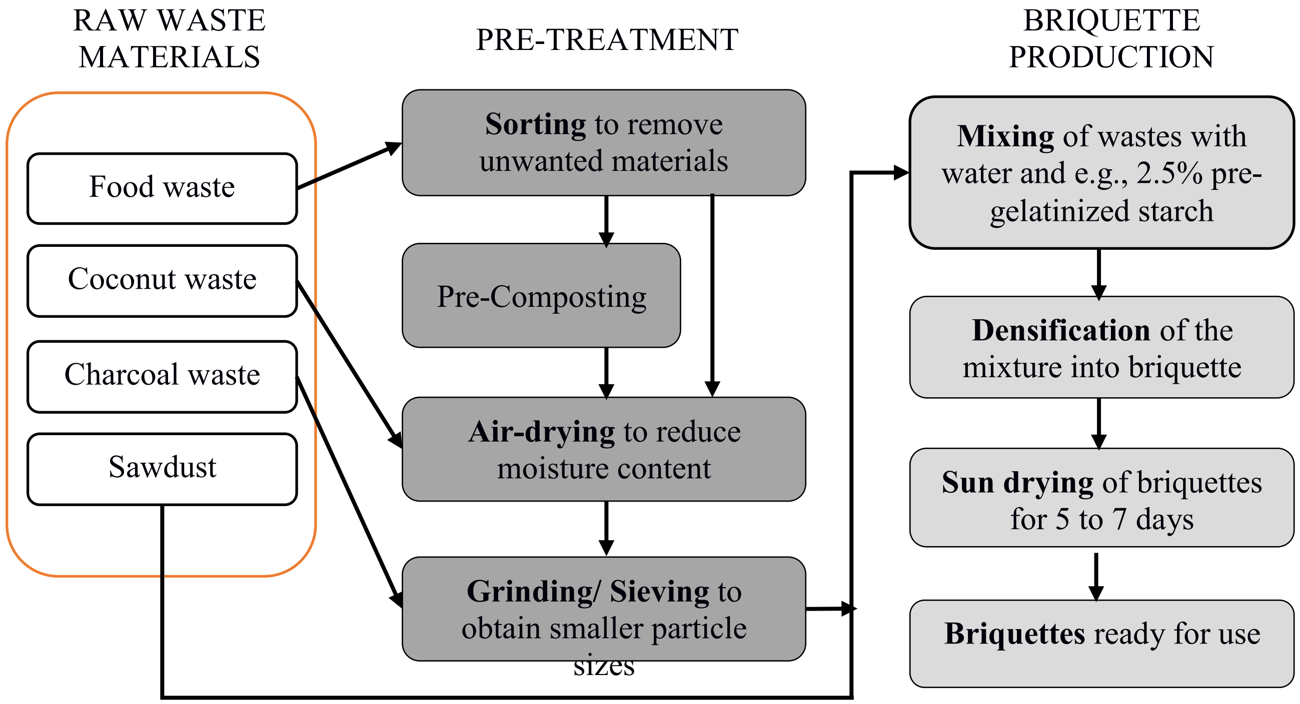

Fig. 1. The briquetting process, from pre-treatment of raw wastes to use of briquettes.

bulk density, durability, net calorific value, burning rate, ash content, burning temperature variation with time and proportion of briquette burnt. Each measurement was repeated three times. To estimate the durability, samples of briquettes (with mass ranging between 20 g to 150 g) were dropped three consecutive times from a height of 2 m onto a concrete floor. The percentage of fines generated after impact were calculated as a proportion of the initial mass and taken as the durability.

Burning characteristics were determined by oven-drying of briquette sample at 50 °C for about 2 days or until constant mass was attained. Then, we put 300 g of dried briquette sample in the cook stove. This cook stove is a ceramic-clad stove, an improvement on the traditional metal coal-pot, widely used in Ghana and across several African countries (Supplemental file - Fig. 3) (Wiedinmyer et al., 2017). The briquette in the stove were ignited using 50 ml of kerosene poured on the surface of the briquette, and a gas lighter. Usually, materials such as leaves, sticks and paper are used by households to enhance igniting (Dudley et al., 2007; Helander and Larsson, 2014). Kerosene was used in this work as a standard means of ignition to remove any inconsistencies and difficulties in ignition introduced using other materials with varying ignition capacity depending on factors such as moisture, etc.

