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Performance Evaluation of the Physical and Combustion Properties of Faecal Sludge Derived Briquettes Using Different Binding Materials

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Abstract

This research aimed at evaluating the performance of faecal sludge briquettes on the quality of briquettes produced in terms physical and combustion properties. Specifically, the research determined the physical and combustion properties of briquette produced from faecal sludge bond with cassava peel, sunflower cake, banana peel and waste paper binders. Physical and combustion properties of the binder materials and briquettes produced were analysed in the Water Resource Engineering laboratory. The laboratory analysis of the combustion properties showed that the Sunflower cake binder had highest calorific value of 16.24 MJ/Kg when compared to other binders including banana peels, cassava peels and waste papers. Similarly, sunflower cake bond briquettes were found to have highest calorific value of 10.81 MJ/Kg than other binders bound briquettes. The drying rates were higher for waste paper, a bond briquette which was observed to be within 6 days from the day of briquette production. The density of faecal sludge briquette was higher in banana peels bond briquettes having the density of 0.99±0.062 g/cm^3. The use of binders has significantly improved the physical and combustion properties and thus the performance of the faecal sludge derived briquettes. It is recommended to use faecal sludge bond with sunflower cake binder.

Keywords: Binders; Briquettes; Energy content; Faecal sludge

Introduction

Inadequate and poor faecal sludge management is one of the growing environmental and public health threats in today's world (Sagor et al. 2022). The global urban sanitation coverage estimates that around 2.8 billion people in low- and middle-income countries are without access to safely managed sanitation (Strande et al. 2015). It is estimated that about 70% of the Sub-Saharan African population relies on the use of on-site sanitation systems (OSSs), such as unimproved pit latrines and septic tank systems of various forms, to meet their sanitation service needs (Jenkins et al. 2015). These OSSs result in the accumulation of large amounts of faecal sludge since they are not connected to the sewerage system (Olugbade et al. 2019). According to the Tanzania WASH portal housed in the Ministry of Health, Community Development, Gender, the Elderly, and Children, by April to June 2020 report, only 63.6% of households in Tanzania had access to improved toilets. Dar es Salaam City, with approximately 78% of unplanned settlements, has about 90% of its population relying on onsite sanitation systems, while only 9% rely on off-site sanitation systems, including decentralized wastewater treatment facilities (Strande et al. 2014). Regrettably, about 1% of the urban population is still practicing open defecation (Hutton & Chase 2016). Most people in Dar es Salaam still rely on the use of onsite sanitation systems, which are characterized by poor hygienic emptying services, which results in the illegal dumping of faecal sludge into either water bodies or other open environments (Mwamlima et al. 2023). The most common unhygienic practice is pit flooding out into the environment, particularly during heavy rainfall. Several studies have reported the potential use of faecal sludge for the recovery of valuable resources such as energy through the production of biomass briquettes (Romallosa & Kraft 2017). Additionally, the 2015 Tanzania National Energy Policy, provides the drive for the establishment of sustainable energy resources that are safe, reliable, cost-effective, efficient, and environmentally friendly. One of the promising solutions towards addressing faecal sludge management challenges and the reliable energy crisis is the application of faecal sludge briquetting (Sen et al. 2016). The use of faecal sludge briquettes has been acknowledged widely as a renewable energy source for addressing the problem of dependency and overconsumption of wood and charcoal as the primary source of energy for over 90% of Tanzanians (Mkude et al. 2022). The performance of faecal sludge briquettes depends on the type and nature of binders used during briquette production (Gold et al. 2017). According to Nazari et al. (2019) binding materials play a significant role in the process of briquette production; the strength, thermal stability, and physical and combustion properties of briquettes all depend on binders (Aransiola et al. 2019). Due to differences in material composition, various types of briquettes need different binding materials (Gold et al. 2017). Generally, the properties required for binding materials are strong bonding, pollution-free, no effect on the heat release or combustibility of the fuel, environmentally acceptable, availability, and economically available (Massaro et al. 2014. According to (Sotannde et al. (2010), they reported the effects of binder type and their proportion on the durability of briquettes produced from Neem residues. The study revealed that the briquettes produced from Arabic gum and cassava starch were significantly different. (Davies 2015) investigated the effects of binder type on the physical and combustion characteristics of composite briquettes made from rice husk and bagasse. It revealed that a binder has a positive effect on the mechanical characteristics of briquettes (Ward 2009). Faecal sludge briquettes made with locally available binding materials would be suitable and sustainable for managing human waste (Sen et al., 2016). However, the physical and combustion properties of the faecal sludge-derived briquettes with various materials have not been adequately explored. Therefore, this study aims to evaluate the performance of faecal sludge briquettes on the physical and combustion properties using cassava peel, banana peel, sunflower cake, and waste paper-binders

