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Evaluating the Role of Feedstock Ratios and Binders in the Performance of Faecal-Derived Briquettes

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ABSTRACT

The increasing population, demand, and high cost of domestic energy sources such as electricity and gas have heightened reliance on charcoal and other combustion fuels recently. This study analysed the performance of composite briquettes produced through briquetting processes. The briquettes were produced by different quantities of feedstock materials with two types of binders, namely cassava starch and paper pulp. The charred faecal sludge (FS) and sawdust (SD) were utilised as feedstock materials in varying ratios by weight (FS:SD) as 70:30, 60:40, 50:50, 40:60 and 30:70. Feedstock materials were densified by a cold manual press machine aided by two binder materials, namely cassava starch and paper pulp binding materials. Briquette performance analysis methods were deployed, including the water boiling test, the shattering index test, the water absorption resistance test and moisture content. The analysis of variance (ANOVA) was applied to analyse mean differences, and further, Fisher's LSD test was used as post hoc. Results showed that the binding materials have more impact on fuel characteristics than the feedstock ratio. Cassava starch binder yielded a higher calorific value (24 MJ/kg) compared to paper pulp (13.75 MJ/kg), even though all briquettes met durability standards (shatter resistance >50%). The high calorific value of 24 MJ/kg briquette material was obtained from cassava binder briquettes, while all briquette samples passed through the shatter resistance test of above 50%. The study concluded that the use of faecal sludge-based briquettes for domestic energy applications is viable. However, to meet the same level of heating value as wood charcoal, one will need twice as many briquettes as the amount of charcoal. It is further recommended that the frequent use of briquettes should be in an open-air environment to allow air circulation and avoid any potential health effects from air state conversions.

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1.0 Introduction

Future domestic energy security is one of the key issues faced by many developing countries that call for better use of natural resources. Faecal sludge, as one of the waste streams in the large amount collected from residential or public pit latrines and septic tanks in urban areas, can be used as feedstock material in the production of solid fuel. The most technologically challenging characteristics and disadvantages of faecal sludge as feedstock for fuel briquette production are its moisture and pathogen content, which are considered harmful to human beings (Lohri *et al.,* 2016). For human health concerns, care should be taken when handling faecal sludge (Sisay, Gari, and Ambelu, 2024); however, the good news is that the carbonisation process, when performed under recommended conditions, guarantees the killing of pathogens (Koné *et al.*, 2007). When the moisture content of biomass is less than 15%, it can produce fuel briquettes with a calorific value of 17-25 MJ/kg, equivalent to that of fuel coal (Rao *et al.*, 2016). Faecal sludge (FS) with a moisture content of 40% can be used as a binder and mixed with municipal waste, like sawdust and paper, to produce briquettes without carbonisation. For superior quality and smokeless briquettes, faecal sludge of 25% moisture content can either be carbonised or solar dried to generate 5% moisture content dry material (Gebrezgabher *et al.,* 2016). Another option is to mix 80% faecal sludge, 19% sawdust, and 1% lime, yielding a 15.5 MJ/kg heating value (Owino *et al.,* 2024).

Carbonisation, or pyrolysis, is an anaerobic decomposition process whereby biomass is burned in the absence of limited oxygen to produce char (Lohri *et al.,* 2015; 2016). The carbonisation process is a function of temperature, pressure, reaction time and energy demand. The raw materials used are firstly dried to reduce moisture content below 18% and carbonised at a temperature above 300°C for 2 hours (Manya, 2012). The small particles and non-uniform char materials can be reconstituted into larger, uniform briquettes to densify and make them into a defined shape (Kpalo *et al.,* 2020). The use of pressure typically entails a mechanical compaction process that is necessary for briquetting (Lohri *et al.,* 2015).

When faecal sludge is used as the main feedstock, it is recommended to add another organic waste to be treated together (Muspratt *et al.*, 2014). Carbonised briquettes can be obtained through either manually or mechanically operated machines, depending on the production scale. Faecal sludge alone as a feedstock material when producing briquettes cannot densify enough. To produce strong briquettes, binders are added to raw materials to enhance the bonding and stability properties of the briquettes produced. These are substances with adhesive properties to agglomerate the briquetting material to produce briquettes with higher density, durability and compressive strength (Sen, Wiwatpanyaporn and Ann, 2016).

Different materials with good binding ability have proved to be used as binders, including biodegradable paper soaked in water, subsoil, fibres, lignin, lime, molasses and starch (Kpalo *et al.,* 2020). An optimum amount of binding material for optimal briquetting is needed to be mixed with feedstock, recommended 6%-25% of the material (Sadef *et al.*, 2016). For uncarbonised briquettes, binders can be mixed with feedstock material, while for carbonised briquettes, binders are mixed after carbonisation (Kpalo *et al.,* 2020). A binder with high binding properties needs to be used to avoid the loss of binding elements in raw materials during carbonisation.

