



Research article

Heating and emission characteristics from combustion of charcoal and co-combustion of charcoal with faecal char-sawdust char briquettes in a ceramic cook stove

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ABSTRACT

Over reliance on charcoal has accelerated deforestation in sub-Saharan Africa. Seeking alternative sustainable and environmentally friendly sources of biomass energy to meet the escalating energy demand is therefore vital. However, limited evidence exists on the concentrations of toxic emissions of different biomass fuels. Herein, dried human faeces and sawdust were pyrolyzed at 350 °C to produce biochar and mixed in equal ratio to produce briquettes through densification, with molasses (10 wt.%) used as a binder. A comparative study on the heating properties and emission level of carbon monoxide (CO), nitric oxide (NO), and hydrogen sulphide (H₂S) during combustion of charcoal, and co-combustion (50:50 wt. %) of charcoal with briquettes was conducted. The thermal profile of the flue gases indicated rapid combustion of volatile gases followed by slow oxidation of the char. Co-combustion significantly ($P < 0.05$) enhanced the amount of heat energy released with flue gases temperatures reaching a peak of 475 °C. The briquettes had a gross calorific value of 19.8 MJ/kg which was lower than 25.7 MJ/kg for charcoal. Combustion of charcoal did not emit NO, however the concentration of CO was above the critical short term limits of 35 ppm. The concentration of CO and H₂S was above the short term exposure limits of 35 ppm, and 0.005 ppm, respectively, during co-combustion, whereas NO concentration was below dangerous exposure levels of 100 ppm. These results suggest that co-combustion of charcoal with the briquettes is a promising approach to generate safe and sufficient heat energy for cooking and reduce deforestation.

1. Introduction

The rising energy demand with the ever-growing human population is one of the major challenges facing the world today. Globally, about three billion people rely on solid biomass fuels to meet household energy demand (Quinn et al., 2018). In sub-Saharan Africa, over 90% of the rural households rely on fuelwood as the main energy source for cooking and heating (Sulaiman and Abdul-Rahim, 2020) while charcoal, which is produced by pyrolysis of fuelwood in kilns, is the principal source of energy for heating and cooking for majority of the urban households (Amoah, 2019). With the projected urban population in the African cities indicating an increase from 30% in 2000 to 60% by the year 2050 (UN-HABITAT, 2010), there is likelihood that the rise in charcoal

demand will pose an increasing pressure on forest resources of the rural areas resulting into forest degradation in sub-Saharan Africa (Sedano et al., 2016). Moreover, the already declining forest cover in the rural areas is not only affecting the natural forests but also impacting negatively on the social and economic livelihood of the rural population (Chiteculo et al., 2018). Hindrance to adoption of petroleum based fuels has been as a result of the high cost of such fuels and related cooking appliances, as well as their unreliability (Jagger and Jumbe, 2016). Therefore, seeking alternative sources of biomass energy to replace or supplement fuel wood and charcoal is of immediate concern in Africa.

Biomass conversion to different forms of bioenergy has recently attracted the attention of scientific community, policy makers, and industry advocates as a way of meeting the escalating energy demands with

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minimal carbon footprint (Reid et al., 2020). The existing biomass conversion technologies currently in the market are categorized into three pathways notably, biochemical, chemical and thermochemical (Chan et al., 2019). Briefly, biochemical conversion uses enzymes, bacteria or microorganisms to convert the biomass into biofuel (Siddiki et al., 2022) such as biogas and ethanol. On the contrary, chemical conversion technologies utilize a chemical agent to transform biomass into high energy value products, such as biodiesel which is produced through transesterification of biomass (Banerjee et al., 2019). In the thermochemical process, biomass is broken down into smaller hydrocarbon chains through controlled heating or oxidation, resulting to the production of biofuels in solid, liquid or gaseous forms (Zhang and Zhang, 2019). Of the existing biomass conversion technologies, thermochemical technology is gaining much interest among researchers compared to biochemical and chemical conversion due to the versatility of the feedstock application, product distribution (solid, liquid and gas) and product upgrading (Chan et al., 2019). The four main biomass thermochemical conversion technologies that have been widely reported are gasification, pyrolysis, liquefaction and hydroprocessing (Bora et al., 2020). Investment in a given conversion technology is however dependent of the level of technical know-how and the capital cost required. Pyrolysis which involves heating biomass material under inert atmosphere to yield a carbon-rich solid product called biochar which are energy carriers (Liang et al., 2021; Mishra and Mohanty, 2018), is considered a relatively inexpensive and simple technique operating at a relatively lower temperature of up to 500 °C and can thus be easily applied and up-scaled in low-income countries compared to the other existing thermochemical conversion techniques (Osman et al., 2021). Moreover, the technique of producing solid fuels through densification of the moistened pyrolyzed biomass materials is already adopted by many households to meet energy demands for cooking and heating (Lubwama et al., 2020). In addition, these solid fuels hereon referred to as briquettes, burn for a longer period of time and are cheaper compared to charcoal. The sustainability of bio-energy production from biomass is definitely dependent on the availability of the raw materials. Thus, seeking sustainable biomass sources for energy generation which simultaneously provide an additional benefit of environmental protection against degradation could be an attractive approach.

