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Production of low emission briquettes from carbonized faecal sludge as an alternative source of cooking energy

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Abstract

Background In Tanzania, firewood, charcoal, and agricultural waste play a crucial role in daily life as sources of cooking energy, especially in rural areas. Using these energy sources contributes to deforestation and the emission of harmful substances, leading to health problems. This study highlights the potential of faecal sludge briquettes as an innovative, environmentally friendly, and sustainable alternative to traditional energy sources to meet the increasing demand for cooking energy in Tanzania. The process involved sludge characterization, drying, sorting, carbonization, milling, briquette making, and characterization.

Results A study was conducted to assess the presence of zinc (Zn), cadmium (Cd), and lead (Pb) in faecal sludge collected from households. The results indicates that the levels of these metals were all within the acceptable limits set by the Tanzanian Standards (TZS) for sludge disposal and use in the environment, which are 5.00 mg/L, 5.00 mg/L, and 30.00 mg/L, respectively. Septic tanks and pit latrines sludge had a concentration of 0.5 mg/L and 0.5 mg/L for Zn, 0.55 mg/L, and 0.6 mg/L for Cd, and 10.01 mg/L and 4.87 mg/L for Pb, respectively. Adding 75% charcoal dust improved the gross and net heating values from 10.47 and 10.16 to 19.29 and 18.86 MJ/kg, respectively. Similarly, adding 50% charcoal dust improved the gross and net heating values to 19.24 and 18.78 MJ/kg. The emission of particulate matter (micrograms/m^3) was reduced from 30.4 and 35 to 10.3 and 11.8 for $PM_{2.5}$ and 7 and 8 for $PM_{10,}$ while carbon monoxide emission decreased from 51.2 to 19.7 ppm.

Conclusion The results strongly suggest that briquettes made of carbonized faecal sludge mixed with other biomass materials could offer an alternative to traditional solid fuels, with the added benefits of reducing greenhouse gas emissions, deforestation, and longer burning times.

Keywords Alternative energy, Biomass, Briquettes, Cooking energy, Low emission

Background

Like many other developing countries, Tanzania faces the challenge of inadequate access to clean energy sources. According to the IEA [1], many of the residents in Tanzania still depend on traditional sources of energy, such as firewood and charcoal. They use firewood and charcoal as primary energy sources for cooking, contributing to deforestation, soil degradation, and air pollution. This traditional cooking energy leads to adverse health effects such as respiratory diseases and cancers [2, 3].

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The increasing need for energy and growing environmental awareness has prompted a search for alternative energy sources. This study discusses the production of low-emission briquettes from carbonized faecal sludge as an alternative source of cooking energy. The objective is to develop an eco-friendly method to produce efficient fuel briquettes from faecal sludge. Faecal sludge management is a significant challenge in many developing countries, including Tanzania, where many rely on onsite sanitation systems. Improper disposal and treatment of faecal sludge pose significant public health and environmental risks. Briquetting offers a promising solution for converting faecal sludge into a usable fuel source, providing economic benefits, and reducing contamination.

Faecal sludge is a type of waste generated from onsite sanitation systems. It is also a byproduct of wastewater treatment, and its management is a critical issue in many urban areas of Tanzania [4]. The inadequate management of faecal sludge can result in public health risks and environmental pollution. However, recent studies by Kizito et al. [5] and Mwamlima et al. [6] have shown that faecal sludge can be appropriately applied and converted into briquettes, which can serve as a source of cooking energy and solve the challenges associated with faecal sludge management in developing cities [7]. In this study, the faecal sludge used was obtained from pit latrines and septic tanks emptied by vacuum trucks in Arusha, Tanzania.

Briquettes are similar to wood pellets, but they are compressed and dried to form a larger, almost smokeless and slow-burning material. This makes them easy to store, transport and shape as needed [8]. The size and shape of the briquettes have a significant impact on their efficiency, handling, emissions, and other important performance factors [9]. Through this study, we hope to gain a better understanding of sustainable energy options for developing countries, particularly regarding cooking energy. By exploring the potential of faecal sludge as an alternative energy source, Tanzania and other developing nations can reduce their reliance on traditional biomass fuels, promote sustainable development, and improve public health.

In a study conducted by Hans, Komakech et al. [10], the availability of organic waste, including faecal sludge, in Arusha, Tanzania, was examined. The researchers discovered that the city produces roughly 6,230 m^3 of human waste per day, with 6,000 m^3 being collected through the sewerage system, and 230 m^3 being collected by vacuum trucks. As for solid waste, the city generates about 348 tons of it daily, with biomass accounting 86%. Food, paper, and wood waste, which can be used as a safe energy source and improve sanitation, decrease deforestation, and reduce the burden on city wastewater treatment facilities.

This study aimed to create high-quality briquettes in Tanzania using faecal sludge mixed with locally available materials like charcoal dust and sawdust. To achieve this, a simple technique was used that involved carbonization, sieving, mixing, agglomeration with molasses binder, and drying. The quality of the briquettes was then evaluated through various tests, including calorific value, elemental analysis, ash content, and emission measurements. The findings of this research offer valuable insights into developing effective and sustainable methods for faecal sludge briquetting that are safe for the environment. These results can help guide the implementation of faecal sludge briquetting initiatives to address sanitation challenges and provide clean cooking energy alternatives.

Methods

Study area

This research was carried out in Arusha, Tanzania (as depicted in Fig. 1), where the materials were gathered and processed to create briquettes. Materials were carefully selected and prepared to ensure precise and consistent results. Figure 2 shows the process of emptying the faecal sludge and the drying greenhouse. The drying process typically takes 21–35 days, during which the faecal sludge was handled and managed with utmost care and protective equipment was used. Faecal sludge was carefully handled and managed, and personnel protective equipment was used. The Arusha Urban Water Supply and Sewerage Authority provided collection trucks for gathering and dumping the sludge in a protected area that is inaccessible to residents, minimizing the risk of epidemics (as seen in Fig. 2). The charcoal dust and sawdust was sourced from local charcoal and timber merchants, who provided these unused resources. The molasses binder used was acquired from local agrovets store, which supplies agricultural products and services to support farming and livestock operations. Molasses is often sold as a supplemental feed for dairy cows to moderately increase milk production.

The laboratory analyses were conducted at three institutions: The Nelson Mandela African Institution of Science and Technology Laboratory (NM-AIST), University of Dar es Salaam (UDSM), and Arusha Technical College (ATC). Analytical grade chemical reagents were used to ensure the accuracy and precision of the analyses. To ensure standardization of the results, recommended standard methods were followed during sample collection, storage, preservation, and analysis of heavy metal ions and pathogens, as described by the American Public Health Association [11].