This paper analysed the feasibility of using faecal sludge char and sawdust char materials as feedstock for briquette production using two different binding materials. The efficiency, durability and combustion behaviour of composite briquettes for domestic applications were produced and compared.

2.0 Materials and Methods

2.1 Research Design

The carbonisation process of feedstock materials, faecal sludge and sawdust materials was performed between 2020 and 2023 at the University of Dar es Salaam. Five different faecal sludge (FS) to sawdust (SD) char ratios by weight (FS:SD) were prepared: 30:70, 40:60, 50:50, 60:40 and 70:30 using two types of binding materials, cassava starch and paper pulp, at 25% of total feedstock weight as recommended by Waheed, Akogun and Enweremadu (2023).

Proximate and emission analyses were conducted to express characteristics of feedstock for briquette materials to analyse for the most durable briquettes yet with the most efficient characteristics and fewer emissions when combusted. The proximate analysis involves moisture content (MC), volatile solids (VS), fixed carbon (FC), ash content, and calorific value – High heating value (HHV) gives the potentialhigh efficiency and durability of the briquettes to be produced (Danso-Boateng *et al.*, 2015; Gold *et al.*, 2018). Generally, good-quality and efficient fuel briquettes depend on high fixed carbon with low MC, VS, and ash content (Roy and Corscadden, 2012).

Emission analysis was conducted to quantify the gases emitted during fuel combustion that might influence combustion behaviour. It includes levels of emitted gases needed to be monitored for air quality control when consumed indoors. The gases include carbon monoxide (CO), nitrous oxides (NOx) and sulphur oxides (SOx) (Lohri et al., 2015; Singh *et al.*, 2017).

2.1 Experimental Process

The experimental processes for briquette production were done following four procedures, including treating sludge, mixing binder and filler, compacting and drying. Treatment of faecal sludge was done by dewatering and pyrolysis processes to obtain char material. Then two types of binders were used separately. Briquetting of carbonised materials was performed by compacting them using a manual pressing machine without pressure/force control or record before the final products were set to dry. The compaction process was done by a manual pressing machine with a capacity of triple briquette ejection sections, as shown in figure 1(A). The briquettes were then transferred to an open space where they were air-drying, as shown in Figure 1(B). During the rainy season, the drying was facilitated by an oven at a controlled 25°C to 50°C temperature for 24 hours before being removed for further air drying.

Figure 1
(A) A Manual Pressing Briquette Machine and (B) Dried Briquettes Produced with Different Feedstock Ratios and Binder Materials

2.2 Analytical Methods

2.2.1 Physical and Mechanical Analysis

Mechanical and physical characteristics were determined to assess the durability of the briquettes. The analyses are important for understanding how the briquettes will react to various conditions, such as during packaging, in storage facilities, or when they accidentally come into contact with water or during the rainy season. Also, to understand the burning rate and specific fuel consumption as well as the combustion properties and analyse the emitted gases during the consumption. On every production occasion, three random briquette samples were selected from each batch for analysis.

2.2.1.1 Drop Shatter Test

The durability of the briquettes was determined by a shattering test based on the impact resistance index (IRI). The test involved dropping briquette samples, in triplicate and totalling approximately 500 g, from a height of 2 m onto a smooth floor made of pozzolana concrete, following the shattered index (ASTM D440-86) as described by Chaiklangmuang, Supa, and Kaewpet (2018). The weight of retained briquettes was used as an index of briquette breakability. The percentage weight loss of briquettes was expressed as a percentage of the initial mass of the material remaining on the solid floor, while the shatter resistance was obtained by subtracting the percentage weight loss from 100 (Sengar *et al.*, 2012). For the laboratory test, the minimum IRI value of 50% is acceptable as the impact resistance for fuel briquettes (Richards, 1990). The percentage weight loss was given by Equation 1 below.

$$Weight\ loss\ (\%) = {(W_1 - W_2)}/{W_1} \times 100 \text{ (Eq.1)}$$

Where W_1, W_2 = Weight (g) of briquette before and after shattering in gram and IRI = 100 - % weight loss

2.2.1.2 Water Resistance Test

The water-absorption resistance test shows how briquettes will respond when in contact with water accidentally or during the rainy season. The water resistance capacity of dry briquettes was performed by immersing the briquette samples in triplicates that make a total weight of approximately 500 g in a wide container filled with tap water at room temperature (28 ± 2°C) for about 15 to 30 seconds until they disintegrate or fail to hold water anymore (Davies and Davies, 2013). The percentage of water absorbed was calculated using the weight difference before and after being immersed in water, as in Equation 2. A reasonable target of the Water Resistance Index (WRI) recommended for most briquettes to maintain integrity is 95% (Richards, 1990).

