

Performance of Composite Fecal Sludge-Biofuel in Improved Cook Stoves

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Abstract

This study tested the performance of fecal sludge - saw dust biofuel briquettes (FssDbb) in three commonly used cook stoves in Kenyan households by the standardized Water Boiling Test (WBT). The governing briquettes physical characteristics obtained were; calorific value (25.93 MJ/Kg), ash content (26.7%), fixed carbon (51.3%), moisture content (5.49%) and volatile matter (15.9%). The fuel had good burning characteristics (fuel consumption, CO₂, CO, specific fuel consumption, thermal efficiency, burning rate and time to boil) indicated by the cook stoves. Based on the findings, the product performance was identified as a suitable alternative to conventional fuel for households. A preliminary market study confirmed the viability of introducing the briquette fuel product in the Nakuru market.

Keywords: Briquettes; Performance; Cook stoves; Adaptability; Water boiling test

Introduction

There has been a quest to develop efficient, environmental friendly, safe and sustainable energy technology methods (cook stoves) together with alternative biomass fuels using locally available materials. The Nakuru Water and Sanitation Services Company (NAWASSCO) and partners implement the Nakuru County Sanitation Programme (NCSP) [1] and developed the innovative FssDbb using sludge obtained from septic tanks, pit latrines and combined with sawdust from within the township. Technologies testing have been one of the crucial activities for the performance indicators of the alternative biomass fuels and cook stoves. The study is a follow-up on the briquette product (FssDbb) development (design) process and aims at testing the performance with different types of cook stoves for house hold use. The fuel briquettes are designed and intended for both household and institutional use. After briquette development [2,3], the water boiling test was carried out using Kenya Ceramic Jiko (KCJ), Jiko Koa and Envirofit super at the University of Nairobi laboratories using the WBT as outlined in the International Workshop Agreement (IWA) framework for cook stove testing. The test is in response to a number of developed cook stoves and improved biomass fuels that call for testing their efficiency and efficacy.

A high percentage of households in developing countries use biomass fuel such as charcoal and firewood as their main source of household energy. Past studies [4] have linked traditional methods of consumption of biomass fuel, for example cooking with firewood and charcoal; with low efficiency, negative environmental consequences, including high rate of desertification due to cutting of trees, and increase in carbon emissions. NCSP conducted a market study in the Nakuru town area both by qualitative (focus groups discussions) and quantitative (Akvo Flow survey tool) methods. This was to determine the market size and the suitability of the fecal sludge related biofuel products for the Kenyan market.

Methodology

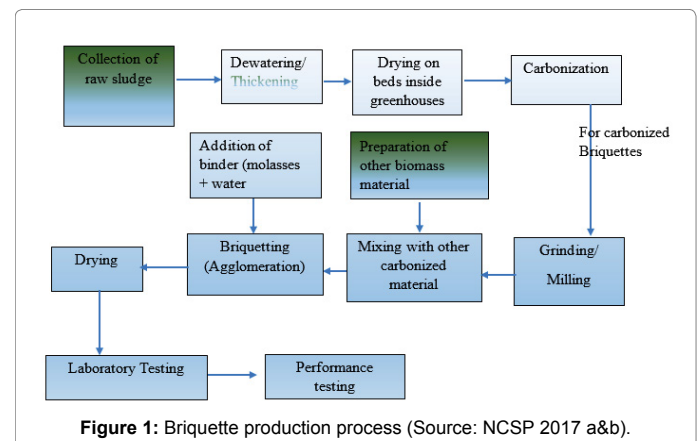
Briquette production

The briquettes were made using fecal matter, sawdust, and charcoal dust (FssDbb) at a ratio of 1:1:2 and 5% molasses as a binding agent. The blend was chosen after a previous NCSP research where several tests were performed on raw materials and with different binding agents. The

bio-fuel products were made using carbonized raw materials (sludge, sawdust and charcoal dust), produced by using improved drum kilns, agglomeration with a rotating drum and the output spherical fireballs were open air dried [2,3]. The briquette making process is as shown in Figure 1.