Human excreta are widely abundant biomass with a daily worldwide production of approximately 9.5 million m³ (Mateo-Sagasta et al., 2015). However, the treatment of faecal matter and eventual safe disposal is still a challenge in many developing countries due to inadequate coverage of sewerage systems and poor faecal sludge management (WHO & UNICEF, 2017). Bioresource recovery from human excreta is considered the most sustainable approach towards managing them. Of the existing useful resources that can be recovered from human excreta, energy recovery is the most attractive and marketable approach in developing countries (Diener et al., 2014). In Kenya, utilization of treated human faeces for production of briquettes for household use is currently practiced by sanitation entrepreneurs (www.sanivation.com). Major consumers of the briquettes made from the human faeces have been in refugee camps, urban and peri-urban areas (Karahalios et al., 2018). To sanitize human faeces for use in briquettes production, dried human faeces is pyrolyzed to generate biochar which is then moistened with binders such as starch and molasses and finally densified by applying pressure. Pyrolysis of human faeces at temperatures >300 °C can lead to: (i) complete elimination of pathogens (Atwijukye et al., 2018), and (ii) minimized oxygen containing functional groups, while also increasing the aromatic carbon content, which in turn lessens the emission of CO₂ and smoke (He et al., 2018). However, this process also lowers the calorific values of human faeces due to the degradation of energy rich aliphatic hydrocarbons with increasing pyrolysis temperature (Ward et al., 2014). Despite the degradation in energy content, the gross calorific values of human faeces pyrolyzed between 300 °C and 450 °C are within 18–26 MJ/kg (Ward et al., 2014), a range comparable to 19–25 MJ/kg of wood fuel (Ruiz-Aquino et al., 2019). Hence, blending of pyrolyzed human faeces

hereon referred to as faecal char, with other waste streams such as sawdust is recommended to improve the calorific values of the briquettes produced (Atwijukye et al., 2018).

Similarly, sawdust, a woody biomass residue generated from saw-milling activities by wood-based industries, is widely abundant in developing countries and have potential to replace energy sources such as firewood in meeting domestic energy needs (Elehinafe et al., 2017). However, only a small proportion of the residues are used as fuel because of their high moisture and low energy density (Njenga et al., 2013). It has been demonstrated that the calorific values of wood biomass such as sawdust increases with pyrolysis temperature due to an increase in their fixed carbon content (He et al., 2018). Carbonization could therefore overcome the drawbacks of using uncarbonized sawdust as a fuel source. Additionally, carbonized sawdust hereon referred to as sawdust char, could be a suitable material to blend with faecal char to improve their calorific values.

Studies involving production of briquettes by densification of faecal char and sawdust char mixed with starch or molasses binders to form durable solids for domestic heating and cooking have been reported (Aguko Kabok et al., 2018; Atwijukye et al., 2018; Ward et al., 2014). These studies have explored on the influence of organic binder types (molasses and starch), binder ratios, densification pressures, and carbonization temperatures on the combustion behaviours and heating values of the briquettes. All these studies reported that molasses at 10 wt. % was the most ideal to obtain durable briquettes at lower densification pressures. Moreover, molasses improved the heating values of the briquettes. Also, equal weight of faecal char and sawdust char (50:50 wt. %) produced desirable heating values comparable to the fuel wood. Based on these findings, our study produced the briquettes at 50:50 wt. % of faecal char and sawdust char and 10 wt. % of molasses. Despite the increasing attention on briquettes production from human faeces, studies on emission of toxic gases liberated during combustion of these briquettes have not been reported. Household air pollution associated with burning biomass fuels resulting to emission of harmful pollutants is the seventh-largest risk factor for global burden of disease (Forouzanfar et al., 2015). There is therefore need to link the briquettes quality with the level of emission of toxic gases rather than focus on combustion properties and heating values alone. A good fuel should therefore emit gases below the threshold limit value as recommended by the occupational safety and health administration (OSHA). OSHA (2010) defines threshold limit value as the upper permissible concentration limit of the gases believed to be safe for humans even with an exposure of 8 h per day, 5 days per week over a period of many years. OSHA limits are based on industrial settings, however, short term exposure limits for various toxic gases which is applicable for domestic settings are also defined by organizations such as World Health Organization (WHO), Environmental Protection Agencies (EPA), and National Institute for Occupational Safety and Health (NIOSH) (EPA, 2002; Schieb, 1976; WHO, 1981).