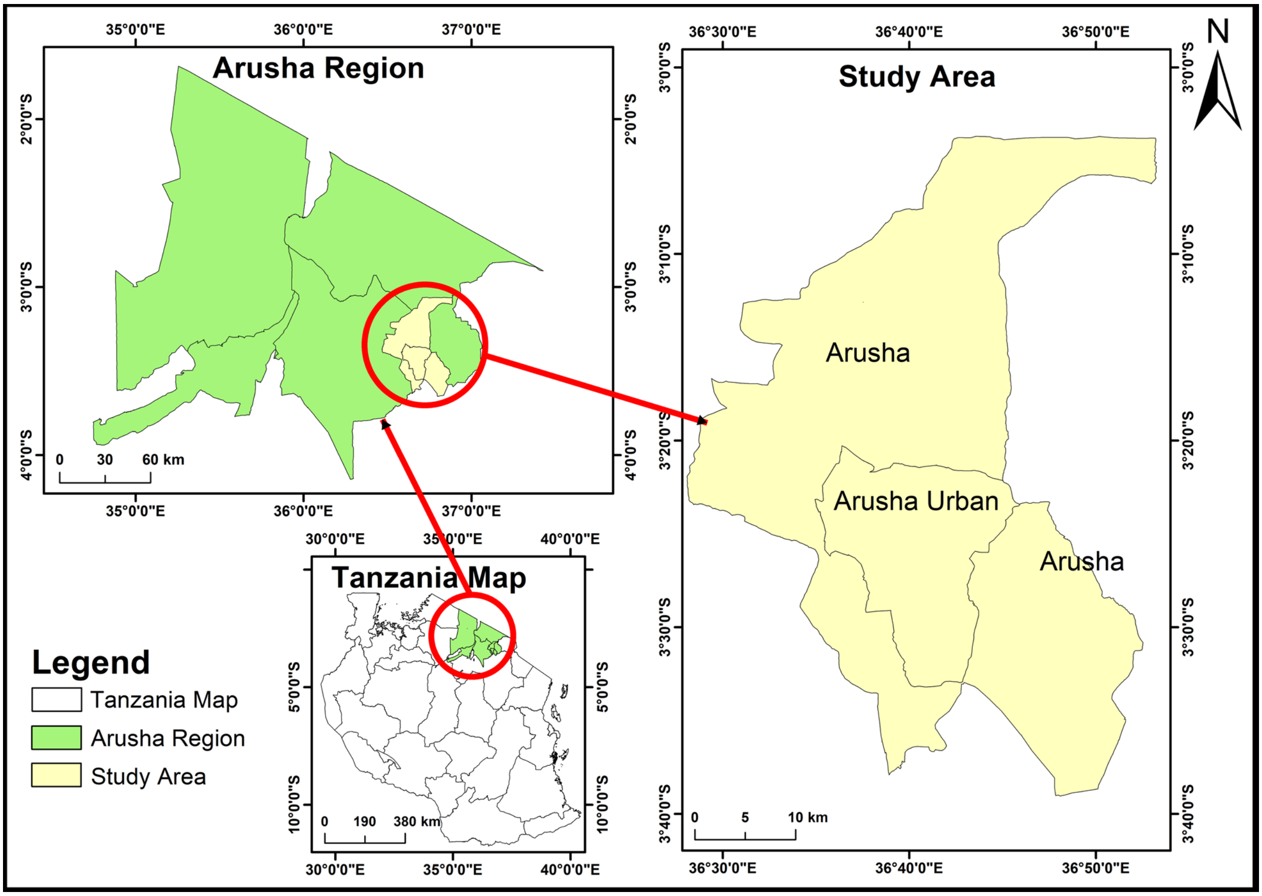

Fig. 1 Study area

Fig. 2 Emptying Faecal sludge to the greenhouse for drying

Faecal sludge characteristics

The HQ40d multiparameter was appliedto assess the characteristics of faecal sludge from septic tanks and pit latrines. Inorganic pollutants such as Zn, Cd, and Pb in faecal sludge were analyzed with atomic absorption spectrophotometer (Beijing Rayleigh Analytical Instrument

Table 1 Faecal sludge results

Sample ID	Raw faecal Sludge from the septic tank	Raw faecal sludge from pit latrines
BOD_5 (mg/L)	2125	50
COD (mg/L)	13600	161
TS (mg/L)	60.77	0.56
VS (mg/L)	44.07	0.54
Fixed Solid (mg/L)	16.7	0.2
Zinc (mg/L)	0.5003	0.501
Copper (mg/L)	0.3346	0.843
Cadmium (mg/L)	0.5522	0.6
Lead (mg/L)	10.019	4.866
pH	6.73	7.09
Temperature (°C)	22.5	22.4
EC (µS/cm)	3405	1716
TDS (mg/L)	1711	857
DO (mg/L)	0.19	0.1

Corporation). The solid contents, including volatile solid (VS), total solid (TS), fixed solid (FS), chemical oxygen demand (COD) and biological oxygen demand (BOD_5), were analyzed using the standard methods for the examination of water and wastewater, as outlined in Table 1.

The levels of pathogens, including E. coli, Salmonella, Shigella, Ascaris lumbricoides, and hookworm eggs, were analyzed in the raw faecal sludge obtained from septic tanks and pit latrines. Standard methods for the examination of water and wastewaters, as listed in Table 2, were used for the analysis. To create an unfavorable environment for the pathogens, the faecal sludge was spread thinly on plastic surfaces and exposed to sunlight and high temperatures, resulting in rapid dehydration. This dehydration process, which is known to accelerate pathogen die-off, was aided by temperatures exceeding 45 °C in tropical areas at the surface of drying beds. Pathogens require sufficient moisture to survive, and the lack of moisture in this situation proved to be effective in reducing their presence [12].

Briquette preparation and quality assessment

The process of preparing and assessing the briquettes was conducted with great care to ensure that the final product met all the desired standards for safety and quality, free from harmful pathogens contaminants. Throughout the drying process, the faecal sludge and sawdust were manually turned on a daily basis to promote optimal drying, followed by carbonization (as shown in Fig. 3).

A locally made carbonization furnace was used, employing empty metal drums with removable tops to facilitate the introduction of faecal sludge materials. Each drum was fitted with a chimney to release smoke, the clarity of which served as an indicator of process completion. Once finished, the carbonized materials underwent screening to remove extraneous matter and were subsequently ground through 2 mm sieves (as shown in Fig. 4).

Table 2 Pathogens level of the raw faecal sludge

Sample ID	Pathogens				
	E-Coli (CFU/100 mL)	Salmonella (CFU/100 mL)	Shigella (CFU/100 mL)	Ascaris lumbricoides	Hookworms eggs
Raw faecal sludge from the septic tank	TNTC	TNTC	TNTC	Positive	Positive
Raw faecal sludge from pit latrines	TNTC	TNTC	TNTC	Positive	Positive
Dried faecal sludge from the septic tank	0	0	0	Positive	Positive
Dried faecal sludge from pit latrines	0	0	0	Positive	Positive
Carbonized faecal sludge from the septic tank	0	0	0	Negative	Negative
Carbonized faecal sludge from pit latrines	0	0	0	Negative	Negative