Selection of cook stoves

The FssDbb performance was tested by applying the standardized WBT using three commonly used varieties of cook stoves in Kenya to provide a basis for comparison of the new fuel relative to the existing fuels. The tests were guided by the international organization for standardization (ISO) framework for testing cookstoves based on four specific parameters; efficiency, indoor emissions, total emissions and safety. The frame work provides for categorization of cook stoves into



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five tiers (0-4), where tier 0 is the lowest and tier 4 with the highest performance [5]. The commonly used cook stoves for the target test market (households within Nakuru County), were selected with the following details:

KCJ: Is a commonly used Jiko within Nakuru County. In a previous study [6] it was identified to have a good rating in thermal efficiency with low fuel consumption especially in the low power phase (long duration cooking) when different types of cook stoves were compared. It is thus the most preferred cook stove in a majority of low income households in urban and peri-urban areas in Kenya.

Jiko koa: The cook stove is an industry produced standard model with no variation and is an improved cookstove which is second in penetration in the Kenyan market.

Envirofit super: Is a cook stove on the list of emerging improved technologies.

Water boiling test

The WBT tests were undertaken at the University of Nairobi laboratory and repeated three times as in the standardized protocol. The tests were done for efficiency and emission of cook stoves in a controlled laboratory setting that consisted of three phases; Phase 1 (High power-Cold start), Phase 2 (high power-Hot start) and Phase 3 (Low power-Simmering). The FssDbb were used as fuel for the three categories of cook stoves. The parameters determined included emission of carbon dioxide (CO₂), carbon monoxide (CO), time to boil, burning rate, thermal efficiency, specific fuel consumption, fuel consumption and amount of particulate matter as in the following subsections.

Performance and efficiency testing

The performance testing encompassed time to boil, specific fuel consumption (sfc), thermal efficiency and burning rate as is described in the (WBT) with brief definitions as below:

Time to boil: is the time (t) in minutes taken to bring water to boil.

Specific fuel consumption: Is the amount of solid fuel equivalent used in achieving a defined task divided by the weight of the task, that is, the amount of fuel needed to boil 1 kg or 1 liter of water when starting from a cold cook stove and also is applicable in the other phases, expressed as:

$$\text{Specific Fuel Consumption} = \frac{\text{Mass of fuel burnt (kg)}}{\text{Mass of boiled water in the pot (kg)}}$$

Fuel consumption: Is the amount of fuel in grams that is consumed in bringing the water to boil and is calculated by subtracting weight of dry fuel after water boils from the dry weight of fuel before ignition.

Thermal efficiency: Is the extent to which a cook stove transfer's heat to the pot when cooking or the portion of heat utilized in directly heating the cooking pot until water reaches boiling point. The remaining portion of heat is lost to the surrounding environment and is represented by the following formula:

$$hc = \frac{(\Delta E_{H_2O} + E_{H_2O\text{evap}})}{E_{\text{released,c}}}$$

Where: Energy required to boil water ($E_{H_2O,Heat}$) equals to mass of water (M_{H_2O}) multiplied by specific heat capacity (C_p) and by change in temperature (Δt) given in equation

$$\Delta E_{H_2O,Heat} = m_{H_2O} \times C_p \times \Delta T$$

C_p is estimated at 4.186 KJ/KgK

Where; W_{vc} is mass of water evaporated and $\Delta h_{H_2O,fg} = 2,260 \text{ KJ/Kgk}$

Energy released is equal to mass of fuel (M) used multiplied by heating value (HV)

$$E_{\text{released,c}} = F_{CD} \cdot LHV$$

Burning rate: Is the weight of fuel consumed (F_{cd}) divided by the time (Δt_c) taken to boil the water or the consumption of fuel when water is brought to the boiling point.

$$R_c = \frac{F_{cd}}{\Delta t_c}$$

Specific fuel consumption (SC_{cold}): Is the amount of fuel that is needed to produce 1 unit of output. In this case output is boiled water. In the high power cold starting the specific fuel consumption is the amount of fuel that is needed to boil 1 kg or 1 liter of water when starting from a cold cookstove. The same formula is used in the high power hot star calculated as:

$$SC_{\text{cold}} = \frac{F_{cd}}{W_{cT}}$$

Fuel consumption: Is the amount of fuel in grams that is consumed in bringing the water to boil. It is calculated by subtracting weight of dry fuel after water boils from the dry weight of fuel before ignition.

$$F_{\text{Consumed}} = F_{\text{coldstart}} - F_{\text{boil}}$$

Emission testing

Involved measurement of concentration and composition of Carbon Monoxide (CO), Carbon Dioxide (CO₂) as well as Particulate Matter or generally the emissions form the exhaust fumes. Emission testing is part of WBT protocol version 4.2.3.