% of water absorbed by briquettes=

$$\frac{M_2 - M_1}{M_1} \times 100 \quad \text{(Eq. 2)}$$

Where M_1 is the initial weight (g) before being immersed in water, M_2 is the final weight after being immersed in water. Then; Water resistance index (WRI) capacity (%) = 100% - % water absorbed.

2.2.1.3 Water Boiling Test

The water boiling test was carried out to compare the cooking efficiency of the fuels according to modified procedures for the water boiling test (Lubwama and Yiga, 2017). A traditional charcoal stove of small size and a steel pot were used for the test. Two groups of briquette samples, made from different binding materials, were used, with each group containing an amount equivalent to the smallest common measuring size for charcoal available in the local market, which costs 1,000 TShs (0.40 USD) to boil the same volume of water. The same amount of wood charcoal was used for comparison. The total time taken to boil an equal volume of water under similar conditions was analysed. The burning rate and specific fuel consumption were also determined using equations 3 and 4 (Borowski *et al.*, 2017). The level of smoke emitted was also observed during the test.

$$\text{Fuel-burning rate (g/min)} = \frac{\text{Mass of fuel consumed (g)}}{\text{Total time taken (min)}} \quad \text{(Eq.3)}$$

Specific fuel consumption(kg/l)=

$$= \frac{\text{Mass of fuel consumed (kg)}}{\text{Total mass of boiling water (liter)}} \quad \text{(Eq.4)}$$

2.2.2 Proximate and Emission Analysis

The proximate analysis gives combustion properties; hence, it shows the importance of energy use. It provides the composition of fuel, detailing the percentages of materials that burn in gaseous form (volatile matter), solid-state (fixed carbon), and inorganic waste materials (ash). A 5 g of pulverised samples were analysed in triplicate. All analysis followed the specific standard methods as described.

i. Total solids (TS) were determined gravimetrically by drying the sample in an oven at 105°C for 12 hours to obtain a dry weight (ASTM E871-82, 2013).
ii. Moisture Content (MC) was determined by drying materials at 105°C using the standard method (APHA, AWWA and WEF, 2005) as per standard ASTM E871-82, 2013, and calculated as stated in Equation 5.

$$MC\ (g) = 100 - \left(\frac{W_{3(g)} - W_{1(g)}}{W_{2(g)}} \times 100\right) \text{ (Eq.5)}$$

iii. Volatile solids (VS) which determined by the loss of sample weight when crucibles with lids are put in a muffle furnace at 950°C for 7 minutes (ASTM E872-82, 2013). The analysis was done in Equation 6.

$$VS\ (g) = \frac{W_{3(g)} - W_{4(g)} - W_{l(g)}}{W_{2(g)} - W_{l(g)}} \times 100 \text{ (Eq.6)}$$

iv. Ash content was determined following the ASTM E1755-01 (2015) procedure that gives the weight of remaining material after the sample left for 2 hours at 550°C without a lid.

$$Ash\ content\ (g) = \frac{W_{5(g)} - W_{1(g)}}{W_{3(g)}} \times 100 \text{ (Eq.7)}$$

v. Fixed carbon is the subtraction of volatile solids and ash content from 100% following

Standard method (ASTM D 3172; Basu, 2013) and calculated as in equation 8.

$$FC = 100\% - VS(\%) - AC(\%) \quad \text{(Eq. 8)}$$

vi. Calorific value Standard method, ASTM D 5865 (ASTM, 2003); Parikh *et al.,* 2005 and estimation using equation 9.

$$Calorific\ value = 0.3536FC + 0.1559VS - 0.0078AC \quad \text{(Eq.9)}$$

The Flue gas analyser equipment (Testo 360) was used for analysing the gas emissions. By using the special double-stage stove, the flame was captured and CO, NOx and SOx (in ppm) were automatically recorded after every 1-minute interval of sampling.

Where; W_1: weight of dried crucible (g), W_2: initial weight of sample (g), W_3: weight of dried sample (g), W_4: weight of sample after 750°C (g), W_l: weight of lid (g) and W_5: weight of sample after 550°C (g).