Material and Methods

Material and preparation

This study was carried out in the laboratory whereby the briquettes were produced from pyrolyzed faecal sludge using four binding materials; cassava peel, banana peel, sunflower cake and waste paper. Faecal sludge was collected in dry condition from faecal sludge dry bed at Mburahati Decentralized Wastewater Treatment System (DEWAT's) which is located in Dar es Salaam.

The collected faecal sludge was further dried under the sun for (7) days at the College of Engineering and Technology (CoET), University of Dar es Salaam as they were collected during rainy season. About 69.9 kg of dried faecal sludge was fed into pyrolysis reactor for carbonization. Carbonization was conducted in a locally made ceramic carbonization reactor at 450 to 500 ℃.

The faecal sludge char produced were sieved using 2 mm mesh. The 2 mm particle size was appropriate for homogeneous mixing with the binding materials for briquettes.

Binder preparation and mixing combination

Four different binding materials were used in this study; cassava peel powder, banana peel powder, waste paper slurry and sunflower cake, all of which are locally available. All the binding materials used in this study were selected based on their availability, accessibility, quality, affordability and energy efficiency.

Cassava peel flour

A cassava paste was made from 150 g of cassava peel flour and 0.2 L cold water from tape water and thereafter was poured into 1 L of boiling water at a temperature of 100 ℃. Continuous stirring (mixing) was done to produce a good slurry with more sticky. After 6 minutes, the slurry was taken off from the stove, cooled and mixed with faecal sludge char.

Banana peel flour

A banana paste was made from 200 g of banana peel flour and 0.4 L of tap water and thereafter, the paste was poured into 1 L boiling water at a temperature of 100 ℃ continuous mixing of the mixture was done, until the sticky slurry was formed. The pot containing the mixture was taken off from the stove cooled and mixed with faecal sludge char with different ratios (5:3, 4:3 and 3:1).

Waste paper

1 kg of waste paper was chopped into small pieces and was put into a 10 L bowl of water and was left for 3 days to get a sticky slurry. After three days, the waste paper slurry was stirred for homogenization and was mixed with faecal sludge at different ratios.

Sunflower cake

Sunflower cake is the final product from sunflower oil production and was used for binding purposes. 1000 g of sunflower cake were taken and mixed with 2 liters of water to form sunflower cake slurry. A band of different ratios (5:3, 4:3 and 3:1) were conducted to determine the desired efficiency of the binder which provided the best results.

Banana peels floor

Waste paper

Sunflower cake Cassava Peels

Figure 1: Binders used

Mixing combination

Different mixing combination/ratios were used by weighing the charred faecal sludge with corresponding binders using a digital weighing scale. The ratios in this study was done using trial and error method until a desired ratio was obtained as depicted in Table 1. This process was done on-site at Environmental Science and Technology.

