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Energy for generations

SEEK: Fuel performance of faecal sludge briquettes in Kampala, Uganda

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Acronyms and abbreviations

Acronym	Term or definition
ASTM	American Society for Testing and Materials
CEDAT	College of Engineering, Design, Art and Technology
CI	confidence interval
CO	carbon monoxide
CO2	carbon dioxide
COV	Coefficient of Variation
CREEC	Centre for Research in Energy and Energy Conservation
g	gram
GACC	Global Alliance for Clean Cookstoves
ISO	International Standards Organisation
IWA	International Workshop Agreement
Kcal	kilocalorie
kJ	Kilojoules
kg	kilogram
kW	kilowatt
l	litre
m	meter
mg	milligram
min	minute
MJ	megajoule
MJd	megajoule useful energy delivered
PM2.5	particulate matter with an aerodynamic diameter ≤ 2.5 microns
PCIA	Partnership for Clean Indoor Air
RTKC	Regional Testing and Knowledge Centre
SEEK	Sludge to Energy Enterprises in Kampala
SD	standard deviation
SYF4DIN	Strong Youth Foundation for Development International
ug	microgram
WBT	Water Boiling Test

1. Introduction

The goal of the Sludge to Energy Enterprises in Kampala (SEEK) project was gasification of faecal sludge (FS) pellets to produce electricity (Englund et al.,2016). However, with the gasifier available to the project, reliable gasification of FS pellets was not feasible (Tukahirwa et al., 2016).

The project thus sought to explore the potential of FS char briquettes as already indicated in past research papers (Ward et al., 2014; Cunningham et al., 2015), media articles (Namagembe, 2016) and evidenced by a group of women that are already producing FS char briquettes in Kampala, Uganda on a small scale. From the business development workshop held 18 June 2016 with briquette companies in Uganda, one limitation identified to up-scaling was the lack of reliable data on the quality and performance of FS briquettes. The SEEK project proposed to close the knowledge gap by comparing a variety of FS char briquettes to conventional wood charcoal and briquettes produced from agricultural waste.

The objectives of this study were:

- To determine the performance of FS briquettes;
- To compare the performance of FS briquettes to wood based charcoal and char briquettes produced from agricultural wastes.

The following fuels were analyzed as part of this study:

- Wood charcoal from three local vendors in Kampala, Uganda
- Agro-char briquettes from Green Heat, Uganda
- Agro-char briquettes from Green Bioenergy (Briketi), Uganda
- FS briquettes from Sanivation, Kenya (www.sanivation.com)
- FS briquettes from Water for People (SYF4DIN, Strong Youth Foundation for Development International), Uganda
- FS briquettes from a women's group CAPIDA, Uganda

2. Materials and methods

2.1 Study samples

The following fuel samples were analyzed for this study (see Fig 1). They were randomly purchased from the local market to avoid the manufacturers providing a non-representative sample.

CH: Wood charcoal

Ch-1: Agro-char briquettes

Ch-2: Agro-char briquettes

FS-1: FS briquettes

FS-2: FS briquettes

FS-3: FS briquettes

Fig 1: Fuel samples

CH: Wood charcoal from three local vendors in Kampala, Uganda
CH-1: Agro-char briquettes from Green Heat, Uganda
CH-2: Agro-char briquettes from Green Bioenergy (Briketi), Uganda
FS-1: FS briquettes from Water for People (SYF4DIN), Uganda
FS-2: FS briquettes from Sanivation, Kenya
FS-3: FS briquettes from a women's group CAPIDA, Uganda

The composition of the fuels is included in Table 1. However, it is important to note that not all details on composition were provided by the fuel manufacturers.

Table 1: Composition of study fuels

Fuel type	*Composition*	*Cost per kg (USD)*
Wood charcoal local vendors	• *Obtained from locally grown or natural trees in Uganda*	*0.19*
Agro-char briquettes Green Heat	• *Charcoal dust, agricultural waste* • *Cassava flour / molasses*	*0.29*
Agro-char briquettes Briketi	• *Charcoal dust, agricultural waste* • *Cassava flour / molasses*	*0.23*
FS briquettes Water for People (SYF4DIN)	• *Charcoal dust, agricultural waste, clay* • *Cassava flour , faecal sludge - 50%*	*0.29*
FS briquettes Sanivation	• *Charcoal dust* • *Faecal sludge - 30%*	*2.4*
FS briquettes women's group (CAPIDA)	• *Charcoal dust, clay* • *Molasses, faecal sludge - 40%*	*0.38*

*** Exchange rate 1 USD: 3400 Uganda Shillings*

Cookstove

The BURN Jikokoa stove was used as the standard stove to burn the fuels and to conduct the performance tests (see Fig 2). This stove was chosen because it has less variation across samples in comparison to other stoves. It is factory made and is not clay insulated. This means that the weight does not change between test cycles. The same sample stove was used for all tests.

Fig 2: BURN Jikokoa cookstove

Cooking vessel

A flat-bottomed aluminium pot of 7 litres capacity was used to boil 5 litres of water (see Fig 3). The pot had a diameter of 27 cm and a height of 12 cm. The pot was cylindrical in shape.