The scope of the present investigation is therefore to evaluate the heating and emission properties from combustion of charcoal in comparison to co-combustion of charcoal with briquettes densified from faecal char, sawdust char, and molasses. The proximate parameters (fixed carbon, volatile matter, moisture content, ash content) and calorific values of the briquettes and charcoal were determined to assess their fuel quality. The concentration of CO₂, CO, H₂S, and NO, emitted during the combustion of charcoal and co-combustion of charcoal with briquettes (50:50 wt. %) were measured during the combustion period. In addition, oxygen concentration and temperature of flue gases during the combustion period was monitored. The results from this work are expected to be helpful in providing vital information on the safety of indoor combustion of briquettes densified from sawdust char, faecal char, and molasses, and exhibiting the significance of co-combustion of charcoal with faecal char-sawdust char briquettes as a way of reducing deforestation and mitigating unsafe faecal waste disposal issues.

2. Materials and methods

2.1. Sample collection

Human faeces was obtained from a dry toilet and dried in a greenhouse for 7 days attaining constant moisture content, while sawdust was obtained from saw millers and also dried in a greenhouse for 7 days attaining constant moisture content. The charcoal used in this study was produced in a tradition kiln as is the practice in African countries. The charcoal was from acacia tree of species (*Acacia nilotica*) which is among the preferred tree species for firewood in dryland areas in Kenya (Oduor et al., 2019). Molasses used as a binder originated from a sugar processing factory.

2.2. Sample preparation and characterization

Both the dried human faeces and sawdust were pyrolyzed in an electric muffle furnace FUW232PB (Toyo Seisakusho Kaisha, Ltd) at 350 °C for 2 h under a vacuum. The resulting char was crushed and particles with $\leq 300 \mu\text{m}$ sieved and stored in air tight plastic containers. Elemental analysis (C, H, N, and O) of faecal char and sawdust char was done using elemental analyzer (AAS iCE 3300).

2.3. Briquettes production

An electronic weighing machine was used to obtain equal weights (450 g each) of both faecal char and sawdust char and then mixed homogeneously in 50:50 wt. % ratio. 100 g of cane molasses representing 10 wt. % of the overall weight was added to the charred samples and mixed homogeneously to stick the particles together. A cylindrical plastic mould of internal diameter 23 mm and height of 100 mm and a cylindrical wooden die of diameter 22 mm were used to compress the materials (15 g) fed into the mould upon application of 5 MPa pressure from a hydraulic press. With the applied pressure and the diameter of the dies, cylindrical briquettes of diameter 22 mm and height of 60 mm were ejected from the mould and dried in an oven at 104 ± 1 °C for 24 h to a constant weight.

2.4. Characterization (proximate parameters and calorific value) of briquettes and charcoal

The amount of heat energy released by burning a unit mass of the briquettes and charcoal (gross calorific value) was determined using an Oxygen bomb calorimeter (Yoshinda 1013J), while the proximate parameters (fixed carbon, volatile matter, moisture content, and ash content) were determined according to ASTM D1762-84 standard test method for chemical analysis of wood charcoal (ASTM, 1984) as detailed below;

2.4.1. Moisture content determination

Samples of the briquettes and charcoal were each weighed, and put separately in the oven at 104 ± 1 °C for 24 h after which they were removed and weighed again. The difference in weight gave the moisture content which was used to calculate the percentage of moisture present in the samples as expressed in Eq. (1)

$$M\% = \frac{m_o - m_f}{m_o} \times 100 \quad (1)$$

where $M\%$ is the percentage of moisture in the samples, m_o is the mass of the samples before oven drying, m_f is the mass of samples after oven drying.

2.4.2. Ash content determination

Samples of the dry briquettes and charcoal were each ground, weighed, and then placed in separate crucibles and heated gradually in

furnace at controlled temperatures to about 600 °C. The samples were burned until all the carbon was consumed and the residual ash attained constant weight.

2.4.3. Volatile matter determination

1 g of oven-dried specimen of briquettes and charcoal was each weighed, and then placed in separate platinum crucible with a tight-fitting lid and heated in a furnace at 930–970 °C for about 7 min while occasionally stirring with a wire. After cooling in a desiccator, the weights of the residues were taken. The loss in weight was then recorded as the weight of volatile matter in the samples.

2.4.4. Fixed carbon determination

Fixed carbon was determined according to Eq. (2) shown below:

$$\% FC = 100 - (\% Ash + \% VM) \quad (2)$$

where FC is the fixed carbon, VM is the volatile matter.

2.5. Combustion of the charcoal and co-combustion of charcoal with faecal char-sawdust char briquettes samples and monitoring the emission levels

The concentration of CO, CO₂, H₂S and NO emitted from charcoal was measured by burning 450 g of the charcoal in a small-sized energy saving cook stove called Kenya Ceramic Jiko (KCJ) as practiced by households. Co-combustion was done by burning equal amount (225 g) of charcoal and briquettes in the cook stove which amounted to a total weight of 450 g of fuel filled in the cook stove. A conical shaped chimney/stack made of aluminium metal of 1.3 m height was fabricated such that the larger diameter could fit the top of the cook stove to minimise escape of gases before sampling, while the top of the chimney was left open to allow gases to escape. A circular opening of 1 cm diameter was made on the chimney to act as a sampling pot for the gases. The height from the cook stove to the sampling pot was 100 cm E8500P industrial integrated emissions system combustion gas analyser was used to monitor the gas concentrations and gas temperatures with the sensor positioned at the sampling pot. Schematic diagram depicting the experimental set-up in shown in Figure 1.