Exhaust carbon concentration (CO₂ and CO): Includes the carbon atoms in Carbon Dioxide (CO₂), Carbon Monoxide (CO) and carbon content in particulate matter (PM). The measure determines the carbon atoms in the cook stove exhaust fumes as;

$$CC_c = CO_{2\text{carbonic,c}} = CO_{\text{Carbonic}} + PM_{\text{Carbonic}}$$

A molecule of Carbon Dioxide or Carbon Monoxide contains 1 atom and are determined respectively by the following formulae

$$CO_{2\text{carbonic,c}} = CO_{2c} - CO_{2b}$$

$$CO_{\text{carbonic,c}} = CO_c - CO_b$$

Particulate matter: In exhaust fumes is calculated by equation 10 and is assumed to contain 80 percent carbon, based on WBT.

$$PM_{\text{carbonic,c}} \left[\frac{\mu\text{g}}{\text{m}^2} \right] = 0.8 \cdot (PM_c - PM_b)$$

Findings and Discussions

The results of an average of WBT laboratory tests for the three phases are outlined in sections 3.1 to 3.3 consisting of tables and figures for results illustrations.

Phase 1-cold start

The findings for phase 1 tests are as shown in Table 1. Based on Table 1 and Figure 2a; Cook stove A, was only best in burning rate and equivalent to C. Cook stove B; was best in time to boil, CO, CO₂, and particulate matter. Cook stove C, was best on thermal efficiency, specific fuel consumption and fuel consumption. Overall as in Figure 2b; the performance of Cook stove B was the best based on its low emission except for time to boil, burning rate, specific fuel consumption, thermal efficiency and fuel consumption. Cook stove A was second best in performance for two of the emission parameters while C was best on CO as a parameter though almost comparable to A and highest volume of carbon dioxide and particulate matter. Cook stove B would then be selected based on emissions as A and C were better in thermal efficiency in the range of 20%-50%.

Phase 2-hot start

The findings for phase 2 tests are as shown in Figure 3a and Table 2 that shows the performance of the cook stoves in the high power, hot-start phase. Cook stove A was outperformed by the other cook stoves in regard to time taken to boil, thermal efficiency and high fuel consumption. Cook stove B was rated second in all the parameters but comparable to C on emission parameters. Overall, Cook stove C outperformed the other cook stoves in all aspects during the high power hot start phase. The good performance was notable in low burning rate, high thermal efficiency, and low fuel consumption. Statistically B and C would be in the same range.

Figure 3b shows the results of emission tests for the three cook stoves. Cook stove A produced the highest amount of carbon monoxide and carbon dioxide followed by Cook stove B. This is unlike Cook stove C whose performance was best in CO and CO₂ emissions and highest in Particulate Matter. It was comparatively better in the hot-start phase for both fuel performance and emissions.

Parameters	Units	Cook Stoves		
		A	B	C
Time to boil	Min	31	15	20
Burning rate	g/min	8	14	8
Thermal efficiency	%	19	16	24
Specific fuel consumption	g/liter	110	86	71
Fuel consumption	g	270	217	180
CO	Ppm	67	41	55
Particulate	µg/m ³	108	98	180
CO ₂	Ppm	344	331	402

Table 1: Briquettes performance in Phase 1-Cold start.

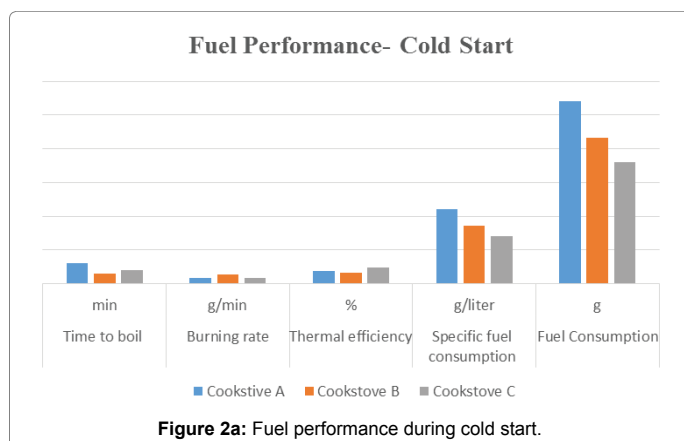


Figure 2a: Fuel performance during cold start.