NB: TNTC Too Numerous to Count

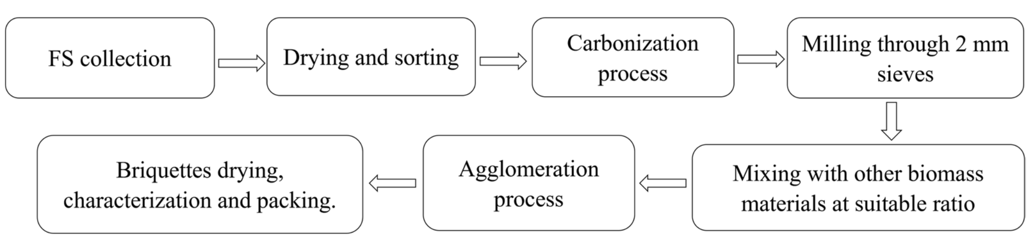

Fig. 3 Briquettes making process flow chart

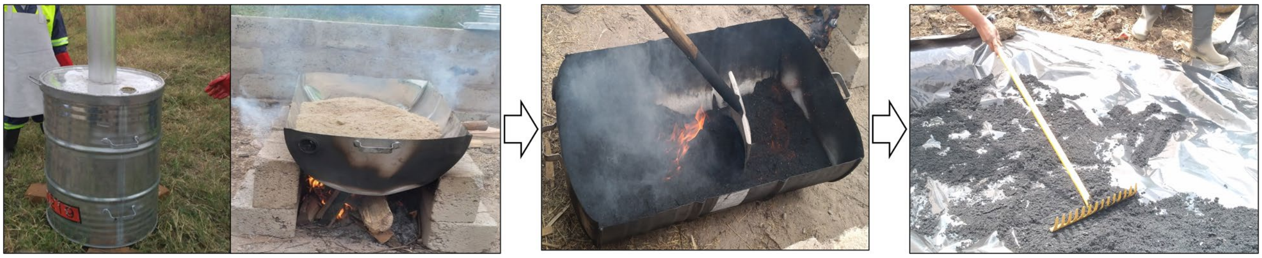

Fig. 4 Carbonization process of faecal sludge by manually made carbonization furnace and sawdust in an open drum (1st two images from left) followed by cooling process and sorting (3rd and 4th images from left)

Table 3 Mixing ratios for faecal sludge, charcoal dust, and sawdust

Sample ID	Mixing Ratio		
	Faecal sludge (wt.%)	Charcoal dust (wt.%)	Sawdust (wt.%)
A	100	0	0
B	0	0	100
C	0	100	0
D	25	0	75
E	50	0	50
F	75	0	25
G	25	75	0
H	50	50	0
I	75	25	0

Different ratios of ground faecal sludge, charcoal dust, and sawdust were mixed together (as shown in Table 3) to determine the most effective formulation for producing briquettes [13]. The process of agglomeration involved slowly adding a molasses solution to the powdered mixture. This solution was made by dissolving 1L of molasses in 20 L of water. The powder mixture (Table 1) was gradually added to the molasses solution in a 45-degree inclined rotating drum. The drum was rotated a quarter turn at a time to prevent the briquettes from fully rotating and forming irregular shapes (Fig. 5). To create uniformly sized briquette balls between 25 and 30 mm in diameter, approximately 2 L of prepared molasses and 6 kg of dust mixture were used. The desired size was achieved by slowly adding the molasses and dust mixture. Round briquettes were preferred due to their superior combustion characteristics, as reported by Nyaanga D M, et al. [8]. After drying for 8 h at an average of 25–30 °C under natural atmospheric conditions, the briquettes

Fig. 5 Illustration of the briquette-making process after carbonization

were ready for packing. The entire process is illustrated in Fig. 5.

After drying the briquette balls in a cage moisture, they were packed for usage. To evaluate the performance characteristics, such as calorific value, ash content, and bulk density a thorough quality assessment of the briquettes was performed. The assessment adhered to standard procedures, and the results were analyzed to determine the overall quality sof the briquettes.

The heating value (HV) of the briquettes was determined using the Organic Elemental Analyzer (Flash 2000) by analyzing the briquette's chemical composition to determine their energy contents as described by Abdullahi et al. [14] and El Hanandeh et al. [15]. The analysis typically involves burning a sample of the briquette and measuring the amount of heat energy released, whereby the resulting data are used to calculate the heating value of the briquette. The American Society of Testing and Materials (ASTM) E873-82 Standard Test Method was applied to determine the bulk density of the briquettes [15, 16]. The bulk density (dry basis) was calculated using Eq. (1), which measured the mass of briquettes occupying a container.

$$\text{Bulk density g/cm}^3 = \frac{m}{v} \tag{1}$$

where m is the weight of the sample, and v is the volume of the vessel.

Proximate analysis, which includes determining the moisture content, volatile matter, and ash content, was conducted according to the standard methods of ASTM D3173, D3175, and D3174 [13, 14, 16, 17]. Proximate analysis indicates ignition properties, combustion efficiency, calorific value, and potential operational issues, thus helping to assess the overall performance of the briquettes. The moisture content of a sample was determined by measuring the loss in weight after heating the sample at a temperature of 105 °C for 2 h. The weight loss during the drying process represented the sample's moisture content. An oven (Binder 56) was used for drying, followed by cooling in a desiccator and weighing. The percentage of moisture content was calculated using Eq. (2), which represents the percentage of weight loss due to moisture [14, 18].

$$\%\,\text{Moisture Content} = \frac{W_b - W_a}{W_b} \times 100 \tag{2}$$

where Wb is the weight of the sample before oven drying, and Wa is the weight of the sample after oven drying on a dry basis.

Volatile matter (%), which is content that indicates the proportion of combustible materials that can be released as gas or vapour during heating, was determined by heating the sample in a furnace (Cole Parmer Box Furnace/CBFL518C) at a temperature of 920 °C for 7 min [19]. The weight loss of the sample after heating represents the volatile matter content. The percentage volatile matter (%VM) was calculated by using Eq. (3):

$$\%\,\text{VM} = \frac{\textit{Loss in weight}}{\textit{Weight of the sample}} \times 100 \tag{3}$$

The percentage of ash content that represents the inorganic residue left behind after complete combustion of the sample was determined by burning the sample at a temperature of 700 °C ± 20 °C for two hours in a muffle furnace (Cole Parmer Box Furnace/CBFL518C), followed by a cooling process in a desiccator and weighing. Equation 4 was used to calculate the percentage ash content (AC).

$$\%\,\text{AC} = \frac{W_1}{W_2} \times 100 \tag{4}$$

where W_1 is the weight of the ash sample, and W_2 is the weight of the oven-dried sample.

The percentage of fixed carbon (%FC) was calculated using Eq. (5). A maximum fixed carbon content indicates better quality briquettes regarding energy content, combustion efficiency, stability, reduced emissions, and lower ash content [20, 21].

$$\%\ \text{FC} = 100\% - (\%\ \text{VM} + \%\ \text{AC} + \%\ \text{MC}) \tag{5}$$

Elemental composition in the percentage of common organic elements such as carbon, hydrogen, and oxygen were analyzed using the Organic Elemental Analyzer (FLASH 2000 CHNS/O Analyzers) [22].

For cooking experiment, a charcoal-burning cooking stove made from metal and clay, commonly referred as the Gyapa charcoal stove in Ghana was used. This stove features a ceramic core for the fuel with two handles for easy lifting, with three metal rods to hold the pan [23]. Approximately 25 briquette balls were loaded onto the metal and clay cooking stove with a surface diameter of 300 mm and a bottom diameter of 200 mm with holes for air circulation. To start a fire, a combination of firewood and kerosene were used.