2.2.3 Statistical Analysis

The collected data were first checked for normality by using the Shapiro-Wilk test before being subjected to statistical analysis. An independent t-test was applied to analyse the mean difference for normally distributed parameters between binding materials. Analysis of variance (one-way ANOVA) was used to test for differences in variances of the fuel-independent parameter (high heating value) and other dependent parameters separately among briquette feedstock ratios. For the non-normally distributed parameters, the Wilcoxon test and Kruskal-Wallis's test were used instead for median differences between binders and among the ratios, respectively. The results were considered to be statistically significant at a 95% level of significance when P ≤ 0.05. All analyses were performed and visualised using Microsoft Excel and R software.

3.0 Results and Discussion

3.1 Physical and Mechanical Properties

The physical and mechanical properties of fuel materials are important to understand how they will react during different activities. From the consumers' perspective, briquettes would be subjected to different conditions; hence, they need to withstand loads and abrasions and should resist the penetration of water when transported over short distances. Different tests were analysed for faecal sludge char briquettes in comparison to the recommended standards. However, the standards used were designed for coal briquettes, which might be of high value as compared to faecal sludge briquettes.

3.2 Statistical Results of Impact Resistance Index (IRI) and Water Resistance Index (WRI)

The impact resistance index (IRI) and water absorption resistance index (WRI) were used for analysis of physical properties of briquettes. Results from the t-test analysis show a statistically significant difference (P=0.05) in the impact resistance between the binding materials. The highest recorded impact resistance index of 96.35% is observed from cassava starch binding briquettes, while the lowest is 66%, from paper pulp briquettes. The range of IRI values obtained from this study conforms to that recorded in previous studies. All recorded values in this study are within the recommended 50% working standard IRI (Richards, 1990). Similarly, the briquette's durability tested by Wachira *et al.* (2015) showed differences in the form of binder materials, where the paper binder was higher (99%) than that produced from clay material. The IRI of 96.35% recorded in this study for cassava binder aligns with palm kernel shell briquettes (97%) as reported by Abdullahi *et al.* (2017) in the study conducted in Malaysia, while Tembe and Ekhuemelo (2014) obtained an IRI of 90.4% from briquettes made by the mixture of Daniellia oliveri and groundnut shell biomass. This study's physical properties results imply that the durability and resistance to handling stresses of briquettes differ with binding materials and may be used to guarantee the production of failure-free briquettes. Other factors like briquettes' weight, height, and number of droppings can be regulated to reduce the failure of briquettes during the shatter resistance test.

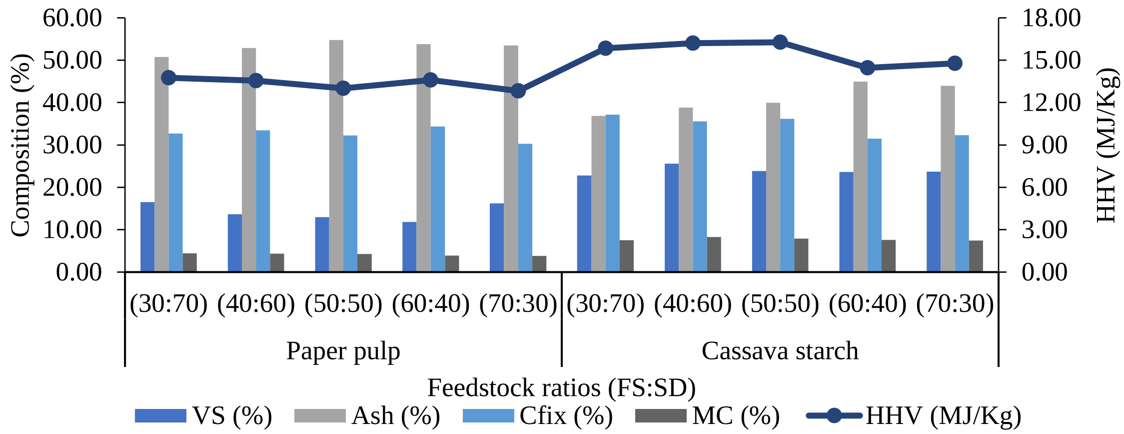
Test results for water absorption resistance indicate a statistically significant difference between the binding materials at $p=1.005\times10^{-5}$.During the test, paper binder briquettes were found to disintegrate sooner, a few seconds after being immersed in water, as compared to cassava starch briquettes due to the softening and swelling of paper pulp in the presence of water. The highest percentage of water absorption resistance was 71.71%, recorded from briquettes made with cassava starch binder. Furthermore, all ratios of cassava binder briquettes showed higher water resistance than briquettes made from paper pulp, as shown, although no single sample conformed to the water resistance index (WRI) of 95% (Richards, 1990). Despite failing to meet the 95% WRI standard, cassava binder's higher resistance suggests better suitability for humid environments because it can resist more than the paper pulp binder. This feat can be done by taking care of the storage and handling of faecal sludge-based briquettes before consumption in a way that can avoid briquettes getting into contact with water during storage, consumption and transportation.