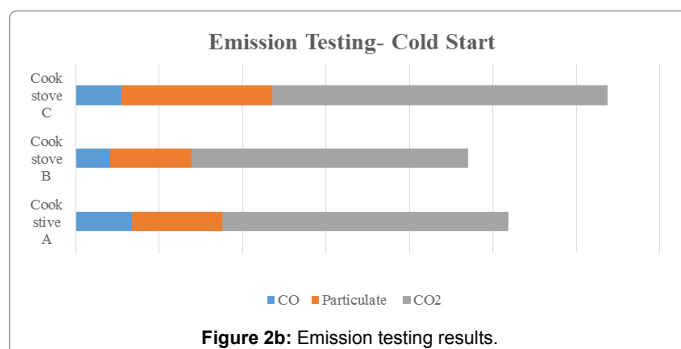


Figure 2b: Emission testing results.

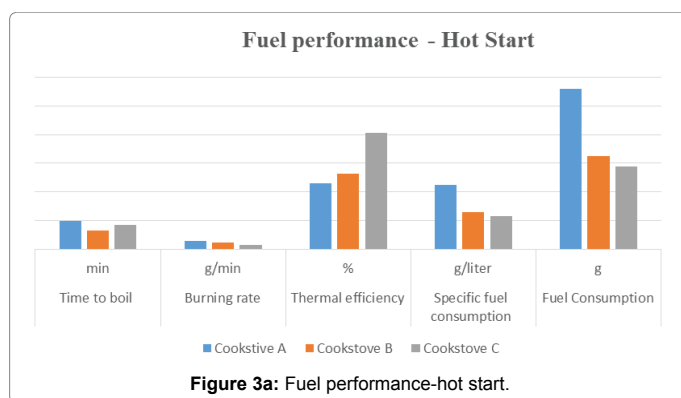


Figure 3a: Fuel performance-hot start.

Parameters	Units	Cook stove A	Cook stove B	Cook stove C
Time to boil	Min	20	13	17
Burning rate	g/min	6	5	3
Thermal efficiency	%	46	53	81
Specific fuel consumption	g/liter	45	26	23
Fuel consumption	g	112	65	58
CO	Ppm	54	42	25
Particulate	µg/m ³	34	46	47
CO ₂	Ppm	336	333	326

Table 2: Briquettes performances in phase 2-Hot start.

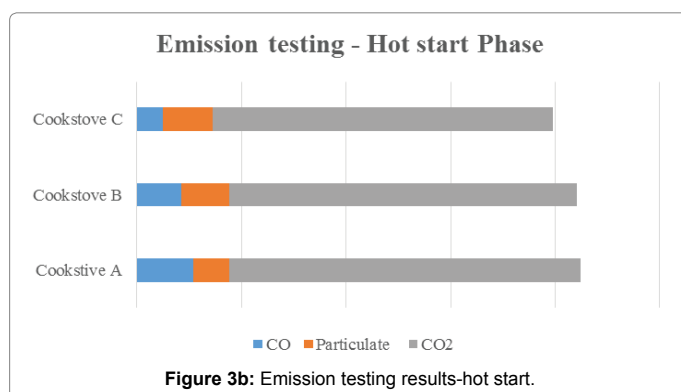


Figure 3b: Emission testing results-hot start.

Phase 3-simmering

The findings for phase 3 tests are as shown in the Table 3 and Figure 4a below that shows the results for fuel performance in the low-power simmer phase. The time to boil and burning rate were similar for the three cook stoves. However, the performance of B was second to C in most cases except in thermal efficiency and CO₂. Notably, Cook stove C outperformed all except on Particulate Matter.