The Portable Gas Detector (BH-4S) and Multi-Gas Detector (M2109002) were used to detect CO_2 and CO emissions. Particulate matter ($PM_{2.5}$, $PM_{10,}$ and PM_1) was analyzed using a VSON WP6930S Portable Air Quality Detector. The Portable Gas Detector (BH-4S) and Multi-Gas Detector (M2109002) were used to detect CO_2 and CO emissions. Particulate matter ($PM_{2.5}$ and PM_{10}) was analyzed using a VSON WP6930S Portable Air Quality Detector. The BH-4S, M2109002 and VSON WP6930S are handheld devices that display the atmosphere's gas and particulate matter concentrations.

The ignition time and burning rate of the material were measured through local observations using a stopwatch. To obtain accurate results, the measurements were replicated multiple times, and the average value was calculated based on the recorded data. This approach was adopted in accordance with the guidelines provided in references [14, 24, 25].

The ignition time was computed using Eqs. 6 and 7 below:

$$\text{Ignition time} = t_1 - t_0 \tag{6}$$

where t_1 = time the briquette ignited (min) and t_0 = time the ignition started (min).

Deducting the time taken to change entirely into ashes from the ignition time provides the burning rate that was computed by using the following Eq. (7) [26]:

$$\text{Burning rate} = \textit{Ashing time} - \text{Ig}\textit{nition time} \tag{7}$$

The force required to break the briquettes was measured in newton/square millimetre (N/mm^2) using the Universal Testing Machine (8551 MFL System) [27]. All the briquettes were tested for compressive strength and had a uniform diameter of approximately 30 mm. The briquettes were loaded at a 1 mm/min rate until failure, and the load was recorded. The compressive strength was calculated as the maximum load divided by the cross-sectional area of the briquette [28, 29].

Results

Briquette characteristics

The properties of briquettes were thoroughly evaluated, including their heating values and proximate analysis, which encompassed the percentages of volatile matter, moisture content, fixed carbon, and ash content. Additionally, other parameters were measured, such as carbon, nitrogen, hydrogen, and sulfur elemental compositions, ignition and burning rate, and compressive strength.

Compressive strength

This study examined the compressive strength of briquettes made from various biomass materials, as shown in Fig. 6. Results demonstrated that faecal sludge briquettes (Sample A) required a force of 1.53 N/mm^2 to break, while charcoal dust briquettes (Sample B) required a force of 0.78 N/mm^2 to break and sawdust briquettes (Sample C) required a force of 0.37 N/mm^2. These findings suggest that faecal sludge briquettes are more stable and durable than other biomass briquettes and can be easily handled and managed.

Other studies have examined the compressive strength of various biomass materials. For example, Dragusanu et al. [30] found that wheat straw briquettes had a compressive strength of 1.15–2.17 N/mm^2 and splitting mechanical strength of 0.17–0.39 N/mm^2. Meanwhile, Srinivasan et al. [29] studied coal char and found a compressive strength of 10.78 N/mm^2, as well as a compressive strength of 0.55–0.8 N/mm^2 for cassava peel and saw dust briquettes. The high compressive strength observed in this study for faecal sludge briquettes confirms their stability and durability when compared to other common types of biomass briquettes. This findings are in consistent with those of similar studies on agricultural waste and charcoal briquettes, providing evidence to support the use of dried, compressed faecal sludge as a viable alternative source of cooking energy [31, 32].

Proximate analysis

The analysis of briquette's includes measurements of volatile matter (%), moisture content (%), fixed carbon (%) and ash content (%). Briquette made from faecal sludge was found to have a high volatile content of 46.2%, indicating that more energy is required to burn off the volatiles before the thermal energy is released [24, 33]. However, by adding other biomass materials like sawdust and charcoal dust, the volatile content can- be reduced, resulting in better performance in terms of ignition and burning rates [33, 34]. Increasing the amount of faecal sludge in the mixture can affect the combustion capacity of the briquettes and increased the ash content. According to the results in Table 4, samples B and C (made from charcoal dust alone and sawdust alone, respectively) had the lowest ash content, at 26.2% and 26.02%. Sample G and H (made from a mixture of 25% faecal sludge 75% charcoal dust, and 50% faecal sludge and 50% charcoal dust, respectively) had ash content values of 31.28% and 33%. The highest ash content of 47.31% was observed in sample A, which was made from entirely faecal sludge.

According to the results obtained in Fig. 7, the amount of fixed carbon is directly proportional to the heating value as shown in Fig. 10. Samples B, D, G and H had the highest fixed carbon content, with values of 41.6%, 40.3%, 30.4% and 27.1%, respectively. Conversely, the briquettes made from entirely faecal sludge, 75% faecal sludge and 25% sawdust, and 50% faecal sludge and 50% sawdust (Sample A, F and E) had the lowest fixed carbon content, with values of 1.65%, 2.7% and 6.4%, respectively. The study found that higher fixed carbon content in briquettes leads to increased performance and energy output, indicating a positive correlation between fixed carbon content and calorific values [35]. In terms of performance and energy output, charcoal dust improved the quality of the faecal sludge briquettes.

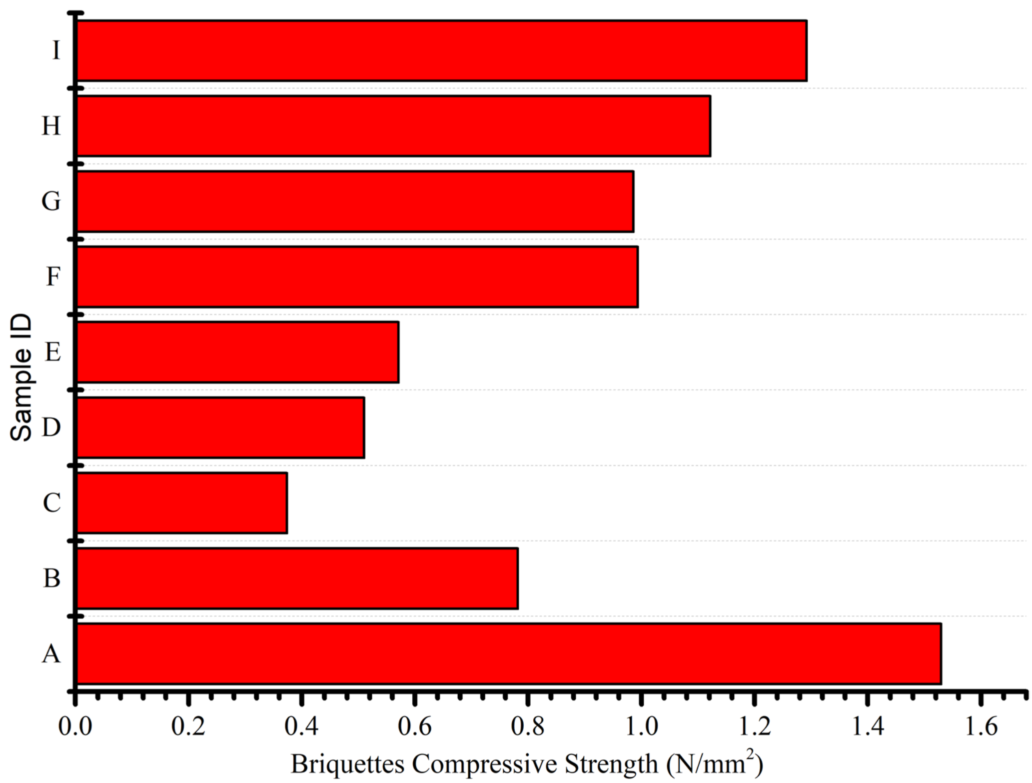

Fig. 6 Briquette compressive strength

Table 4 Percentage of volatile matter and ash contents of the briquettes

Sample ID	A	B	C	D	E	F	G	H	I
% Volatile matter	46.2	27	26.3	39.5	43.9	46	29.8	33	36.9
% Ash contents	47.31	26.2	26.02	39	43	45.5	31.28	33	40.7