3.3 Briquettes Combustion Characteristics

The proximate analysis for fuel combustion characteristics was performed separately per feedstock ratio and different binders, as summarised in Figure 2.

Figure 2

The Proximate Analysis Results of Briquettes with Different Faecal Sludge and Sawdust Ratios (FS:SD) and Different Binding Materials



3.3.1 The Effect of Binder Materials and Feedstock Ratios on Fuel Combustion Characteristics

The independent t-test and Wilcoxon rank sum test were used for the analysis of mean differences for each combustion parameter between types of binding materials. The difference in means among the feedstock ratio groups was analysed by a one-way ANOVA test for normally distributed numeric data and a Kruskal-Wallis test for non-normal data. The null hypothesis (*H0*) tested was "There is no difference in the means of combustion characteristics parameters between binder materials and among the feedstock ratio groups." The null hypothesis was rejected at $p<0.05$.

3.3.2 Moisture Content (MC)

Moisture content, or the water in the fuel, can affect briquette quality. The t-test results proved a statistically significant difference in moisture content (MC) at $p=2.4\times10^{-7}$ between briquettes made from both binder materials but no statistically significant difference among the feedstock ratio groups at $p=0.924$. The lower the moisture content in briquettes, the better to produce high heating values, decrease combustion pressure, and make them easy to ignite or initially burn. It is recommended that the moisture content of briquettes made of biomass should be within the range of 5–10% in order to increase the durability and density of agglomerates (Nurek *et al.*, 2019). The highest MC of 8.1% was recorded from cassava starch binder briquettes, while the lowest value of 4.4% was from paper pulp binder briquettes, both found to be within the required operating limits of biomass briquettes. This implies that to obtain the required moisture content of briquettes, the amount and type of binding materials are important because they influence how water is absorbed within the product. These results are in line with previously reported values. Inegbedion (2022) recorded a maximum MC value of 5.04% from sawdust-based briquettes, while the highest value of 8.95% was obtained from corn cob charcoal briquettes (Sunardi, Djuanda and Mandra, 2019). It is important to maintain the moisture content of briquettes to avoid smoke formation from incomplete combustion of the volatile matter and unburnt carbon. During combustion, the moisture in the briquettes absorbs heat to form vapour due to heat of vaporisation, thereby appreciably reducing the heating value of a used fuel and lowering the combustion characteristics.

3.3.3 Volatile Matter (VM)

Volatile matter (VM) represents the components of carbon, hydrogen, and oxygen present in the biomass that, when heated, are converted to vapour (Sunardi, Djuanda, and Mandra, 2019). Results of volatile matter were found statistically significantly different between binders ($p = 7.12 \times 10^{-5}$), but there was no statistical difference among the feedstock ratio groups at p = 0.972. Cassava starch binder briquettes recorded a higher value of 24.7% than that from paper pulp binder (16.4%). Similarly, Haruna, Kimwaga and Richard (2024) observed high VM results of briquettes with cassava starch as compared to other types of binders, which reached as high as 89.47%. Generally, a higher percentage of VM can be influenced by chemical components in the materials (Sunardi, Djuanda and Mandra, 2019); thus, it is not desirable as it correlates with rapid combustion but lower energy density and higher emissions (Inegbedion and Erameh, 2022). High value of VM, which entails that cassava material had more chemical components than paper pulp. Since volatile matter combines both short- and long-chain hydrocarbons, such as combustible or incombustible gases released during burning, the optimal carbonation process is necessary to be reached. Falemara *et al.* (2018) suggested that the higher the volatile matter of a briquette, the higher the emissions during burning; hence, it is suggested that low volatile matter is required for a good-quality briquette.

3.3.4 Ash Content

Further results of the t-test showed a statistically significant difference in ash content between the binding materials (p = 0.0001716). No statistical difference in ash content has been proved by a one-way ANOVA test among the feedstock ratio groups at p=0.515. The higher amount of ash content was obtained from the briquettes with a paper pulp binder. While the highest 54.3% of ash content was recorded, the briquettes with cassava starch binder recorded 44.5% as the highest ash content amount. The ash content implies the combustion of residues, which lowers the heating value of briquettes. The lower the ash content, the higher the heating value of briquettes (Obi, Akubuo and Okonkwo, 2013). As a baseline, the ash content of a good-quality fuel should be between 0.5% and 5% (Lohri *et al.*, 2016). That means both briquette types had relatively high amounts of ash content for being fuel of good quality. One reason for the high ash content obtained in this study is the large amount of sand content in faecal sludge feedstock. This is due to two main reasons. One was poor designing, construction and management of pit latrines in most of the areas in Dar es Salaam that allow the entrance of sand into pits; hence, faecal sludge contains a large amount of sand content during desludging (Seleman *et al.*, 2020; Fløytrup, Gabrielsson and Mwamlima, 2022). Another reason is the type of drying beds used for faecal sludge dewatering. Faecal sludge dried in unplanted drying beds that contain sand layers allows water percolation, but during the removal of dry faecal sludge, there is the possibility of raking out the amount of sand together.