2.6. Statistical analysis

The difference in the means of the oxygen concentrations and flue gases temperatures during the combustion of charcoal and co-combustion of charcoal with briquettes was tested using a notched box plot at 95% confidence level. The same was checked using a student t-test at 95% confidence level.

3. Results and discussion

3.1. Proximate analysis results and heating values of briquettes (faecal char-sawdust char-molasses), and charcoal

The major parameters; volatile matter (VM), fixed carbon (FC), ash content (ASH), moisture content (MC), and gross calorific value (GCV) used to assess the quality of solid fuels depicts that charcoal made from acacia tree can liberate more heat, and produce less ash making it a better fuel compared to the briquettes produced in this study (Table 1).

The higher gross calorific value of charcoal could be due to its higher fixed carbon content (He et al., 2018). Moreover, biomass fuels with low ash content have higher calorific values since the amount of heat absorbed by the inorganic fraction in ash is reduced (Hafford et al., 2018). Other studies (Carnaje et al., 2018; Saeed et al., 2021) have reported that solid fuels with lower moisture content have larger voids/pores which allow easy diffusion of oxygen from air to sustain better combustion in solid fuels consequently releasing more heat.

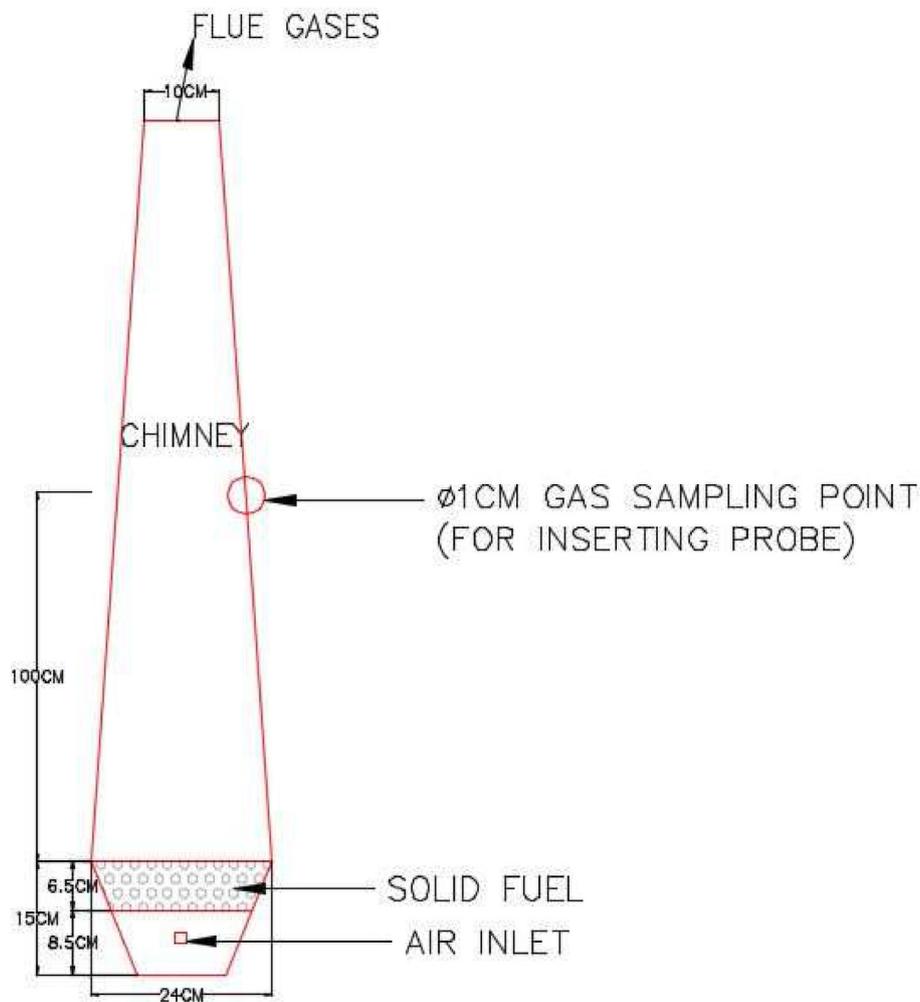


Figure 1. Schematic diagram of the combustion system.

Nevertheless, despite the briquettes having lower fixed carbon content, high moisture content, and higher ash content which lowers the calorific value of solid fuels, the reported value of 19.8 MJ/kg is comparable to 19–25 MJ/kg of fuel wood (Bulmau et al., 2010) and hence it can still provide net benefit during combustion.