Elemental composition

The elemental composition of briquettes, specifically nitrogen, carbon, hydrogen and oxygen plays a crucial role in determining their performance and efficiently as a fuel source [22]. A study conducted found that Sample C, made entirely from charcoal dust, had the highest carbon content at 54.7%. In comparison, Samples G and H, made of a mixture of faecal sludge and charcoal dust (75% charcoal dust and 25% faecal sludge as well as 50% charcoal dust and 50% faecal sludge), had maximum carbon content percentage of 47.8% and 48.1%, respectively (as shown in Table 5). Charcoal dust's primarily composition is over 60% elemental carbon by weight [36]. Briquettes with a high H/C and low O/C ratio (Sample A, B, and F) have higher energy density and better combustion, resulting in cleaner emission [37]. Samples A, B and F were 100% faecal sludge, 100% sawdust and a mixture of 75% faecal sludge and 25% sawdust. A lower O/C ratio was observed in Sample B and F. A low oxygen-to-carbon ratio improves heating value, as oxygen has no heating value [38]. Excessive oxygen can reduce combustion efficiency and lead to incomplete combustion [39]. Therefore, selecting and processing the appropriate feedstock is essential for optimizing the elemental H/C and O/C ratios, resulting in high-quality briquettes that have excellent heating value, combustibility, and low smoke emissions.

Ignition and burning time

Compared to sawdust/charcoal dust briquettes, those made from faecal sludge take a long time to ignite a fire. While sawdust briquettes (Sample B) ignite faster due to their porous nature, they do not last as long as other materials (Fig. 8) [40]. Sawdust briquettes have the lowest ignition time, taking less than 5 min, followed

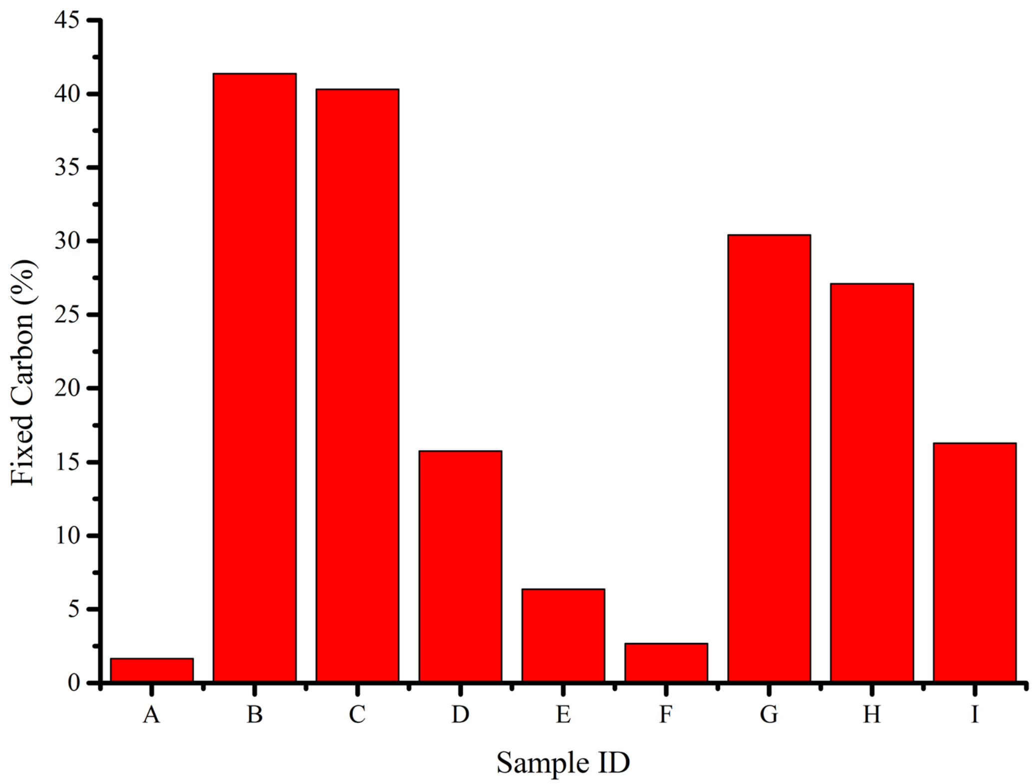

Fig. 7 Percentage of fixed carbon at different mixing ratios

Table 5 Elemental composition of the briquettes at different ratios

Sample ID	Nitrogen (%)	Carbon (%)	Hydrogen (%)	Oxygen (%)	H/C ratio	O/C ratio
A	2.19	24.38	1.46	9.71	0.060	0.398
B	1.09	47.1	2.25	12.25	0.048	0.260
C	1.27	54.66	2.17	27.38	0.040	0.501
D	1.45	38.48	1.91	20.18	0.050	0.524
E	1.43	33.9	1.50	17.02	0.044	0.502
F	2.06	33.79	1.79	13.08	0.053	0.387
G	1.34	47.8	2.00	27.28	0.042	0.571
H	1.33	47.14	2.12	25.68	0.045	0.545
I	1.64	40.22	1.79	18.71	0.045	0.465

by the mixture of sawdust and faecal sludge materials (samples D, E and F). Briquettes prepared from charcoal dust and the mixture of charcoal dust and faecal sludge (samples C, G, H and I) require a longer ignition time. The briquettes made from faecal sludge take over 20 min to ignite a fire under the same conditions. Therefore, the addition of sawdust aids the ignition and burning time of the faecal sludge briquettes, while charcoal dust provides the maximum burning time.

Emission level

Briquettes are gaining attention as a sustainable alternative to traditional fuels due to their potential to reduce emissions and mitigate environmental impacts [21]. In this study, faecal sludge briquettes showed the highest CO emission compared to mixtures with other biomass materials (Fig. 9A, B). This is because faecal sludge contains a high concentration of organic matter, which undergoes incomplete combustion during the briquette burning process, releasing higher amounts of CO [3].