Table 1: Mixing ratios between FS and binders

Experimental Run	Faecal Sludge Vs Binder Mixing Ratios			
	FS vs CP	FS vs SC	FS vs WP	FS vs BP
Run 1	3:1	3:1	3:1	3:1
Run 2	5:3	5:3	5:3	5:3
Run 3	4:3	4:3	4:3	4:3

Faecal sludge briquettes fabrication

This process involved loading of each mixture combination into manual lifting jerk machine (piston) and thereafter, a jerk was pressed which lifted the briquettes out of the holes. The pressing force was opposed by the stopper which was inserted across the machine until the briquettes were well compacted. To release briquettes from the machine the stopper was removed and the manual lifting jerk was pushed upwards and finally the briquettes were removed by hands from the machine as shown in Figure 2. Sixteen (16) squared faecal sludge briquettes with the diameter range of 4.3-4.5 cm and length of 9.7-10.5 cm were produced from mixing ratios of binder combination (5:3, 4:3 and 3:1). The produced briquettes were then dried under the sun for 10 days before they were sent at Water resource Engineering laboratory for testing.

Figure 2: Practical procedures for briquettes production

Physical properties testing

The physical properties of briquettes produced including shatter resistance test, tumbling resistance test, water resistance test, density and drying rates were physically done. The physical properties of briquettes are very important because they help to know the strength and durability of briquettes when exposed to stress such as during transportation, when immersed in water and when falls down un expectedly.

Shatter resistance test

This test is also known as drop test. The test intended to determine the mechanical strength of briquettes. The test is determined as impact resistance index, which is a quality parameter to measure the ability of the densified material to remain intact when handled especially during transportation and storage. According to Abdulkareem et al. (2018) the briquette with known weight and length was dropped from a height of 2 m to the concrete floor.

$$IRI = \frac{W1 - W2}{W1} \times 100\% \qquad (Eqn. 1)$$

$$\%Shatter\ resistance = 100 - Weight\ loss \qquad (Eqn\ 2)$$

Where;

IRI-Impact Resistance Index

Density of briquettes

Density of each briquettes sample was determined to note the potential energy available per unit volume of bio-briquettes. Density is an important property of briquettes since; it enhances the burning rate of the briquettes while heating. The mass of briquettes was obtained using electrical balance while the essential parameters in determination of volume, height and diameter denoted as h was measured using a rule (Andriessen et al. 2017)

$$Density = \frac{Mass}{Volume} \qquad (Eqn. 3)$$

Combustion properties of faecal sludge briquettes

Moisture content of faecal sludge briquettes was determined using gravimetrical oven dried method as per ASTM E871-82. The volatile matter was determined as per ASTM E872-82 (2013) standard procedures. The ash content of faecal sludg briquettes produced was calculated as per ASTM D3174-12 standard procedures. The percentage fixed carbon was determined using the equation used by Awulu &Audu (2018) where the sum of moisture content, volatile matter and ash content was subtracted from 100%. The heat calorific value of the faecal sludge briquette was computed as per ASTM D5865-19.

Results and Discussion

The physical and combustion properties of faecal sludge briquettes produced were limited to density, water resistance test, impact resistance test (shatter), drying rates, moisture content, volatile matter, ash content, percentage fixed carbon and calorific value of the fuel.

Physical properties of faecal sludge briquettes produced

Density

The average densities for faecal sludge briquettes from each binder combination are shown in Table 2. The results in Table 2 showed that faecal sludge briquettes bond with banana peels from all ratios used has the highest densities of 0.99±0.062 g/cm^3, 0.98±0.12 g/cm^3 and 0.95±0.06 g/cm^3 for ratio 4:3, 3:1, and 5:3 respectively. The lowest densities were observed in faecal sludge briquettes bond with sunflower cake for ratio 3:1 and 5:3 having 0.71±0.024 g/cm^3 and 0.72±0.014 g/cm^3 respectively, except for ratio 4:3 having 0.74±0.04 g/cm^3 which is greater than that found in faecal sludge briquette bond with waste paper binder. The difference in densities could be due to the level of binder used, increasing the binder ratio generally results into denser briquettes. The binder helps to fill the gaps between the particles of FS briquette, leading to a more compact structure. The results of densities obtained in this study was lower than those reported by Ajimotokan et al. (2019) which ranged between 1.86 to 1.19 g/cm^3. The reason for the differences might be due to the differences in compaction pressure applied by the two studies. In the reported study they used electrical machines for compaction, while in this study we used manual operated machines for compaction. Higher pressures generally improve the density.