Solid fuels of higher volatile matter content ignites faster (Aguko Kabok et al., 2018) and thus desirable. However, higher moisture reduces the speed of ignition of briquettes thereby necessitating pre-drying before combustion or co-combustion of briquettes with charcoal particles or wooden sticks so as to initiate the combustion process (Ngusale et al., 2014). Pre-drying may however not be practical during rainy seasons. The higher moisture content in the briquettes produced in this study could have been contributed by molasses due to its hygroscopic nature as a result of the fructose content (Palmonari et al., 2020).

3.2. Elemental composition of human faecal char, sawdust char, and molasses

The elemental composition of the main materials (faecal char and sawdust char) used in the briquette production is presented in Table 2. Properties of cane molasses reported in previous studies are also presented.

Pyrolysis of biomass materials increases their carbon content (Li et al., 2017) which consequently increases their calorific values (He et al., 2018). Faecal char had lower carbon content than sawdust char and therefore blending the two materials could produce a solid fuel with higher calorific value than faecal char. The nitrogen content in faecal

char was also observed to be higher compared to sawdust char, a property that can be attributed to the presence of proteins in faeces that constitute the larger fraction of nitrogenous compounds in faecal mass (Rose et al., 2015). Nitrogen content in human faeces can however be significantly reduced by increasing pyrolysis temperature that consequently causes degradation of proteins (Yahav Spitzer et al., 2018). It was also noted that sulphur content in faecal char and sawdust char are negligible which makes them safe in terms of sulphur emission during combustion. Although the study did not characterize molasses, other researchers (Dirbeba et al., 2021; Zhai et al., 2018) have reported that can molasses contains sulphur and therefore it could be a contributor of sulphur containing gases during combustion of briquettes produced in this study.

3.3. Concentration of flue gases (CO_2 , CO , H_2S and NO) from combustion of charcoal and co-combustion of charcoal with faecal char-sawdust char briquettes

The profile of flue gases emitted against combustion time is presented in Figure 2. The concentration of the gaseous emissions increased rapidly after ignition up to a peak and then declined sharply. This depicts an increase in burning rate after ignition resulting to an increase in the amount of gases liberated. The combustion rate of biomass however declines once significant portion of the organic fraction in the biomass fuel have been oxidised coupled with agglomeration of incombustible ash on the outer layer of the fuel particles thereby blocking the pores which consequently affects the flow of oxygen in the fuel mass

Table 1. Proximate analysis results and heating values of briquettes and, charcoal.

Fuel source	Proximate analysis				Heating value (MJ/kg)
	VM	FC	ASH	MC	
Briquette	16.9 ± 0.1	62.7 ± 0.4	12.3 ± 0.5	7.1 ± 0.6	19.8 ± 0.1
Charcoal	14.4 ± 0.3	76.2 ± 0.1	4.2 ± 0.2	5.2 ± 0.2	25.7 ± 0.2

(Al-Shemmeri et al., 2015; Ryu et al., 2006). Noteworthy is the sudden rise in the amount of flue gases liberated after the declining phase in both set-ups. This was as a result of the shaking of the cook stove so as to shed off the incombustible ash fraction that had formed and agglomerated on the surface of the solid fuel particles during combustion, consequently allowing more heat and gases to be liberated.

Release of CO₂ results from complete combustion of fuel and therefore not regarded as a pollutant while CO which is a product of incomplete combustion, is toxic to human health (EPA, 2002; Townsend and Maynard, 2002). The amount of CO and CO₂ released during combustion is influenced by a range of factors. For instance, Kim et al. (2021) in their attempt to compare emission from different briquettes attributed the lower CO and CO₂ emission from combustion of briquettes densified from spent coffee grounds to their less carbon content (46.1–54.9 wt. %) compared to the anthracite briquettes (75.23 wt. %). High moisture content in biomass fuel also reduces oxidation reactions during combustion hence significantly increasing CO emission while CO₂ emission slightly declines due to the reduced dry biomass per kg of the fuel (Bhattacharya et al., 2002). Thus, the higher moisture content of the briquettes could have contributed to the higher CO emission during co-combustion with charcoal. Combustion of the charcoal and co-combustion of charcoal with briquettes caused CO concentrations above the critical limit of 35 ppm allowed for human exposure for 1 h (EPA, 2002). It can be recommended that proper ventilation is necessary when the fuels are used for indoor heating to enhance oxidation of the carbon content in fuel.