An aluminium container filled with 3000 ml of water was placed on the stove. As the fuel burnt, the temperature of briquette flame was monitored at least every 10 min by means of a temperature probe inserted into the burning fuel. The temperature of the water was monitored, but evaporation of the water was not recorded. After burning was completed, each briquette residue was allowed to cool and subsequently weighed as indication of ash content. The calculation of the percentage of briquette burnt was done using the following equation:

$$Briquetteburntfraction(\%) = 100\% \times \left(1 - \frac{massofresidue(g)}{300g}\right) \qquad (1)$$

$$AshContent(\%) = 100\% - Briquettebruntfraction(\%) \qquad (2)$$

The analysis of gas emissions was done using a real-time gas analyser connected to a stove as presented in the supplemental file (Figure 4). Procedures for remaining parameters were described earlier (Nikiema et al., 2016; Onchieku et al., 2012; Sengar et al., 2012).

Analysis of briquette performance

We used the software Design-Expert, version 10.0.1.0 with confidence level of 95% to assess the effect of briquette composition on the performance of the briquettes, analysed in terms of bulk density, net calorific value, moisture content and burning characteristics. To generate the model, four factors (i.e., the amount of each waste type in the mixture) were considered (Table 2). The Design-Expert software was used to randomize the runs and assess the response surface. The model selected for data analysis was the two-factor interaction (2FI), meaning that the model would be assessing impact of main factors as well as all two-factor interactions and, when it was not significant, the linear model was considered, which only enable to assess the main factors. The model included some aliased terms, i.e., A (food waste) with A-D (i.e., the interaction between food waste and sawdust (D)); B (charcoal waste) with B-D and C (coconut waste) with C-D. This implied that the model would be unable to measure the impact of D. Yet, it is known that sawdust is one of the best raw materials for briquette production (Asamoah et al., 2016).

A paired *t*-test was applied to compare performance of the regular FW versus decomposed FW used in briquette production. A Tukey's test was applied to compare the effect of different starch levels. Due to challenges with the briquetting machine, we could not produce some briquettes formulations listed in Table 2. This concerned mostly formulations with sawdust amounts corresponding to 50–100% of the mixture mass.

Results and discussion

Optimization of the production process

The briquette machine used for this study necessitated the addition of water to the mixed material to increase the fluidity and facilitate briquette formation. The volume of water required for briquetting depended on type of wastes used; water affects the briquetting process and affects the drying time for the final product (Feng et al., 2020). Insufficient water prevents briquette formation and induces overheating of the briquette motor whereas excess water results in flaky briquettes