3.3.5 Calorific Value/High Heating Value (HHV)

The HHV results were found not to be normally distributed. The Wilcoxon rank sum test results showed a statistically significant difference of high heating value (HHV) or calorific value at p=0.0079 between binding materials. On the contrary, the Kruskal-Wallis test did not prove a statistical difference in HHV among the feedstock ratio groups at p=0.802. The recorded highest value of 24 MJ/kg was from cassava binder briquettes, higher than that from paper pulp binder briquettes. The calorific value between 28 and 33 MJ/kg is recommended for good energy quality for cooking (Lomunyak *et al.*, 2024). However, the obtained calorific values from this study improved from the previous results of 11 MJ/kg. Calorific value could be used in the estimation of briquettes' potential to substitute the current energy sources consumed, such as wood charcoal. In comparison, the energy value of faecal sludge briquettes analysed in this study implies the need of energy as twice the energy amount of wood charcoal (28 MJ/kg) in cooking (Lohri *et al.*, 2016). There was not enough evidence shown to conclude the statistically significant difference in fixed carbon (FC) between briquettes of different binding materials (p=0.095) and among the feedstock ratio groups (p=0.274). The highest fixed carbon (FC%) of 58.4% was recorded for cassava starch binder against 33.3% from paper pulp briquettes.

3.4 Emissions from Briquette Samples

Briquette samples and wood charcoal were analysed for gas emissions. Sulphur oxides (SOx), carbon monoxide (CO) and nitrogen oxide (NOx) were used as indicators of gases being emitted, and the amounts were compared with Tanzanian air quality standards code number 837 revised in 2014

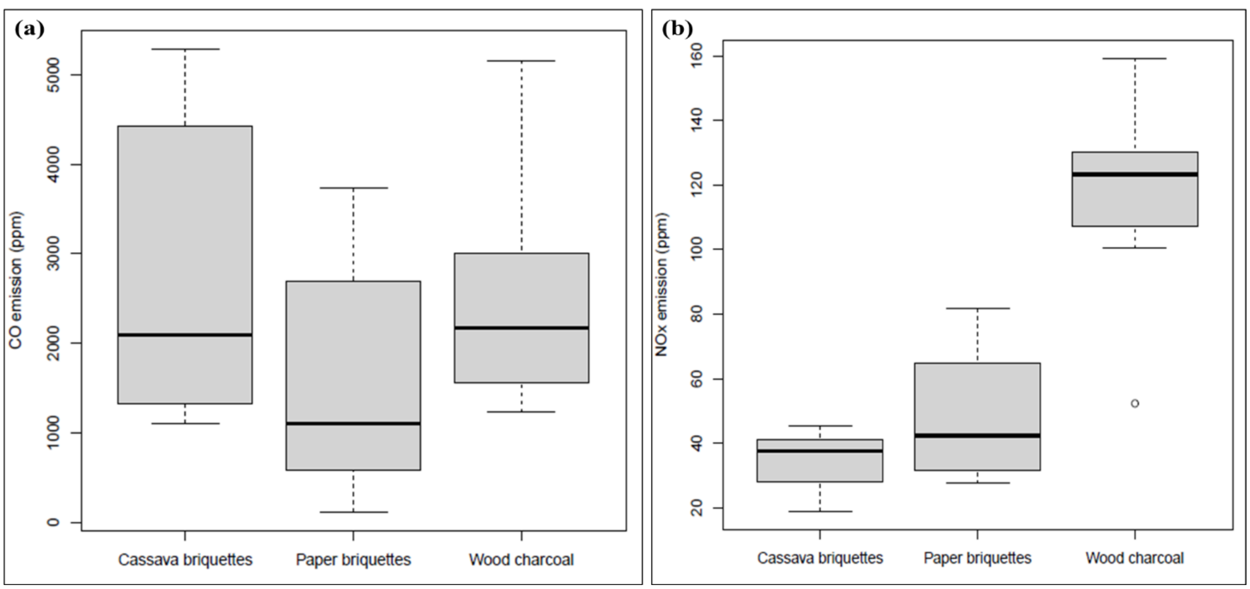
(TBS, 2021) and the WHO standards baseline. Findings from emission analysis of both briquettes and wood charcoal show no SOx emitted, while the NOx and CO were detected with different trends during analysis.