Liberation of H₂S during fuel combustion has been reported to be as a result of reduction of SO₂ that is formed due to oxidation of compounds containing sulphur in the fuel. For instance, Shirai et al. (2013) observed

that during coal combustion in a furnace, SO₂ released reacts with H₂ to form H₂S and H₂O as shown in Eq. (3)



Study by Ryason and Harkins (1967), also reported that the SO₂ in flue gases released during coal combustion in a furnace reacts with carbon monoxide to form CO₂ and elemental sulphur as depicted in Eq. (4)

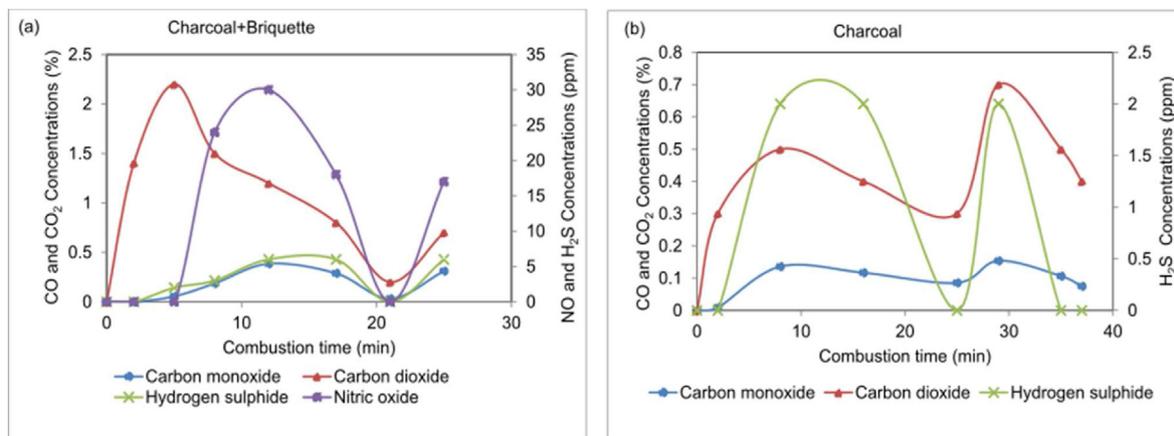


Based on WHO short term (30 min), H₂S odour guidelines (WHO, 1981), it can be stated that combustion of faecal char-sawdust char briquettes could cause more discomfort throughout the combustion duration by liberating offensive odours since H₂S concentration was >0.005 ppm as opposed to combustion of charcoal which only exhibited short lived peaks. Moreover, the briquettes could cause other health effects such as coughs, throat irritation and low oxygen uptake as had been reported by Bhambhani and Singh (1991) since the emission was above 2.5 ppm. Other than health effects, H₂S poses a challenge of corrosion of metal wares (Malone Malone Rubright et al., 2017).

Whereas, combustion of charcoal did not liberate nitric oxides (NO), co-combustion of charcoal with briquettes liberated NO throughout the combustion period. Nitric oxides are mainly formed during combustion of solid fuels as a result of oxidation of the organic nitrogen (fuel-N) that they contain (Aho et al., 1995; Zevenhoven and Kilpinen, 2001). Prompt NO and thermal NO may also form from atmospheric molecular nitrogen (N₂) during combustion. However according to Hayhurst and Lawrence (1996), formation of prompt NO which normally result from reaction between N₂ and hydrogen radicals from the fuel is small. The formation

Table 2. Elemental composition of human faecal char, sawdust char, and molasses.

Feedstock	Pyrolysis Temp (°C)	%C	%H	%N	%S	%O	References
Human faeces	350	55.3	5.8	3.1	–	35.8	This study
Cyprus wood sawdust	350	78.2	4.6	1.1	–	16.1	This study
Cane molasses		37.9	5.2	0.5	1.4	42.6	(Dirbeba et al., 2021)
Cane molasses		47.40	7.87	2.63	0.33	41.97	(Zhai et al., 2018)

**Figure 2.** (a) Emissions from co-combustion of charcoal with faecal char-sawdust char briquettes, and (b) emissions from combustion of charcoal.

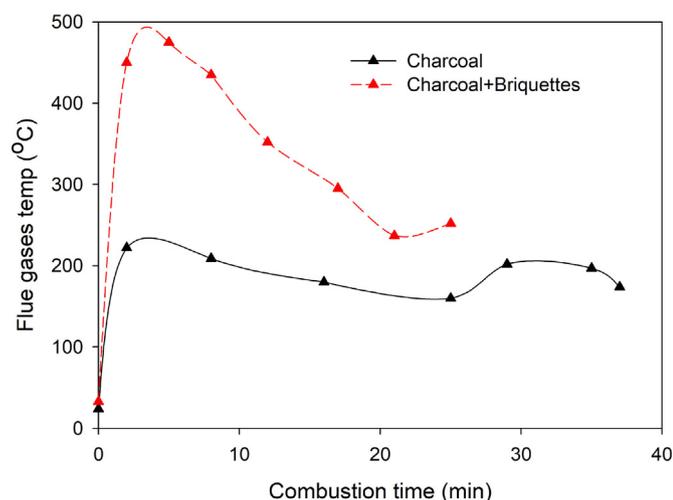


Figure 3. Variation of flue gases temperatures with combustion time.