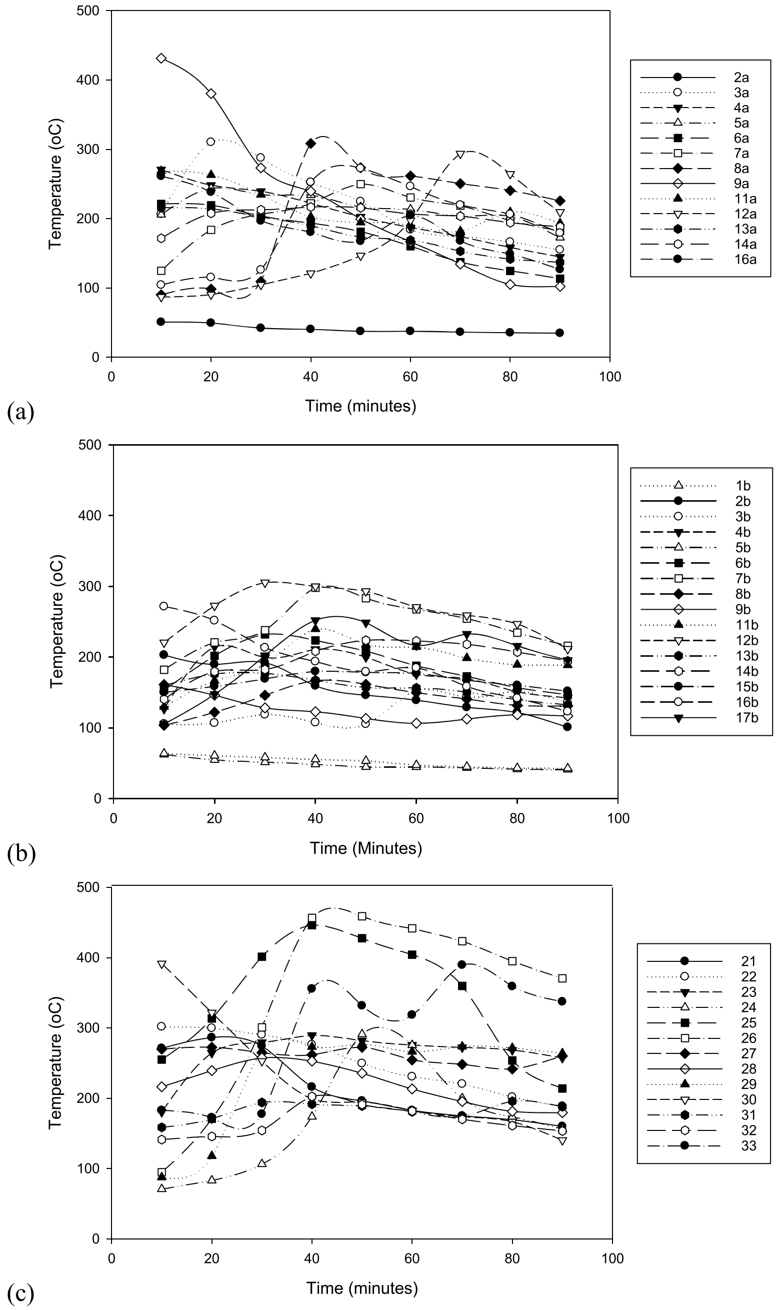

Fig. 2. Temperature profile of burning of briquette with various amounts of (a) regular FW, (b) decomposed FW and (c) without FW.

with associated increase in the drying period.

Eq. (3) ($R^2 = 0.98$) was generated empirically from our tests. It gives the amount of water to be added to the process depending on the raw material used.

$$W = 0.3271 \times X_A + 0.3468 \times X_B + 0.5212 \times X_C + 1.0148 \times X_D \tag{3}$$

Where W: Amount of water needed for briquette production [ml]

Xi: Amount of waste material i in g, with i = A, B, C or D

Our study showed that the amount of water required to produce briquettes using 3000 g of either charcoal waste, FW, coconut waste, or sawdust were 1 litre, 1 litre, 1.5 litre, and 3 litres, respectively (Supplemental file - Fig. 5). This corresponds to a proportion of 25% to 50% in water. Our findings are like values reported by Sawadogo et al. (2018). In their tests for carbonized cashew wastes, they established that a moisture content of 35% was adequate, after having tested water contents of 25% to 35%.

To ensure the production of visually appealing briquettes, cassava starch was added to enhance densification. Many other studies also used cassava starch to formulate briquettes. For instance, Sawadogo et al. (2018) adopted a 10% concentration of cassava starch in their process after testing concentrations varying from 5% to 25%. However, the starch did not undergo pre-gelatinization before the briquetting process. High starch content results in more expensive briquettes. Some initial results we obtained (Table 3) show that for the same waste mix, increasing the percentage of starch resulted in increased true density (i. e., obtained after crushing) of briquette. For example, with briquette BV_1 (obtained from 50% sawdust and 50% charcoal dust), the true density doubled from 296 to 502 g/l with addition of 10% starch. But this observation was not always consistent with other materials. In addition, the effect of the quantity of starch on other briquette

Table 2
Briquette formulations produced in this study.