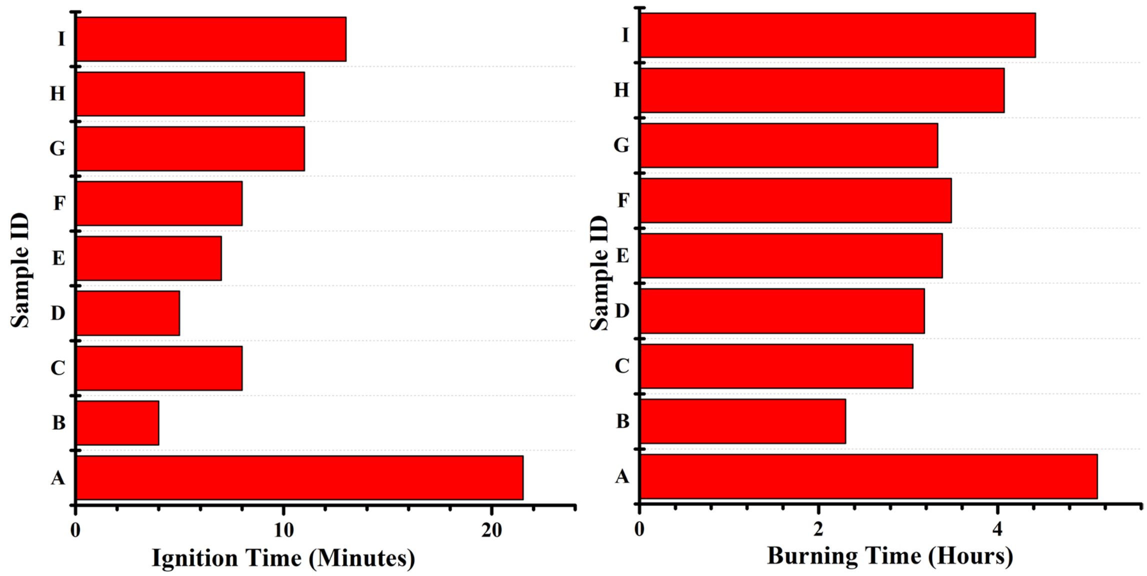

Fig. 8 Briquettes ignition and burning time

However, adding other biomass materials improve the combustion capacity of the briquettes and reduces the emission of toxic gases.

Regular charcoal showed the maximum emission levels of particulate matter ($PM_{2.5}$ and PM_{10}), total volatile organic compounds (TVOC) and formaldehyde (HCHO) (Fig. 9C, D). Conversely, the lowest concentration of particulate matter and total volatile organic carbon was observed in briquettes prepared from solely from faecal sludge. High levels of $PM_{2.5}$ and PM_{10} indicate poor indoor air quality and increased risks of cardiovascular and respiratory diseases while high TVOC levels can cause eye, nose and throat irritation and headaches [41]. Long-term exposure may affect the liver, kidneys, and central nervous system. High formaldehyde levels are linked to increased risks of nasopharyngeal cancer and leukemia. Extended exposure can also cause respiratory symptoms and allergic reactions [42, 43]. Therefore, faecal sludge briquettes can be considered a safe and more eco-friendly alternative to regular charcoal used in Tanzania for cooking energy.

Heating value (HV)

Different mixing ratios of briquettes were analyzed to determine their gross heating value (GHV) and net heating value (NHV), as shown in Fig. 10. The highest GHV and NHV were observed in briquettes made solely from charcoal dust, with values of 21.89 MJ/kg and 21.42 MJ/kg, respectively. On the other hand, charcoal dust with high moisture content (Sample C) resulted in the lowest heating values (Table 6) [44]. The mixture of the faecal sludge and charcoal dust in a ratio of 25% faecal sludge and 75% charcoal (Sample G) and 50% faecal sludge and 50% charcoal dust (Sample H) showed the maximum heating value (GHV and NHV) of 19.29 MJ/kg and 18.86 MJ/kg and 19.24 MJ/kg and 18.78 MJ/kg, respectively. The order of briquettes, in terms of heating values was C > B > G > H > I > D > F > E > A. By adding charcoal dust or sawdust biomass to faecal sludge, the heating value of the briquettes was improved by increasing the amount of volatile matter and creating a porous structure that can better absorb and release heat [45]. A porous briquette structure has the potential to burn more completely, release more energy, and reduce the ash content.

Bulk density

The slower burning rate of briquettes with the maximum bulk density is due their denser structure, which requires more time for the heat to penetrate and ignite the fuel [46]. Briquettes made entirely from faecal sludge (Sample A) had the highest bulk density of 1.23 g/cm^3, while charcoal dust (Sample C) had the lowest bulk density of 0.74 g/cm^3, and those made entirely from sawdust (Sample B) had a bulk density at 0.89 g/cm^3 (Table 6). These findings indicate that the show that the addition of faecal sludge to the mixture increases the bulk density and directly affects the burning rates for the briquettes.

Discussion

The presence of heavy metal ions such as zinc, copper, and cadmium, as well as pathogens like E. coli, Salmonella, Shigella, Ascaris lumbricoides, and hookworm eggs, were evaluated in faecal sludge. Additionally, solid contents, including total solids, volatile solids, and fixed