of thermal NO on the other hand occurs at very high temperatures (≥ 1300 °C), since thermal dissociation of N_2 to N radicals is needed to start NO formation (Saastamoinen and Leino, 2019). The highest temperature (475 °C) attained during the co-combustion of briquettes with charcoal in this study could not result to the release of thermal NO. The briquettes therefore released NO majorly as a result of oxidation of the organic nitrogen contained in the faecal char. According to NIOSH exposure limits, it can be reported that no immediate health hazard due

to NO can be posed by combusting the briquettes produced in this study since the peak emission of 30 ppm recorded was <100 ppm (Schieb, 1976). It is also worth noting that although oxygen was measured in the flue gases, oxidation of NO to NO_2 gas was not observed. Formation of NO_2 requires reaction between hydrogen peroxide radical (HO_2) and NO which can only occur when in the cooler zones of the flame or when rapid cooling of the flame occurs (Aho et al., 1995; Glarborg et al., 2018; Zevenhoven and Kilpinen, 2001). Furthermore, NO_2 rapidly decomposes back to NO if it moves to the hot parts of the flame (Aho et al., 1995). Cooling process does not exist in a furnace or in the experimental set-up adopted in our study and thus possibly the reason as to why NO_2 wasn't detected. NO_2 is therefore mostly formed under normal ambient conditions in the atmosphere (Saastamoinen and Leino, 2019).

3.4. Variation of flue gases temperatures with combustion time

The thermal profile depicted during combustion of charcoal and co-combustion of charcoal with briquettes is presented in Figure 3.

It can be seen from Figure 3 that after ignition, a sudden rise in temperature of flue gases occurs for all the combustion set ups followed by a sharp decline in temperature and finally a gradual temperature loss as combustion proceeds towards the end. Al-Shemmeri et al., (2015) made similar observation in a study on combustion of various biomass fuels in a small-scale biomass combustor. The authors attributed the sudden rise in temperature of flue gases up to a peak to the combustion of volatile gases, which is immediately followed by a reduction in the calorific content of the fuel resulting to the sharp decline in the flue gases temperature since they are carriers of the significant proportion of the

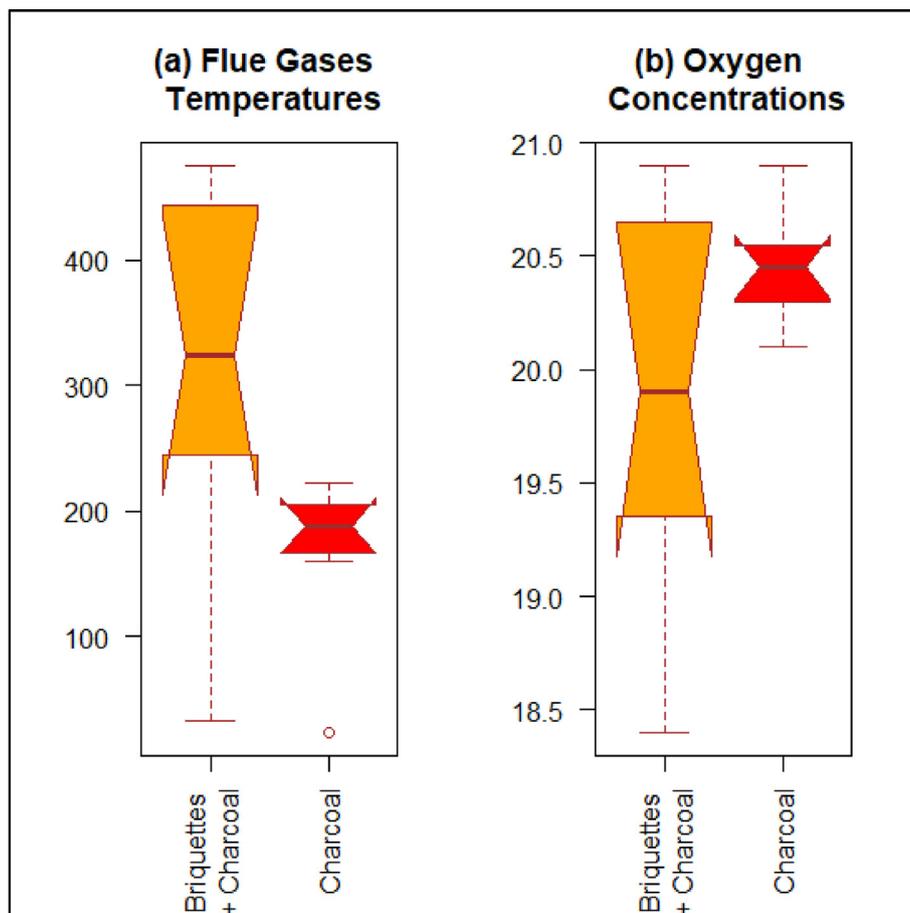


Figure 4. Notched box plots of (a) Flue gases temperatures during co-combustion of briquettes with charcoal and combustion of charcoal, (b) Oxygen concentrations during co-combustion of briquettes with charcoal and combustion of charcoal.