Experiment number [1]	Type and amount of waste			
	A: FW	B: Charcoal waste	C: Coconut waste	D: Sawdust
	g	g	g	g
1a or 1b	3000	0	0	0
2a or 2b	2250	750	0	0
3a or 3b	2250	0	750	0
4a or 4b	2250	0	0	750
5a or 5b	1500	1500	0	0
6a or 6b	1500	750	750	0
7a or 7b	1500	750	0	750
8a or 8b	1500	0	1500	0
9a or 9b	1500	0	750	750
10a or 10b*	1500	0	0	1500
11a or 11b	750	2250	0	0
12a or 12b	750	1500	750	0
13a or 13b	750	1500	0	750
14a or 14b	750	750	1500	0
15a or 15b	750	750	750	750
16a or 16b	750	750	0	1500
17a or 17b	750	0	2250	0
18a or 18b*	750	0	1500	750
19a or 19b*	750	0	750	1500
20a or 20b*	750	0	0	2250
21	0	3000	0	0
22	0	2250	750	0
23	0	2250	0	750
24	0	1500	1500	0
25	0	1500	750	750
26	0	1500	0	1500
27	0	750	2250	0
28	0	750	1500	750
29	0	750	750	1500
30	0	750	0	2250
31	0	0	3000	0
32	0	0	2250	750
33	0	0	1500	1500
34*	0	0	750	2250
35	0	0	0	3000

* These formulations could not be produced in sufficient quantities to perform detailed analysis, due to limitations with the briquette machine.

[1] Briquette formulations including (a) regular or (b) decomposed FW.

Table 3
Characteristics of briquettes with different raw materials and varying quantities of cassava starch.

Briquette variety (BV)	Cassava starch (%)	True density[1] (g/l)	Tukey parameter ($T_{0.05}$)
BV$_1$. Sawdust and charcoal dust wastes, 1500 g of each	0	296 ± 31	30
	1	355 ± 17	
	2.5	321 ± 9	
	5	375 ± 10	
	10	502 ± 12	
BV$_2$. Sawdust and coconut wastes, 1500 g of each	0	203 ± 8	19
	2.5	204 ± 5	
	5	220 ± 9	
BV$_3$. Sawdust and charcoal dust and coconut, 1000 g of each	0	258 ± 7	28
	2.5	274 ± 6	
	5	339 ± 17	

[1] The true density presented here is the mass of crushed briquette per volume of the crushed powder. It is different from the bulk density presented elsewhere.

parameters such as net calorific value, maximum burning temperature, or burning rate was insignificant, probably because of the low quantities added. The use of starch did not affect the amount of water added to manufacture the briquettes.

For subsequent trials, the volume of water added was derived from Eq. (3) (refer to supplemental file - Fig. 5 and Table 2) while the amount of starch added was set at 2.5%. This was to ensure that the lack of binder would not negatively affect the response of some formulations.

Effect of waste materials on the quality of briquette

To assess the effect of decomposing FW on the briquettes and to assess the effects of the other raw materials, we conducted a series of tests. The full set of results obtained with regular FW (Scenario 1) and with decomposed FW (Scenario 2) is given in the supplemental file (Table 3, Table 4 and Fig. 6). In the following subsections, we discuss the quality of different briquette formulations.

Bulk density and durability

In our experiments, briquettes bulk density ranged between 810 and 1060 g/l. The lowest value was obtained with 50% charcoal and 50% sawdust while the highest value was for 75% charcoal and 25% coconut waste. Significantly different average bulk densities were recorded; 916 ± 50 g/l for Scenario 1 and 938 ± 41 g/l for Scenario 2 (Supplemental file - Table 4). The model generated confirmed that raw materials have obvious impact on the bulk density of the final briquette produced. The key parameters found with Scenario 1 are the same as those of Scenario 2, but with a different relative importance.

FW played a critical role on the bulk density of the briquettes. Addition of FW, especially the decomposed one, increased the bulk density of the produced briquettes. The average bulk density without the use of FW was 909 ± 70 g/l while in the presence of FW, the average was 921 ± 57 g/L and 962 ± 14 g/l for formulations that contain regular and decomposed FW, respectively. Guo et al. (2020) reported that physical characteristics of waste, such as small and uniform particle size, or larger surface area, tend to promote more efficient binding, resulting in stronger and denser briquette. This points to the conclusion that biodegradation of waste modifies its structure and enhances binding abilities of the material. However, it also affects its breakability. We noted in our study that the average durability of Scenario 1 was 13.1 ± 13.1% instead of 17.4 ± 12.8% for Scenario 2. Hence, air dried FW-based briquettes were stronger than decomposed waste-based briquettes. Briquette strength was also affected by amounts of sawdust and charcoal waste, and lower amounts of these wastes resulted in stronger briquettes. According to Okot et al., 2019, to be acceptable, briquettes must maintain a durability below 20%. On average, the briquettes produced in this study met this requirement.