3.4.1 Carbon Monoxide (CO)

Results from the Kruskal-Wallis test indicate that there is no statistical difference in CO emission among the fuel types, at $p=0.44$.CO emission implies the incomplete combustion of the fuel; to reduce the impact, Lohri *et al.* (2016) recommended the use or modification of the stove to allow for excess secondary air for CO conversion into CO_2. Findings from this study show a fluctuating trend of CO emitted from both briquette samples with a slight decreasing pattern with time. A cumulative 64% emission reduction was observed from the initial amount to the end of combustion when wood charcoal was combusted. In comparison, the briquettes with cassava starch recorded high values of emissions with time. This might be due to the higher moisture content observed compared to that of paper binding material that might inhibit the complete fuel combustion. Based on Tanzania's air quality standards, almost all samples emitted an amount of CO above the recommended value of 200 ppm (Table 3). Results suggest that both the briquettes and charcoal are not recommended to be used in a closed room to avoid the limited air going through the stove. It is recommended that the exposure to these harmful gases and particulate matter can be minimised by ensuring proper ventilation before use (Sanka *et al.*, 2024). Figure 3(a) summarises the CO emission from fuels combusted recorded at the 1-minute interval for a total of 11 minutes.

Figure 3

A Boxplots (a) CO and (b) NOx Emissions from FS-Based Briquettes and Wood Charcoal



3.4.2 Nitrous Oxides (NOx)

The NOx was highly emitted at the beginning of the fire, and values for both FS char briquettes and wood charcoal decreased slightly with time (Figure 3(b)). Results imply that the amount of NOx decreases with an increase in fuel heat intensity. Statistically, one-way ANOVA showed a significant difference in NOx among the fuel types at $p=2.16\times10^{-9}$.The highest amount of NOx was detected from wood charcoal, where the NOx was emitted within the initial three minutes and slowly dropped to the end of the analysis, which took a total duration of 11 minutes. The briquettes with cassava starch emitted the least NOx of all, ranging from 23 to 45 ppm. When compared to Tanzanian standards, all values were within standards (293 ppm) (TBS, 2014). However, compared with World Health Organization (WHO) standards, all values exceed the recommended value of 0.1 ppm when the fuel combustion emission is exposed for 15 minutes indoors.

3.5 Fuel-Burning Properties

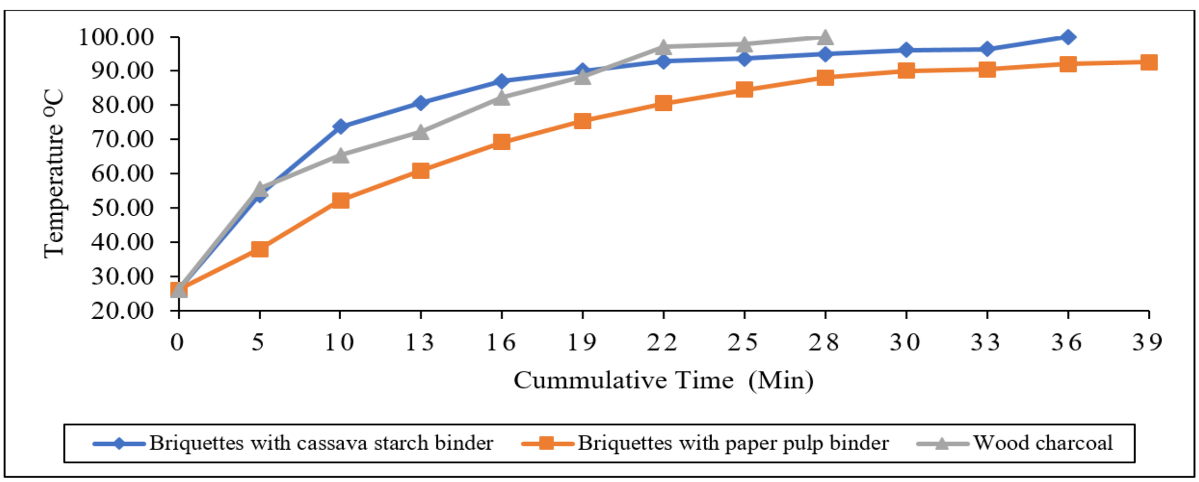
The water boiling test (WBT) gives the characteristics of fuel used during firing up, burning time, water temperature attained at a specific time, amount of fuel used and smoke intensity produced. The WBT was conducted by combusting 450g of briquettes and wood charcoal samples, using traditional and widely used charcoal stoves. The fire was started by spreading a small amount of kerosene, approximately 20 ml for both occasions, a practice that is often used by domestic cooks to aid the firing. One litre (1L) of tap water at 26.10°C was used to test both types of briquettes and wood charcoal at an average room temperature of 25.30°C during the tests. Table 3 shows the comparison of three fuels' burning properties obtained from the water boiling test. The temperature reading was taken at minute intervals with a digital long-probe metal thermometer (Onukak *et al.,* 2017) until the water reached 100°C. Briquettes with cassava starch binder took the longest time to boil 1 litre of water (40 min) compared to those with the paper binder (38 min) and wood charcoal (28 min). The burning rate of the briquette samples showed that briquettes with paper pulp have the slowest burning rate (10.26 g/min), which means the same amount of fuel will burn faster by 1 minute compared to that with cassava starch (11.25 g/min). This might be associated with the addition of waste paper as binding material that can improve the thermal conductivity of the fuel ignition and burning rate due to higher volatile matter content (Hassan *et al.*, 2018). The smoke intensity was observed in the beginning of fuel firing up, and briquettes from cassava starch generated white smoke until all particles completely caught fire. Compared to briquettes from paper pulp, which emitted less smoke, while wood charcoal did not emit smoke at all.