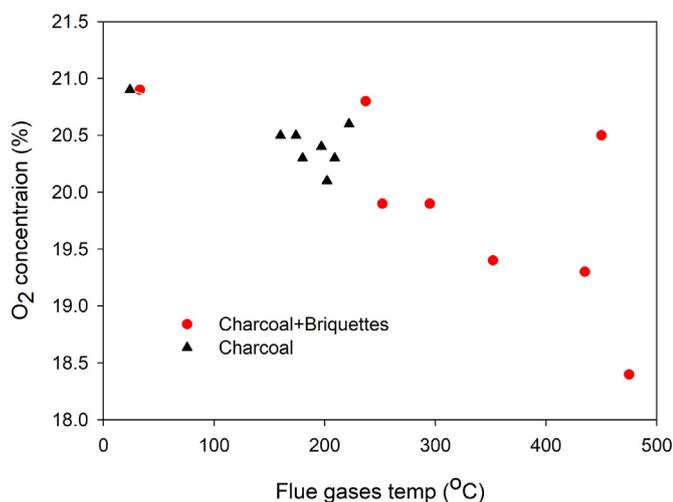


Figure 5. Variation of flue gas temperatures with oxygen concentrations.

heat liberated during combustion. The authors further explained that the gradual decline in temperature of flue gases after the combustion of volatile gases as the fuel diminishes is associated with oxidation of char which is a slow process compared to rate of combustion of volatile gases, resulting in longer periods of combustion before the formation of ash. Other studies (Borowski et al., 2017; Pilusa et al., 2013) with similar thermal profile obtained during combustion of briquettes ascribed the variations in the heat content of the flue gases during combustion of the fuels to heterogeneous complex reactions occurring during combustion of biomass materials. It was also evident that the peak temperature (475 °C) of flue gases liberated during co-combustion of briquettes with charcoal was higher compared to 222 °C attained during combustion of charcoal. This is an indication that synergistic complex thermochemical interactions occurs during biomass co-combustion. Statistical test of the means of the temperatures of the flue gases liberated using both notched box plot (Figure 4a) and student t-test showed that there existed significant ($P < 0.05$) differences during combustion in both set-ups which depicts that co-combustion of briquettes with charcoal enhanced the amount of heat released.

3.5. Variation of oxygen concentration with combustion temperatures of flue gases

Variation of oxygen concentration with combustion temperatures of flue gases is shown in Figure 5.

From Figure 3, a decline in O₂ concentration in the flue gases occurred with increase in temperature. Oxidation of hydrocarbons to form gases is an exothermic process (Ren et al., 2019) therefore, higher oxygen consumption resulted to higher heat energy content liberated and which are consequently carried by the flue gases in the chimney. Similar observation was reported from combustion of eco-fuel briquettes (Pilusa et al., 2013). An increase in O₂ concentration in flue gases is expected as the fuel combustion nears completion since most hydrocarbons will have been oxidised. Statistically, the means of the oxygen concentrations in the flue gases at different temperatures in both set-ups were not significantly ($P > 0.05$) different as depicted by the notched box plot (Figure 4b), which corroborated the results of the t-test. This implies that co-combustion of briquettes with charcoal is beneficial in provision of higher heat energy than combustion of charcoal without consuming significantly higher amounts of oxygen.

4. Conclusion

This study aimed at evaluating the heating and emission properties from combustion of charcoal in comparison to co-combustion of charcoal

with briquettes densified from faecal char, sawdust char, and molasses. The thermal profile of the flue gases after ignition of samples in both set-ups showed that the thermal decomposition occurred in two major steps: (i) combustion of volatile gases, and (ii) oxidation of char before eventual ash formation. Co-combustion of charcoal with briquettes released significantly ($P < 0.05$) higher heat energy than in combustion of charcoal as evidenced by flue gas temperature reaching a peak of 475 °C and 222 °C, respectively, an indication of synergistic complex thermochemical interactions occurs during biomass co-combustion. The gross calorific value of 19.8 MJ/kg for the briquettes were comparable to those reported for fuel wood although lower than for charcoal of 25.7 MJ/kg used in this study, an indication that they could still provide net benefit as source of energy for heating. Co-combustion of briquettes with charcoal released higher concentration of CO, CO₂ and H₂S than in combustion of charcoal. Also, combustion of charcoal did not emit NO while during co-combustion, NO was liberated, an observation attributed to the fuel-N content in human faeces. Thus, properties of the raw materials influence the heating and emission properties of solid fuels. This study provides useful data on the potential of human faeces and sawdust in production of safe fuel of sufficient energy for indoor use to reduce charcoal consumption and also mitigate environmental degradation.

Declarations

Author contribution statement

Austine O. Otieno: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper. Anthony Gachanja: Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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