Table 2: Mean densities of briquettes produced in g/cm^3

SAMPLE	FS+CP	FS+BP	FS+WP	FS+SC
RATIO 5:3	0.87±0.0054	0.99±0.062	0.73±0.04	0.74±0.04
RATIO 4:3	0.86±0.083	0.98±0.12	0.74±0.046	0.72±0.014
RATIO 3:1	0.80±0.11	0.95±0.06	0.76±0.028	0.71±0.024

Whereby, FS= Faecal sludge, CP=Cassava peel binder, BP=Banana peel binder, WP=waste paper binder and SC= Sunflower cake binder.

Drying rates of faecal sludge briquettes produced

The results obtained in this study confirm that faecal sludge briquettes bond with waste paper dried much faster than other faecal sludge briquettes samples. The weight of faecal sludge briquettes bond with waste paper was constant from day 6 to 10 day. The lower drying rates was observed in the faecal sludge briquettes made from banana peel binder for all the ratios used. The drying rate was higher in waste paper bond faecal sludge briquettes followed by sunflower cake, cassava peel bond briquettes and the least were for banana peel bond faecal sludge briquette. The higher drying rates of waste paper bond briquettes could be attributable to large pore spaces between the particles and lower compaction pressure of the waste paper bond briquette which allowed easy exist of moisture by raise in temperature (Oluwatosin et al. 2022). The lower drying rates of banana peel and cassava peel bond faecal sludge briquettes was probably due to the inter-particle attractive forces which reduce the pore spaces between them and therefore affect the release of moisture and thereby affect the rapid drying of the briquette as reported by Sagor et al. (2022). The statistical analysis revealed that there is a significant difference with $p=2.49\times10^{-7}$, 2.9×10^{-6} and 1.72×10^{-7} for ratio 5:3, 4:3 and 3:1 respectively at $\alpha=0.05$.

Shatter resistance test and water resistance test

All binders bound briquette passed the dropping test (shatter) except for ratio 4:3 for waste paper. Ratio 4:3 had the value of 34.21% impact resistance index which is less than the acceptable level of 50%. This maybe contributed by high concentration of binder in the ratio which results to the increase in pore spaces between waste paper bond briquettes which reduce the strength upon dropping (Katimbo et al. 2014). Furthermore, all samples of briquettes did not pass the water resistance test at 95% acceptable limit. The results found in this study are quite similar to those reported by Mwamlima et al. (2023). Water resistance and impact resistance test results showed a statistically significant difference between the faecal sludge briquette samples with p=0.00105 and p=0.0011 at $\alpha=0.05$ respectively.

Combustion properties of faecal sludge briquettes

The combustion properties of faecal sludge briquettes were limited to the determination of moisture content, volatile matter, Ash content and calorific value.

The moisture content of all briquette samples was found to be in a range of 2.9-8.4% as shown in Figure 3. The recorded moisture content values of this study are less than those reported by Nyaanga et al. (2018) which ranged between 7.3-10.9%. The higher moisture content was recorded in ratio 4:3 for banana peel bond briquettes results. This may be due to the level of binder used in ratio 4:3 in which binder level was about 43% while for 5:3 the binder level was about 37.5% and for 3:1 binder level was about 25%. The lower moisture content was recorded in waste paper bond briquettes ranged between 2.9-3.3% for all samples. The statistical results revealed that there is significant difference in the moisture content values of faecal sludge briquettes samples with $p=8.11\times10^{-5}$ at $\alpha=0.05$.