With vegetable waste briquette in India, briquettes had a bulk density comprised between 509 and 747 g/l (Srivastava et al., 2014), but the briquette diameter was 50 mm in their case. Magnago et al., 2020 reported bulk densities of 350 to 440 g/l when processing non-carbonized

Table 4
Summary of characteristics of interesting briquette.

Briquette formulation number	FW content	Charcoal waste content	Coconut waste content	Sawdust content	Key briquette feature
21	0%	100%	0%	0%	Long burning (i.e., at low rate)
27	0%	25%	75%	0%	Steady temperature (± 50 °C burning over 90 min)
15b	25%	25%	25%	25%	
26	0%	50%	0%	50%	High heat (maximum burning temperature achieved)
9a	50%	0%	25%	25%	

briquettes made of citrus peel and rice husk. Our briquettes displayed a bulk density slightly above these reported values, possibly due to the higher densities of the raw materials used in our experiment (Asamoah et al., 2016). It may also be linked to a higher compression strength applied during the briquetting process, or to a reduced feedstock particle size (Magnago et al., 2020; Tumuluru et al., 2021). However, our study reports bulk densities in the same order as Kizito et al. (2022). They produced non-carbonized briquettes with bulk densities of 847 to 1120 g/l from a mixture of FS and individual FW fractions. Our briquettes had a bulk density in the lower range of values obtained from briquette produced solely from charred materials, typically, above 910–1117 g/l (Feng et al., 2020; Sawadogo et al., 2018).

Moisture content

High moisture content in briquette negatively affects energy yield (Afsal et al., 2020; Krajnc, 2015) and hence the need for appropriate drying of briquettes. We found that the moisture content for regular FW briquettes (Scenario 1) was between 1.8% and 10.8% with a mean of 5.3% ± 2.1%. For decomposed FW briquettes (Scenario 2), the moisture content was between 1.2% and 8.6% and a mean of 4.6% ± 1.7%. The latter is slightly lower but not significantly different than the common values for briquettes made from regular FW (Supplemental file - Table 4). The mean moisture content was below the recommended 10% in briquette (Table 1) indicating that the briquettes produced were of good quality in this regard.

More importantly, since the briquettes might be exposed to moisture and even wet conditions during transportation and storage, the quantity of water absorbable was measured as an indicator of the briquettes ability to absorb moisture. Such extra moisture would affect the burning capability of the briquettes. Higher levels of moisture would necessitate further drying before combustion. Our findings show that the average percentage of water absorbed were 46.1% ± 15.5% (Scenario 1) and 41.8% ± 17.1% (Scenario 2), and there was no significant difference observed between the two scenarios (Supplemental file – Table 4).

Net calorific value

The net calorific values for briquettes in Scenario 1 ranged between 8.9 and 19.3 kJ/g with an average of 15.5 ± 2.2 kJ/g. However, for briquettes in Scenario 2, the range was between 8.9 and 24.5 kJ/g, and an average of 17.1 ± 4.1 kJ/g (Supplemental file – Table 4). The net calorific values obtained from decomposed FW were significantly higher than those with regular FW. For instance, average net calorific value for briquette formulations that did not include FW was 15.1 ± 2.8 kJ/g while with FW the average net calorific values were 15.9 ± 1.9 kJ/g and 18.8 ± 4.2 kJ/g for formulations containing regular and decomposed FW, respectively. The high net calorific value with decomposed wastes could be associated to their higher bulk densities and not by the minor difference in moisture content as the briquettes were dried fully before the net calorific value was measured. Another possible factor could be the chemical composition of the raw materials, as decomposed wastes have different chemical structure compared to non-decomposed wastes, potentially promoting heat generation during the combustion. This however calls for additional investigation.