3.5.1 Duration to Reach a Water Boiling Point

Furthermore, the relationship between water temperature and time intervals was observed from the beginning, after setting the pot on the stove, to the maximum water temperature reached. The recording interval varied depending on the observed water boiling rate. Figure 4 shows the water temperature attained at different time intervals during the test.

Figure 4

Water Temperature Changes in Different Time Intervals during the Water Boiling Test



Wood charcoal took the shortest time of 28 minutes to boil water to 100°C and remained with 9% of unburnt charcoal (40.58 g) compared to briquettes with cassava binder, which took 36 minutes and attained 10% of unburnt material. On the contrary, briquettes with paper pulp binder were burnt into ashes within 39 minutes without reaching the water boiling point. This implies that to reach water's boiling point when using briquettes with a paper binder, a greater amount will be needed, added during the occasion. Cassava starch in this case proved that it can contribute to increasing the briquette's density, durability and the time taken to boil water to its boiling point compared to paper pulp binder material. The findings are the same as those obtained by Haruna, Kimwaga and Richard (2024). When comparing charred briquettes of different binding materials, the paper-binding briquettes burnt into ashes more quickly than the starch-binder materials.

4.0 Conclusion and Recommendations

Production and use of briquettes is one among the processes that contribute to the sustainable management achievements in solving the duo challenges of energy as well as waste management in urban areas. However, the produced energy sources using organic waste could achieve different physical and burning properties due to different feedstock materials and types of binding materials used. Processes and technological differences might be other factors impacting physical characteristics of the end products. The study analysed impacts of varying ratios of feedstock materials and two types of binding materials. It was found that both the ratio of feedstock and the types of binding materials have influences on the physical and mechanical properties, including strength and water resistance analysis. Two types of briquettes based on feedstock materials were physically strong enough for storage purposes, loading, packaging and transporting regardless of the binder type used. To promote the use of these briquettes, it is recommended that the government emphasise the alternative policy options. A further recommendation based on findings is that briquettes should be stored in dry, covered areas to prevent water contact in wet areas, as the disintegration characteristics of samples were detected during the water resistance test. Considering the burning properties, which are more crucial to the consumers, they show discrepancies among samples of different binders. This implies that the denser the briquettes become, the further the delay in firing up; however, they will take longer to burn. In this case, cassava starch binder performed better than paper pulp binder did. However, the less dense binder material (paper pulp) resulted in high smoke intensity, which is disadvantageous to the cooks. Similarly, the gas emissions were found to be different with feedstock ratios and binders that accelerated into smoke emission and ash generation. The study recommends that the use of analysed briquettes with CO levels exceeding Tanzanian standards (200 ppm) necessitate outdoor use to allow air circulation and to avoid any potential health effects that could result from the conversion of gas states. The government should create environmental management policies that include incentive schemes to encourage production of briquettes and limit the use of traditional wood charcoal and public education regarding the benefits of alternative briquettes. A thorough reduction in reliance on traditional wood charcoal, which endangers public health and the environment, requires the implementation of these policy decisions. Further research is recommended with the aim of optimising binder material types and ratios to improve WRI and reduce emissions.

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6.0 Disclosure of Conflicting Interests

The author declares no known conflict of interests to report.

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