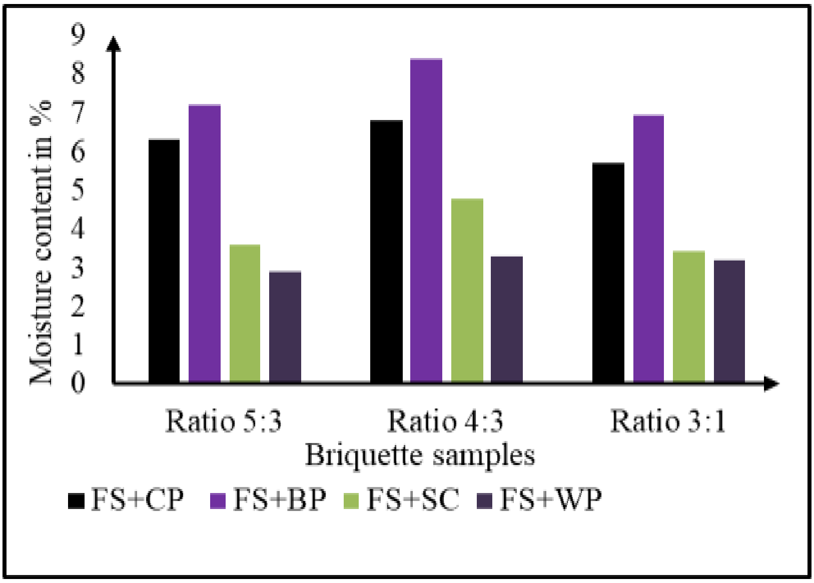

Figure 3: Moisture content of briquettes

The volatile matter was found to be in a range of 40.6-49% with sunflower cake bond briquettes having the higher volatile matter than other briquette samples as shown in Figure 4. The higher volatile matter in sunflower cake bond briquettes for all binder combination maybe contributed by the oil content/property of the sunflower cake which remained even after oil extraction and drying (Zhang et al. 2018). Volatile matter has an effect to the burning and ignition rate of the briquettes, the higher the volatile matter the fast the ignition and the burning of the briquettes.

Ash content is the end product of a solid fuel that remain after fuel combustion. The ash content was found to be in a range of 37.8-47.3% for all briquette samples as shown in Figure 5. The minimum ash content was found to be 37.8% for sunflower cake bond briquette. The maximum ash content was recorded to be 47.3% in waste paper bond briquettes for ration 3:1. The reason for the high amount of ash content in all samples of briquettes produced is the high amount of sand in the faecal sludge collected. This was due to the type of drying bed used in dewatering the faecal sludge. The faecal sludge used in this study was collected from unplanted sand drying beds, therefore, during removal of dried faecal sludge from the bed there is a possibility of sand to remain intact. The difference between ash content results of all samples are statistically significant with p= (0.00021) at $\alpha=0.05$.