The maximum net calorific value was 24.5 kJ/g, obtained in briquettes made from decomposed FW and coconut waste (mass ratio of 25:75) compares well with about 25 kJ/g of charcoal from different tree species and is much higher than that of firewood from tropical tree species (Njenga et al., 2013b; ICRAF, 2009). The net calorific value of briquettes made from FW and charcoal dust (mass ratio of 25:75) was 18–20 kJ/g, i.e., much higher than 14 kJ/g that of briquettes made from soil (added as a binder) and charcoal waste (mass ratio of 20:80) using manual press in Nairobi (Njenga et al., 2013b). Although the difference may have been caused by quality of the tree species from which charcoal waste was produced, there seems to be an indication that decomposed FW produces better quality charcoal briquettes than those made from soil as a binding agent. Experiments comparing use of manual wooden and metal presses in production of charcoal briquettes at the University of Nairobi showed that there was no significant difference in net calorific value and difference was mainly caused by type of raw materials and binding agent used (Njenga et al., 2013b). However, it was not possible to attribute the variations of the net calorific value to any waste component or combination, as we also found in our experiment.

In the study by Afsal et al. (2020) in India, the calorific value for vegetable waste was about 14.0 kJ/g and could be increased up to 15.7 kJ/g through addition of sawdust up to 25% of the mixture. Other studies report a calorific value between 10.3–13.7 kJ/g, depending on the vegetable waste type (Srivastava et al., 2014). These values in India are below the ones obtained in this study. However, calorific value of vegetable waste-based briquettes was increased when other materials were added to it, as also shown in our study when charcoal waste, coconut waste or sawdust were added.

Temperature in flame

Fig. 2 present the temperature profiles of briquettes produced during the first ninety minutes of combustion. In general use, the temperature achieved by the burning briquettes will depend on several factors, including the efficiency of the cook stove being used, air drafts and circulation characteristics, and ambient environmental conditions. Then, the direct measurement of the temperature of the burning fuel could be subject to variations, due to the position of the temperature probe with respect to the flame and the closeness of material in the immediate surroundings of the probe. However, the temperatures measured in the trials with the 'Gyapa' cook stove, though specific, gave a mean value for comparing different briquette formulations; higher maximum temperatures likely suggest better briquette performance.

Most of the formulations started burning at lower temperatures and reached their peak temperature after an average time of 33 ± 17 min for Scenario 1 and 34 ± 17 min for Scenario 2, both not being significantly different. Thereafter, burning temperatures decreased with time. Both the presence of FW and the use of decomposed FW reduced significantly the maximum temperatures achieved. Hence, the average maximum temperature for briquettes not containing FW was 312 ± 84 °C, much higher than the values for regular FW, 242 ± 90 °C, and decomposed FW 200 ± 71 °C. This is in line with earlier studies which showed that decomposed excreta-based briquette has a lower heating potential than non-decomposed wastes (Ward et al., 2014).

The presence of sawdust in some formulations may have contributed to shortening the time required to reach the maximum burning temperature. This aspect could not be adequately studied given the inability of the machine to produce such formulations in sufficient volumes for testing. However, it is typically illustrated in Fig. 2c by the profile for formulation 30 (75:25 wt. of sawdust and charcoal waste) which displayed a short ignition time. The sawdust not being densely compacted and able to burn faster could explain this fact.

Ash content and burning rate

The mean burning rates for Scenario 1 and Scenario 2 were 1.91 ± 0.62 g/min and 1.70 ± 0.59 g/min, respectively, showing that regular FW briquette burn significantly faster than decomposed ones (2.00 ± 0.87 without FW, 1.89 ± 0.84 with regular FW and 1.44 ± 0.77 with decomposed FW). In both scenarios, the most significant factor was identified as the interaction between charcoal waste and sawdust contents, which when taken individually, promote higher and lower burning rates, respectively. The second most important factor identified is linked to the amounts of FW. The first finding is explained by the fact that charcoal had a high amount of ash in it, and therefore, briquette formulations with high amounts of this material were burning more slowly. The second finding shows that high decomposed FW concentrations contribute to slowing down the burning performance for the produced briquettes, compared to sawdust-rich briquettes. The lower burning rate with Scenario 2 as opposed to Scenario 1 may also be due to the higher bulk densities observed with decomposed FW-based briquettes, compared to those from regular FW briquettes. This finding could have induced the lower temperatures reported previously.