Figure 4b is the results of emission testing in the simmer phase. Cook stove A produced the highest amount of carbon monoxide and the reverse was true for Particulate Matter emission. Overall, Cook stove C outperformed the other two in this phase and Cook stove B and A shared equal second position in different parameters. Cook stove B had the highest emission in CO₂. Though Cook stove C was better in all parameter performance, Cook stove A and B showed mixed results.

Table 4 and Figure 5 are given to illustrate and compare the physical performance of lump charcoal (original charcoal that is made by burning logs of wood) and the FssDbb that was tested in the above results and discussions. The charcoal results are from a prior University of Nairobi laboratory test. The variation in the results may be attributed to preparation before testing, the machine for briquetting and the equipment for the testing. It can be noted that specific fuel consumption, CO₂ and CO are within the recommended standards as in Table 4 of the identified reference standards. Time to boil and Particulate Matter are above the range specified. The density and ash

Parameters	Units	Cookstove A	Cookstove B	Cookstove C
Time to boil	Min	45	45	45
Burning rate	g/min	2	2	2
Thermal efficiency	%	66	59	87
Specific fuel consumption	g/liter	72	59	51
Fuel Consumption	g	118	102	86
CO	Ppm	47	44	25
Particulate	µg/m ³	19	32	46
CO ₂	Ppm	206	229	194

Table 3: Briquettes Performances in Phase 3-Simmering.

Briquette Characteristics	Charcoal Source : University of Nairobi Lab	Fecal sludge Briquettes	Standard Values
Moisture Content	6.2	5.49	<12%
Density	-	-	1000-1400 kg/m ³
Ash Content	1	26.7	0.70%
Volatile Matter	10.6	15.9	35%
Fixed Carbon	82.1	51.3	58.13%
Calorific Value	29.8	25.93	17.5 MJ/kg
Specific Fuel Consumption	-	as above	228 g/l
Burning Time	-	as above	14.94 min
Carbon dioxide	-	as above	5000 ppm
Carbon monoxide	-	as above	50-200 ppm
Particulate Matter	-	as above	25 mg/m ³

Table 4: Reference standards.

content were not within limits but the rest of the physical quantities (moisture content, volatile matter, fixed carbon, and caloric value) met the standards in Table 4 for the faecal sludge.

Marketing of Faecal Biomass Fuel

Charcoal is confirmed the main type of fuel used by a majority of households in Kenya and is followed by kerosene and natural gas [7-11]. A market study [1,6] was conducted to establish customer views and attitudes on faecal briquettes and fuel pellets (362 households and 238 businesses/institutions). Perception towards the product was expected to be adverse but households were found to respond positively towards faecal matter briquettes. This was influenced by household assurance on safety of the product through understanding of the production process. Consumer education is thus recommended before introducing the products.

In addition, research should be carried out on stoves to optimise performance of briquettes and marketing [1,6]. It was further noted that there is a tendency for switching of fuels in households with charcoal as the immediate alternative fuel in peri urban areas. Natural gas is ranked top followed by firewood, kerosene and charcoal. The study showed that eighty% of the population were positive about using briquettes made from different biomass wastes including human waste and were more appealing among low-income households. The level of satisfaction with a particular type of fuel is based mostly on factors such as performance, cost and cleanliness (user friendliness). Smoke emission becomes a major cause of dissatisfaction.

Likewise, majority of household's choice of equipment is driven by cost, efficiency and level of smoke emission. The preferred technology for most households was Kenya Ceramic Jiko (KCJ) with Jiko Koa being perceived as efficient although more expensive. To fuel vendors, cost would be a crucial factor as market awareness of alternative fuel

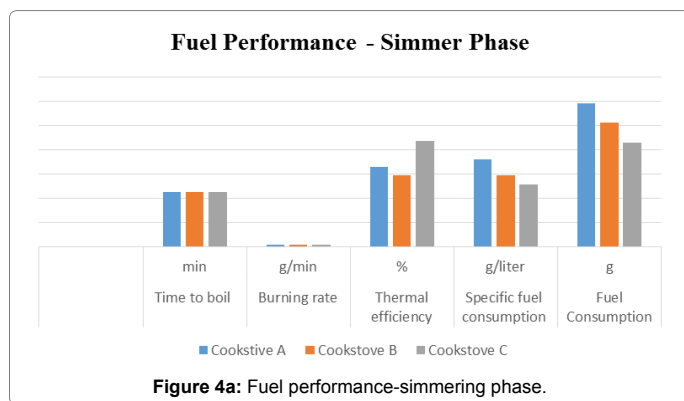


Figure 4a: Fuel performance-simmering phase.