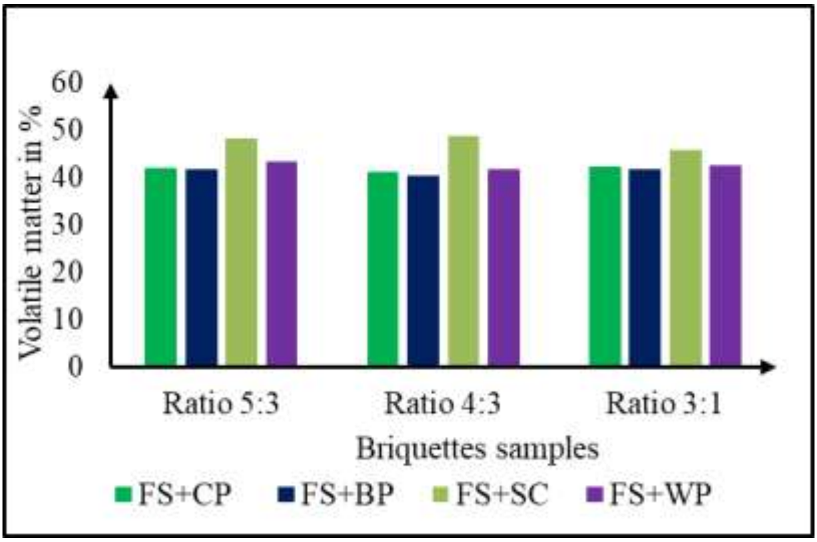

Figure 4: Volatile matter of briquettes

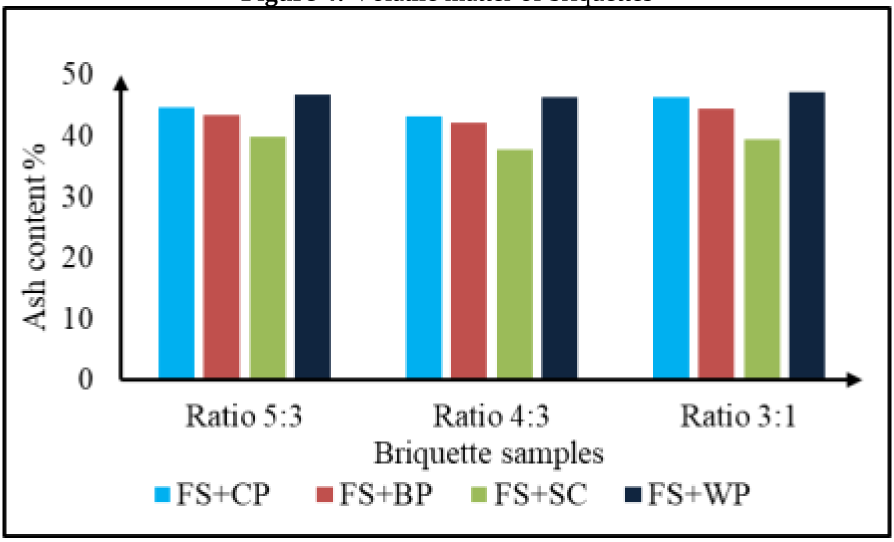

Figure 5: Ash content of briquettes samples

The energy content value of briquette samples produced from the combination of faecal sludge char and binding materials at different ratios are shown in Figure 4. The calorific value of all briquette's samples produced using carbonized faecal sludge were found to be in a range of 8.1-10.81 MJ/Kg. The highest calorific value was recorded in the briquette sample (FS+SC) at a ratio of 3:1. This results are comparable to those reported by Supatata et al. (2013) which ranged between 8.6 to 11 MJ/Kg. This means that the higher the binder level the higher the calorific value and vice versa except for sunflower cake with 25% binder level which had the highest calorific value. This maybe contributed by low ash content obtained (39.4%). The calorific value results of all briquette samples are statistically significant difference with p= 0.0003 at α=0.05 considering 95% level of confidence.

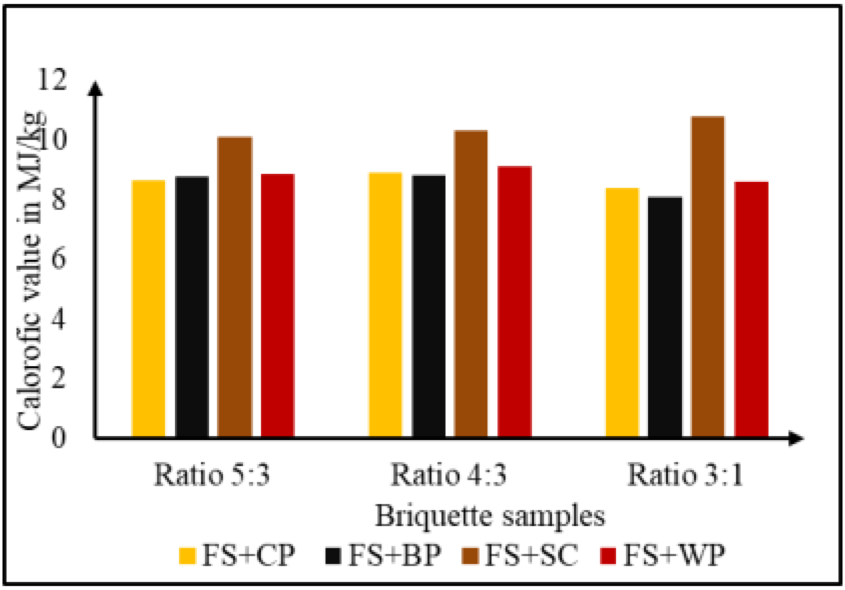

Figure 6: Calorific value of faecal sludge briquettes

Correlation between moisture content, volatile matter, ash content and fixed carbon content on the resulting calorific value.