The average ash content values were 22% ± 11% and 23% ± 11% for Scenario 1 and Scenario 2, respectively (Supplemental file – Table 4) and they were not significantly different. Possible factors could be weather (e.g., wind, relative humidity in the air) or shape of briquette. Other studies conducted with FW mixed with FS, such as by Kizito et al. (2022), report high ash values, in the range of 30.4%.

Selected formulations

The temperatures obtained with FW (decomposed or not) remain within an acceptable range, which demonstrate potential in using such briquettes for cooking and heating purposes. Based on various criteria, we selected five briquette formulations amongst the best formulations found in our study, displaying interesting and optimal characteristics (Table 4). Briquette types that burn in high temperatures, such as those made from sawdust (formulation 26) and some formulations containing the regular FW (formulation 9a), might be suitable for cooking food types that require high heat and fast cooking. Those that burn with lower but steady temperatures such as those made from decomposed FW (formulations 15b) or other wastes (27) might be suitable for cooking food types that need low heat and take a long time to get ready. Finally, briquettes that burn with a low rate (formulation 21) might be suitable for heating space e.g., for use in chicken brooders and hatcheries as practiced in Kenya. These briquette formulations were identified and tested for additional parameters.

Some chemical characteristics of ash from briquettes compared to ash from wastes (sawdust, palm kernel, rice husk, corn bran, faecal sludge, MSW) are presented in Table 5. Ash contains essential minerals such as nitrogen (N), phosphorus (P) and potassium (K) that are required for soil enrichment and plant growth. Compared with compost, N and P contents are low but K content is high in ash. The richest ash is obtained with briquette formulation 9a, which comprises of 50% regular FW, 25% coconut waste and 25% sawdust, while the less rich is obtained from briquette formulation 27 (75% Coconut husk and 25% Charcoal fines). Calcium (Ca) was the principal nutrient obtained in the briquette ash. Levels of heavy metals such as zinc (Zn), lead (Pb), copper (Cu) and cadmium (Cd) in ash were very low (<0.001 in ash versus <0.01 in soil requirement). Briquette ash can therefore be used for soil enrichment to increase the nutrient level, and for composts enrichment. The ash composition recorded in our study is linked to the composition of the MSW used to produce the briquettes as shown in other studies. For instance, bean straw briquette ash was found to also have high Ca levels while K was the dominant mineral in maize cob briquette ash (Okot et al., 2019).

The emissions of CO, CO_2 and $PM_{2.5}$ generated from briquette formulations 9a, 21, 26 and 27 are given in the supplemental file (Table 5). They ranged from 0.14 to 2.55, 19.8–105.6, 2.6–124.9 g CO, $PM_{2.5}$ and CO_2 per g of briquettes, respectively. It is usually difficult to compare gas emissions reported in different studies, as they are affected by stove characteristics, local ventilation, and climatic conditions. In our study, the highest emission levels were measured from formulation 26. Nevertheless, we found that emissions from all other briquette formulations were better or like those from a randomly selected locally available firewood, and these briquette formulations could thus be considered a suitable source of fuel. However, additional tests need to be conducted to better understand gas emissions from wastes-based briquettes.

Conclusions and recommendations

FW is not often used for briquette production especially without prior carbonization. In this study, the potential of using non-carbonised FW as part of a feedstock mix for briquette production has been investigated. The results clearly show the potential for producing quality biomass briquettes for energy as a MSW management strategy while contributing to arresting rural land degradation and deforestation. It was established that non-carbonized briquettes produced with MSW are of better quality and perform better when the FW is decomposed prior to preparing the briquetting feedstock.

Also, the study showed that the use of decomposed FW in the feedstock resulted in briquettes with higher bulk density and net calorific

Table 5
Selected chemical characteristics of briquette ash as compared to other sources of ash.