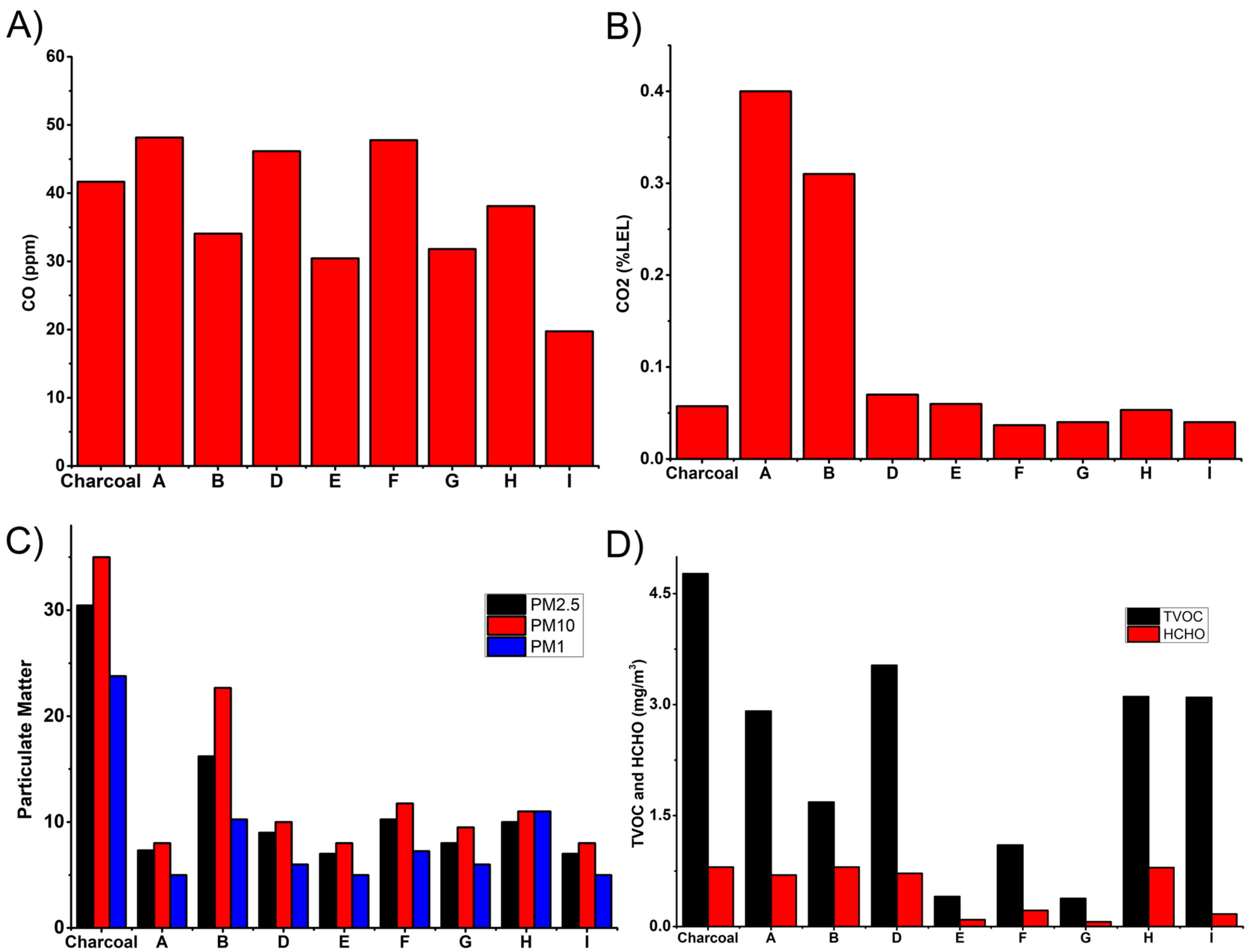

Fig. 9 Emission levels of **A** carbon monoxide, **B** carbon dioxide, **C** particulate matter ($PM_{2.5}$, PM_{10}) and **D** formaldehyde and total volatile organic compounds

solids, were also analyzed. The concentrations of Zn, Cd, and Pb in the faecal sludge from septic tanks and pit latrines were found to be within the acceptable limits set by Tanzanian at 5.00 mg/L, 5.00 mg/L, and 30.00 mg/L, respectively.

Numerous studies have been conducted to determine the presence of selected heavy metal ions in domestic faecal sludge. For instance, Agoro M A, et al. [47] reported concentrations of 0.099 mg/kg, 1.17 mg/kg, and 0.14 mg/kg for Zn, Cu, and Cd in faecal sludge. Similarly, Appiah-Effah et al. [48] reported concentrations of 2.2 mg/L, 4.0 mg/L, 0.045 mg/L, and 0.160 mg/L for Zn, Cu, Cd, and Pb in low-income areas of the Ashanti Region of Ghana, respectively. The concentration were within the acceptable range set by the US-EPA [49]. Therefore, most domestic faecal sludge has acceptable concentrations of the selected inorganic pollutants.

Furthermore, additional characteristics of the faecal sludge from septic tanks and pit latrines were also analyzed. Biochemical oxygen demand (BOD_5) concentration were 2125 mg/L and 50 mg/L, while COD concentration were 13600 mg/L and 161 mg/L. Total solids (TS) and volatile solids (VS) were 60 mg/L and 0.56 mg/L, and 44.07 mg/L and 0.54 mg/L, respectively. Fixed solids (FS) concentration were 16.7 mg/L and 0.2 mg/L for fixed solids (FS), respectively.

The raw faecal sludge from septic tanks and pit latrines contains a variety of pathogens such as E. coli, Salmonella, Shigella, Ascaris lumbricoides, and hookworm eggs. But, once the carbonization process takes place at a temperature ranging between 450 and 700 °C, all these pathogens get killed. The high temperature involved in the carbonization process helps to eliminates bacterial, viral, and parasitic pathogens [50]. Several studies have shown that pathogenic bacteria, such as Salmonella spp., and thermotolerant bacterial, viral pathogens, parasitic protozoa, and helminth eggs, are usually destroyed when exposed to temperatures above 60 °C [51–53].

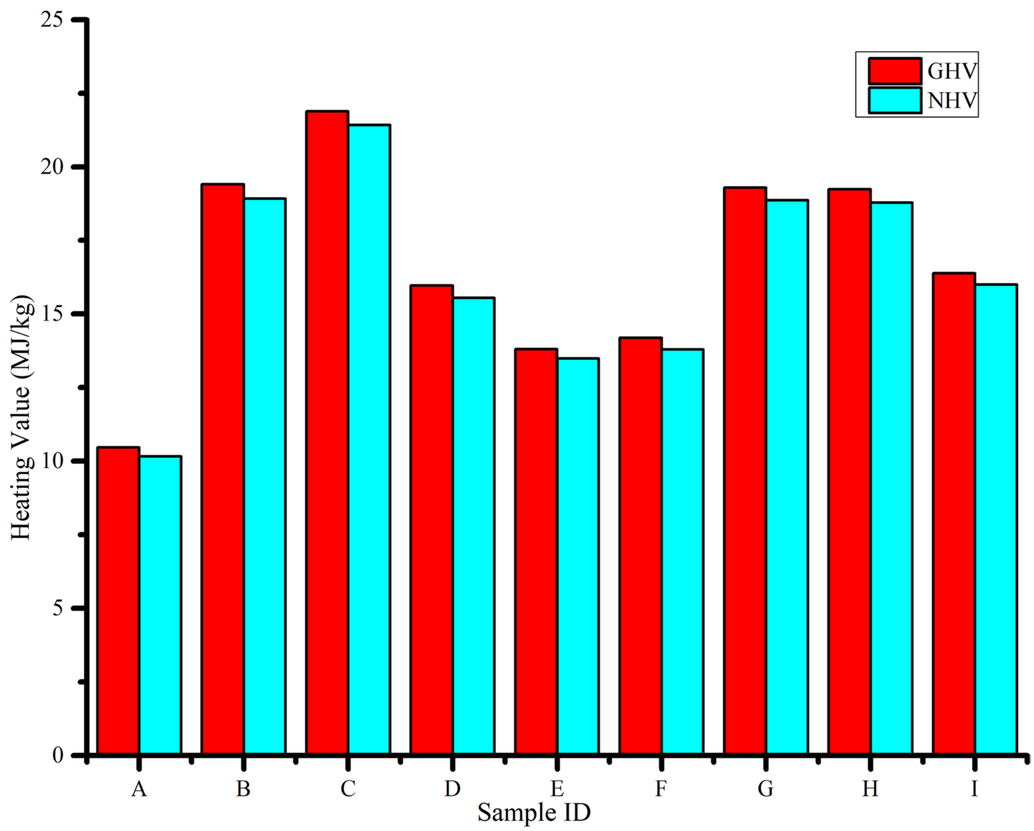

Fig. 10 Heating value (MJ/kg) of the briquettes

Table 6 Briquette bulk density and moisture content

Sample ID	A	B	C	D	E	F	G	H	I
Bulk density (g/cm^3)	1.23	0.89	0.74	0.86	1.01	1.00	0.78	0.97	0.98
Moisture Content (%)	4.87	5.52	7.37	5.78	6.80	5.90	8.50	7.29	6.11

Carbonization also immobilizes organic pollutants and heavy metals through pyrolysis, ash encapsulation, and physicochemical adsorption processes [54]. Therefore, the carbonization process is highly effective in reducing both biological and chemical contaminants in faecal waste.