The volatile matter and fixed carbon were found to be positive correlated with the calorific value at 70.9% of FS bond with cassava peel, 89.07% bond with banana peel, 86.9% bond with sunflower cake and 32.73% bond with waste paper binder and 99.35% bond with cassava peel, 99.98% bond with banana peel, 99.9% bond with sunflower cake and 99.95% bond with waste paper for fixed carbon content respectively. and 97.8% respectively. This result means that when each property of the fuel briquette increases the calorific value of the faecal sludge briquette increases. Nevertheless, moisture content and ash content results from all samples were found to be negatively correlated with calorific value obtained at (-73.28% and -79.53%) respectively. This means that, the higher the ash content the lower the calorific value of the fuel briquette and vice-versa. The relationship found in this study was similar to what other researchers have reported. The study done by Nazari et al. (2019) shows that the increase in calorific value was inversely proportional to ash content values while, other combustion properties were directly proportional to the heat value obtained.

Table 3: Correlation between moisture content and calorific value

		MC			CV			
		FS+BP	**FS+SC**	**FS+WP**	**FS+CP**	**FS+BP**	**FS+SC**	**FS+WP**
	FS+BP	1						
	FS+SC	0.963123	1					
MC	**FS+WP**	-0.38266	-0.11997	1				
CV	**FS+CP**	-0.77662	-0.57848	0.879204	1			
	FS+BP	-0.88891	-0.73288	0.763368	0.978923	1		
	FS+SC	-0.61374	-0.80354	-0.49456	0.02072	0.183906	1	
	FS+WP	-0.90419	-0.75593	0.740613	0.971289	0.999404	0.217729	1

Where MC= moisture content, CV=Calorific value

Table 4: Correlation between volatile matter content and calorific value

		FS+CP	**FS+BP**	**FS+SC**	**FS+WP**	**FS+CP**	**FS+BP**	**FS+SC**	**FS+WP**
	FS+CP	1							
	FS+BP	0.99447	1						
VM	**FS+SC**	0.243364	0.14011	1					
	FS+WP	0.76815	0.696627	0.80796	1				
CV	**FS+CP**	0.70903	0.779193	0.511427	0.093131	1			
	FS+BP	0.8381	0.890779	0.325146	0.294512	0.978923	1		
	FS+SC	0.69034	0.610506	0.86974	0.993511	0.02072	0.183906	1	
	FS+WP	0.85644	0.905936	0.292306	0.327327	0.971289	0.999404	0.217729	1

Where VM= Volatile matter and CV= Calorific value

Table 5: Correlation between fixed carbon content and calorific value

		FC				CV			
		FS+CP	**FS+BP**	**FS+SC**	**FS+WP**	**FS+CP**	**FS+BP**	**FS+SC**	**FS+WP**
MC	**FS+CP**	1							
	FS+BP	0.997337	1						
	FS+SC	0.069536	0.14211	1					
	FS+WP	0.995461	0.999751	0.164166	1				
VC	**FS+CP**	0.993451	0.982471	0.0449	0.978066	1			
	FS+BP	0.995847	0.999835	0.16007	0.999991	0.978923	1		
	FS+SC	0.093652	0.166018	0.999707	0.187984	0.02072	0.183906	1	
	FS+WP	0.99211	0.998612	0.194051	0.999539	0.971289	0.999404	0.217729	1