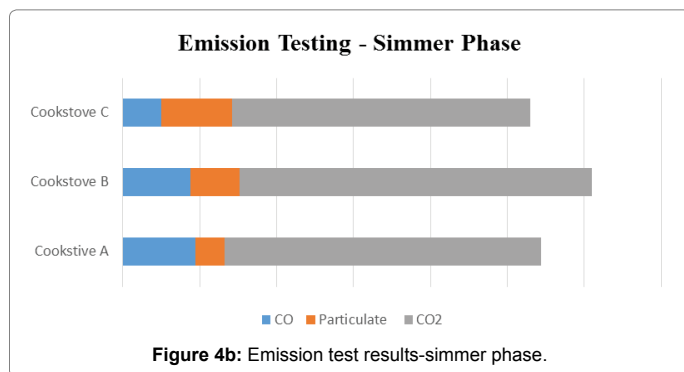


Figure 4b: Emission test results-simmer phase.

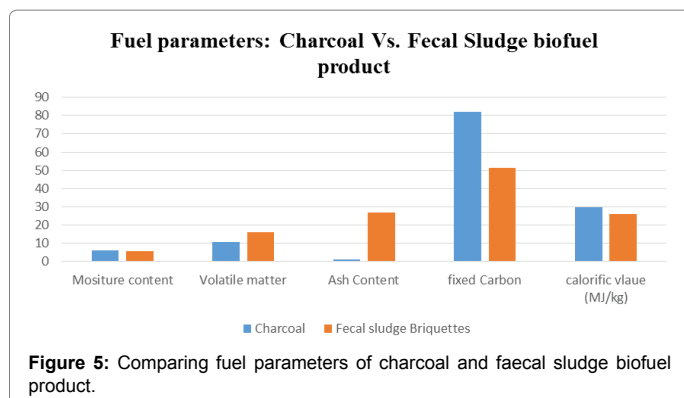


Figure 5: Comparing fuel parameters of charcoal and faecal sludge biofuel product.

(mainly biomass briquettes) was also noted as good. On average, households spend approximately Ksh. 1,323 on purchase of equipment and use approximately Ksh. 1,110 on fuel per month. Consumers proposed packaging in small quantities of 2 kg or 5 kg packets [1,6] and pricing of briquettes to be less than half a dollar per 1 kg.

WBT showed that faecal matter briquettes burnt longer than charcoal and had less emissions and majority of the household's cook in confined places that are without defined kitchen space thus prone to indoor pollution [12]. Briquettes were positively received more than pellets due its compatibility with their fuel equipment and cost efficiency. The households indicated preference to purchase the fuel but this was dependent on household's income.

Conclusion

Briquettes made from a combination of carbonized faecal matter (25%) and sawdust (25%) and charcoal dust (50%) were found to feasible with both Jiko Koa and KCJ cookstoves and are the most common types in the market. The performance of cook stove type A when using fecal sludge biofuel product lagged behind B and C in all the Phases of the WBT tests. The performance of the fuel in the three cookstoves improved from high power phase to Low power phase. Cook stove C was best in all the phases considering the thermal efficiency, specific fuel consumption and fuel consumption. This makes the fuel suitable for cooking food that takes less time to cook as well as for those that takes relatively long time to prepare. Overall Cook stove B was performed better in phase 2. Low briquettes consumption indicated that the faecal matter briquettes are an efficient form of fuel. Burning rate and fuel consumption indicates that the fecal sludge - sawdust briquettes burn for a long period of time which makes the fuel suitable for cooking any type of food. Based on the parameters in the tables and the figures, Cook stove C (Envirofit) performed better followed by Cook stove B (Jiko koa - though preferred) and least was Cook stove A (KCJ) with FssDbb product. High thermal efficiency for the phases indicated that the heat generated was utilized well for the task that was intended. Emissions recorded were relatively low but requires that the stoves should be used in well-ventilated places.

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