The briquettes were evaluated for heating capabilities, and it was found that a higher carbon content leads to greater heating value, resulting in sustainable heat production [55]. The most effective mixing ratios were found to be 25% faecal sludge, 75% charcoal, as well as 50% faecal sludge and 50% charcoal dust, with maximum heating values (GHV and NHV) of 19.29 MJ/kg and 18.86 MJ/kg (as shown Fig. 10). These ratios also had the highest fixed carbon contents of 41.6% and 40.3%, as seen in Fig. 7. This indicates that the briquettes can generate more energy in each period, making them more efficient for variety of applications [56]. Furthermore, a higher heating value can lead to a longer and more intense burn [57]. The charcoal dust in the briquette mixture was responsible for the observed high heating values and fixed carbon content, owing to its rich carbon content.

The study found that the bulk density of briquettes is not the only factor that determine their performance. Other key factors include their composition, moisture content, and other combustion characteristics. However, bulk density still plays an important role in determining the burning efficiency and heat output [21]. The highest calorific values were observed in the briquettes made from the mixture of faecal sludge and charcoal dust, with the best results coming from the mixes containing 25% or 50% faecal sludge and the remainer charcoal dust. These briquettes had maximum calorific values (GHV and NHV) of 19.29 MJ/kg and 18.86 MJ/kg and 19.24 MJ/kg and 18.78 MJ/kg, respectively. The study found out that there was little significant difference in the briquette bulk density and moisture contents between the different mixing ratios tested (see Table 4 for more details).

The study has found that adding other types of biomass material to the faecal sludge mixture can help in reducing the ash contents and volatile matter produced, which in turn increases the combustion efficiency of the briquettes. According to Table 5, briquettes made from a mixture of charcoal dust had the lowest ash contents and volatile matter, followed by those made from sawdust and faecal sludge. These results indicate that by determining the optimal blend ratio, it is possible to overcome the operation challenges related to high ash content and volatile matter in faecal sludge briquettes, making them a more viable alternative to traditional fuel sources. It is important to note that the higher the volatile matter content of a briquette, the lower its heating value because it can contain tar, water, oxygen, hydrogen, methane, and carbon dioxide [58, 59].

The briquettes produced from the combination of faecal sludge with other biomass materials, such as charcoal dust and sawdust, showed the highest fixed carbon content. Fixed carbon is a crucial energy source that ensures a sustainable and efficient burn. The percentage of volatile matter and ash contents presented in Table 5- further support this findings [60]. Increasing the fixed carbon in the briquettes improves the burn rate and energy output. The highest fixed carbon was observed in the mixture of charcoal dust and faecal sludge (Samples G, H and I), followed by the combination of faecal sludge and sawdust (Samples D, E and F). Additionally, fixed carbon also helps bind the briquettes together, strengthening their structural integrity and performance.

The quality of the briquettes can be affected by their elemental composition, which includes nitrogen, carbon, hydrogen, and oxygen. Briquettes with a lower carbon content usually has a lower calorific value, resulting in less energy output [61]. This study showed that sample B, which contained charcoal, had the highest carbon content at 54.6%, and its mixtures (Samples C, G, H and I) produced sustainable heat and longer burning times. Additionally, charcoal dust briquettes (Sample B) and their mixtures (Sample G, H, and I) had the maximum hydrogen percentage when compared to other mixing ratios (Table 6). The presence of maximum oxygen content in these briquettes also indicates that the burn well.

Assessment was done to determine the emissions of toxic gases such as CO and CO_2, and particulate matter like $PM_{2.5}$ and PM_{10} from briquettes (Fig. 8), which result from incomplete combustion. It was found that the exposure to these harmful gases and particulate matter can be minimized by ensuring proper ventilation before use. Prolonged exposure to toxic gases like CO could lead to carboxyhemoglobin levels exceeding 2.5–3% in nonsmoking individuals. The maximum recommended exposure to CO for period not exceeding 15 min is 87.290 ppm [62]. In comparison to charcoal, faecal sludge briquettes have lower emission level of $PM_{2.5}$ and PM_{10} and TVOC as well as HCHO (Fig. 8D). Briquettes made from charcoal dust and sawdust have higher level of CO_2 emission due to their looser structure and larger surface area, leading to faster combustion and increased CO_2 release [63]. Faecal sludge briquettes are denser and more compact, which results in slower and more controlled burning, reducing CO_2 emissions.

Briquettes made from faecal sludge have a distinct advantage over those made from other biomass materials, such that they have a longer burning time, up to five hours to be exact, until completely burned to ash. This longer burning time can be attributed to factors such as the surface briquette areas, moisture contents and oxygen availability [5, 59]. Briquettes that burn longer are especially beneficial in areas where fuel source are scarce. In addition to this advantage, using faecal sludge to create briquettes is also beneficial for sanitation purposes since it promotes proper waste management.

Moreover, briquettes made from faecal sludge have a maximum compressive strength (as shown in Fig. 10), which is a crucial property that determine their resistance to deformation or breakage under applied pressure. A higher compressive strength indicates better structural integrity and durability, enabling briquettes to withstand transportation, handling, and storage without any significant damage or disintegration [64].

Conclusions

In conclusion, faecal sludge briquettes have demonstrated promising results in terms of emission levels, burning time, and compressive strength. However, they require adding other biomass materials, such as sawdust and charcoal dust, to support the ignition and burning rate. Regarding compressive strength, faecal sludge briquettes exhibited remarkable resistance to breakage caused by poor handling and were found to burn longer than charcoal and firewood, approximately 4 h long. Additionally, faecal sludge briquettes emitted the lowest levels of $PM_{2.5}$ and PM_{10}, indicating their safety for reuse in terms of particulate emissions compared to charcoal or sawdust briquettes. The study also revealed that adding charcoal dust and sawdust could enhance the performance of faecal sludge briquettes. Charcoal dust improves the calorific values of faecal sludge by increasing its carbon content and combustion efficiency, resulting in a higher calorific value and improved heat output when used as a fuel. However, when considering emissivity, compressive strength, and burning rates, the optimal mixing ratio was 75% faecal sludge and 25% charcoal dust.

Furthermore, the 25% faecal sludge and 75% charcoal dust mixture demonstrated positive results regarding percentage ash content, volatile components, and fixed carbon compared to other mixture ratios. Therefore, using faecal sludge briquettes to replace charcoal and firewood is justified due to its numerous environmental and health benefits. By converting waste into a usable fuel source, faecal sludge briquettes reduce deforestation, air pollution, and the spread of waterborne diseases. This makes it a sustainable and efficient alternative for cooking and heating needs.

This study demonstrated the feasibility of converting faecal sludge into combustible briquettes to provide an alternative cooking fuel source. The carbonization process effectively eliminated pathogens in the faecal sludge, addressing potential health risks. During cooking tests, the resulting briquettes exhibited comparable calorific value, burn efficiency, and lower emissions to conventional charcoal. Adding sawdust and charcoal dust as binders enhanced the fuel properties of the briquettes.

However, further research is required to evaluate faecal sludge briquette production's real-world viability and scalability. Assessing factors such as supply chain logistics, production costs, community acceptance, and emissions exposure will be critical before full-scale implementation. Public health safeguards must also be in place to ensure proper sludge handling.

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Author contributions
All authors have contributed substantially to the conception, fieldwork design, data collection, curation and analysis, and paper drafting. All the authors have read and approved the final manuscript.

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Availability of data and materials
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Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
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Competing interests
The authors declare that they have no competing interests.

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