Table 6: Correlation between ash content and calorific values of all samples of briquettes

		AC				CV			
		FS+CP	**FS+BP**	**FS+SC**	**FS+WP**	**FS+CP**	**FS+BP**	**FS+SC**	**FS+WP**
AC	**FS+CP**	1							
	FS+BP	0.783865	1						
	FS+SC	-0.43031	0.223203	1					
	FS+WP	0.802972	-0.999507	0.19249	1				
CV	**FS+CP**	-0.90235	-0.97495	-0.00078	-0.98145	1			
	FS+BP	-0.7953	-0.99983	-0.205	-0.99992	0.978923	1		
	FS+SC	-0.449613	-0.20219	-0.99977	-0.17135	-0.02072	0.183906	1	
	FS+WP	-0.7739	-0.99987	-0.23866	-0.99888	0.971289	0.999404	0.217729	1

Where: AC= Ash content and CV= Calorific value

Evaluation of char yield from carbonization and the resulting briquettes produced.

During carbonization, only faecal sludge was carbonized unlike the binders. The binders were not carbonized since carbonization may cause binders to lost their adhesive properties which is required for bonding binding. It was found that when 69.9 kg of dried faecal sludge collected are carbonized yield 31.5 kg of char which is 45.21% yields.

The 31.5 kg faecal sludge char released produced 122 pieces of briquettes with the diameter range of 4.3-4.5 cm and length of 9.7-10.5 cm with an average weight of 108±0.07 g for waste paper, 131.06±1.09 g for sunflower cake, 168.87±0.64 g for banana peel and 142±1.98 g in triplicate. This implies that one ton of dried faecal sludge can produce 450.64 kg of carbonized faecal sludge, which when used for briquetting releases about 1745.34 pieces of faecal sludge briquettes with the same dimensions. According to Mwamlima et al. (2023) the energy potential of 2317 m3/day of the collected faecal sludge yields about 140 tons/day of faecal sludge briquette.

Energy balance during carbonization of faecal sludge.

The input energy calculated during pyrolysis was about 705.99 MJ from a high heating value (HHV) of 10.1 MJ/kg of the dried faecal sludge while, the output energy was approximated to be 337.1 MJ from a high heating value (HHV) of 10.7 MJ/kg of charred faecal sludge. About 52. 25% of the energy used lost during pyrolysis. This result showed that a high percentage of energy was lost and this may be due to the technology used during carbonization which had air spaces below and at the side ways to allow limited amount of oxygen to pass through the pyrolysis reactor (Yustas et al. 2022).

Conclusion

Overall, the use of binders has significantly improved the physical and combustion properties of fecal sludge derived briquettes. The briquettes produced with sunflower cake, waste paper and cassava peel as a binder showed potential as alternative to renewable energy sources. The moisture content and ash content of all briquette samples achieved 2.9-8.4% and 37- 47.3% respectively. Moreover, the energy content greater than 9 MJ/kg of the produced briquettes could be used for sustainable combustion. The faecal sludge charcoal briquettes bond with sunflower cake can be alternative to reuse and manage human waste in a sustainable way.

The physical properties tested depend on the level of binder used. The drying rates of briquettes produced were higher in waste paper bond briquettes as it only started to maintain a constant weight at day 6. Most of the briquette samples tested passed the physical test except for water resistance test in which none of the sample passed the test at the recommended limit of 95%. Briquettes made with waste paper binder for ratio 4:3 did not pass the impact resistance test 50% lower limit. This was because of the higher level of binder (42.85%) and the nature of waste paper to fasten disintegrate and softening while in water.

Faecal sludge bond with different binding materials yields energy content with good prospect to be used as an alternative fuel source for domestic purposes. Nevertheless, based on the calorific value results it is recommended to use faecal sludge bond with sunflower cake binder because their resultant calorific value is higher than other briquette samples at all ratios.

Declaration of Competing Interest

The authors declare that they have no competing interests, financial or non-financial, that could potentially influence the integrity or objectivity of this research.

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