Characteristics of ash (mass%)	Formulation of briquette					Typical Biomass ash (mix of sawdust, grass, palm kernel, corn bran, rice husk)	Typical Compost (Faecal sludge, Sawdust, MSW)
	26	15b	21	27	9a		
Ash content (unburnt fraction)	30	26	33	25	18	< 23.5	–
Organic Carbon	0.68 ± 0.34	1.58 ± 0.20	2.04 ± 0.00	0.79 ± 0.20	0.68 ± 0.34	–	5.91–23.97
Organic Matter	1.18 ± 0.59	2.76 ± 0.34	3.55 ± 0.00	1.38 ± 0.34	1.18 ± 0.59	–	4.33–41.75
Total Nitrogen	0.89 ± 0.02	0.92 ± 0.02	1.03 ± 0.02	1.03 ± 0.03	1.17 ± 0.02	–	0.75–1.50
Phosphorus	1.59 ± 0.00	0.04 ± 0.00	0.04 ± 0.00	0.04 ± 0.00	0.04 ± 0.00	0.08–2.30	1.01–2.06
Potassium	1.18 ± 0.00	3.17 ± 0.00	1.19 ± 0.00	1.06 ± 0.00	4.49 ± 0.00	0.97–16.24	0.26–1.35
Calcium	4.30 ± 0.00	4.90 ± 0.00	4.44 ± 0.00	5.28 ± 0.06	1.50 ± 0.00	21.17–45.00	0.00–5.73
Magnesium	0.42 ± 0.00	0.44 ± 0.00	0.41 ± 0.00	0.43 ± 0.00	0.47 ± 0.00	0.34–9.09	0.05–0.50
Iron x 10	5.92 ± 0.00	6.50 ± 0.00	7.56 ± 0.00	6.22 ± 0.00	5.20 ± 0.00	0.1–11.0	7.2–11.9
Manganese x 10^2	2.05 ± 0.00	2.42 ± 0.00	1.24 ± 0.00	2.53 ± 0.00	1.51 ± 0.00	6–404	0–6
Zinc x 10^2	2.09 ± 0.00	3.31 ± 0.00	1.98 ± 0.00	2.48 ± 0.00	2.65 ± 0.00	1–36	0–10
Lead x 10^3	2.10 ± 0.00	6.60 ± 0.00	9.10 ± 0.00	13.80 ± 0.00	8.90 ± 0.00	<2	<25
Copper x 10^4	1.00 ± 0.00	22.00 ± 0.00	2.00 ± 0.00	5.00 ± 0.00	6.00 ± 0.00	<700	<10
Cadmium x 10^4	6.00 ± 0.00	8.00 ± 0.00	9.00 ± 0.00	9.00 ± 0.00	9.00 ± 0.00	<25	<15

value compared to regular FW. The moisture content and water absorbing capacity are slightly lower, a further indication of the superiority of using decomposed FW. The burning rate with decomposed FW briquettes was on average 24% lower than with regular FW briquettes, meaning they will burn for longer times. However, it was found that the briquettes with decomposed FW had the tendency of breaking more easily than their regular counterparts, and burn at lower temperatures (50 °C of difference with the regular raw FW briquettes), leading to slightly longer times needed to reach maximum temperature. The performance of FW briquettes may be enhanced by combining the feedstock with tree-based raw materials, such as coconut waste, charcoal waste, or sawdust.

The study also identifies the importance of suitable equipment for briquette production. For example, it was found that some briquette formulations could not be processed due to limitations in pressure exerted by the briquette production machine that was used. Obviously, the type of machine used has an impact on the overall quality of the briquette produced and there is need for more tests to assess the characteristics and suitability of the briquetting machine. Finally, this study confirms what has been reported in other studies and countries: briquette quality can be highly variable and is influenced by the quality of waste materials from which they are made. It is therefore important to ensure that quality analysis is carried out before production and should be monitored to ensure quality consistency in the product.

Overall, the study provides a good framework for further research into the production of briquettes using MSW in general. Many parameters have been identified that can be controlled in future studies to ensure better-engineered-briquettes with high durability, high energy density, and hopefully, ease of production. In addition, some statistical models generated from our data were found not to be significant. This is an indication that the average mean would be a better estimate for the concerned parameter than a statistical model. This demonstrates the high variability in the feedstock characteristics which affect the quality of the briquette produced. Additional studies on use of MSW in briquette production remain needed to better appreciate the potential and challenges behind this recycling opportunity and to devise a strategy to control this material variability.

Credit author statement

The authors confirm contribution to the paper as follows:

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Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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