Fig 3: 7 litre flat bottom aluminium pot

Operational Conditions

The operating conditions at the laboratory were as follows:

- Ambient temperature: 18.9 - 25.7 ^{o}C
- Altitude: 1240 m above sea level
- Local boiling point: 95.5 ^{o}C

2.2 Analytical tests

The following tests were conducted:

- Laboratory analyses of fuel properties to determine the calorific value, ash content, moisture content, volatile matter and fixed carbon
- Water Boiling Tests (WBT) to determine the efficiency of the BURN Jikokoa stove whilst using the different fuel types analysed in this study
- Emissions tests to determine CO, CO2, PM2.5, and black carbon emissions from combustion of the different study fuels

2.2.1 Fuel analyses

The objective of the test was to perform a proximate analysis of the briquettes as well as the Gross Calorific Value (GCV) or Higher Heating Value (HHV.). Wood charcoal was also tested as a control.

i. Calorific Value

The heating value or calorific value of a fuel is the amount of heat released during the combustion of a specified amount of fuel. Its unit of measure is energy per unit weight: kcal/kg, kJ/kg or MJ/kg. A 6400 Automatic Isoperibol Calorimeter was used to determine the amount of heat available in the fuel by burning a small sample of it “as received”. A test sample of each fuel type was burned completely in the bomb calorimeter which was pressurized with pure oxygen so that the heat developed by the combustion is absorbed by a definite mass of water. This caused a measurable rise in the water temperature, from which it was possible to calculate the calorific value. The standard method used was ASTM D2015-77 (1981).

ii. Proximate Analysis

Moisture content:

The moisture content was determined by heating a fuel sample at a temperature of 105 ^{o}C for two hours. This heating evaporates the residual moisture from the sample. The weight loss is equivalent to the weight of the moisture. The standard method used was ASTM D1762-84 (1989).

$$Moisture\ Content = \frac{M1 - M2}{M1} * 100$$

M1: mass of sample before heating
M2: mass of sample after heating

Volatile Matter:

The dry fuel sample was heated at 950 ^{o}C in the absence of air for seven minutes. The weight loss is equivalent to the volatile matter content. The standard method used was ASTM D1762-84 (1989).

$$Volatile\ Matter = \frac{M1 - M2}{M1} * 100$$

M1: dry mass of sample before heating
M2: mass of sample after heating

Ash Content:

The dry fuel sample was burned in air at 750 ^{o}C for four hours. The weight remaining is equivalent to the ash content of the sample. The standard method used was ASTM D1762-84 (1989).

$$Ash\ Content = \frac{Mass\ of\ Ash}{Mass\ of\ dry\ sample} * 100$$

Fixed Carbon:

To determine the amount of fixed carbon, the moisture, ash and volatile matter contents (expressed as weights in percent) were added together and this sum was subtracted from 100 percent.

2.2.2 Water Boiling Test (WBT)

The Water Boiling Test (WBT) is a simplified simulation of the cooking process. It is intended to measure how efficiently a stove uses fuel to heat water in a cooking pot. The Water Boiling Test was developed to assess stove performance in a controlled manner, and thus it is probably less like local cooking. The test reveals the technical performance of a stove, not necessarily what it can achieve in real households. Some of the parameters measured during a WBT include thermal efficiency, specific fuel consumption, time to boil, burning rate, turn-down ratio and fire power.

For this study the standard method used to conduct the WBT was the *Water Boiling Test (WBT) protocol version 4.2.3* (GACC, 2014)[1] and data analysed in the relevant data calculation

[1] WBT 4.2.3 was released on 19th March, 2014, and is available at: http://www.cleancookstoves.org/our-work/standards-and-testing/learn-about-testing-protocols/protocols/downloads/wbt-protocol.pdf

spreadsheets. Three test replicates were done for each stove fuel combination, thus a total of 18 tests for the six (6) stove fuel combinations. All three WBT phases were conducted i.e.:

- Cold-start high-power phase: This is the first test phase where the tester begins with the stove at room temperature and uses fuel from a pre-weighed bundle of fuel to boil a measured quantity of water in a standard pot. The tester then replaces the boiled water with a fresh pot of ambient-temperature water to perform the second phase.
- Hot-start high-power phase: This test phase is conducted after the first phase while stove is still hot. Again, the tester uses fuel from a pre-weighed bundle of fuel to boil a measured quantity of water in a standard pot. Repeating the test with a hot stove helps to identify differences in performance between a stove when it is cold and when it is hot.
- Simmer low power phase: This test phase determines the amount of fuel required to simmer a measured amount of water at just below boiling point (3°C below) for 45 minutes. This step simulates the long cooking of legumes common throughout much of the world.

To conduct the water boiling test, a 7 litre pot containing 5 litres of water was heated to boiling point. The study fuels were combusted one at a time in the selected charcoal cookstove i.e. BURN Jikokoa stove to determine the performance of the fuel in the chosen cookstove.

The following technique was used to light the stove for all the fuels:

The cookstove was filled with fuel to the top level of the combustion chamber and weighed together with the fuel. Kerosene was used as a starter, and as per the WBT 4.2.3 protocol guidelines, the amount of kerosene used was 5% the weight of the fuel used. Three to four pieces of the already weighed fuel on the cookstove were dipped into the container with the weighed kerosene for about 2 minutes and then put back onto the cookstove. The remaining kerosene was poured onto the fuel. The process took about 1 minute before lighting the stove to allow proper soaking of the fuel. This marked the start of the lighting phase and thus test start time was recorded at this point as per protocol guidelines. The 7 litre pot filled with 5 litres of water was placed onto the cookstove as soon as the flames from the burning charcoal burned out.

Fig 4: 30 kg digital weighing scale, used during the WBT

2.2.3 Emissions tests

These were carried out to determine the CO, CO_2, PM2.5 and black carbon emissions from the combustion using FS briquettes, wood charcoal and char briquettes. The emissions tests were done simultaneously with the Water Boiling Test (WBT) using:

- Laboratory Emissions Measurement System (LEMS) for CO and CO_2 measurements
- Gravimetric measurement system for particulate matter (PM2.5)
- Sootscan for black carbon measurement

Fig 5: LEMS set up with the gravimetric system for emissions measurement PM2.5

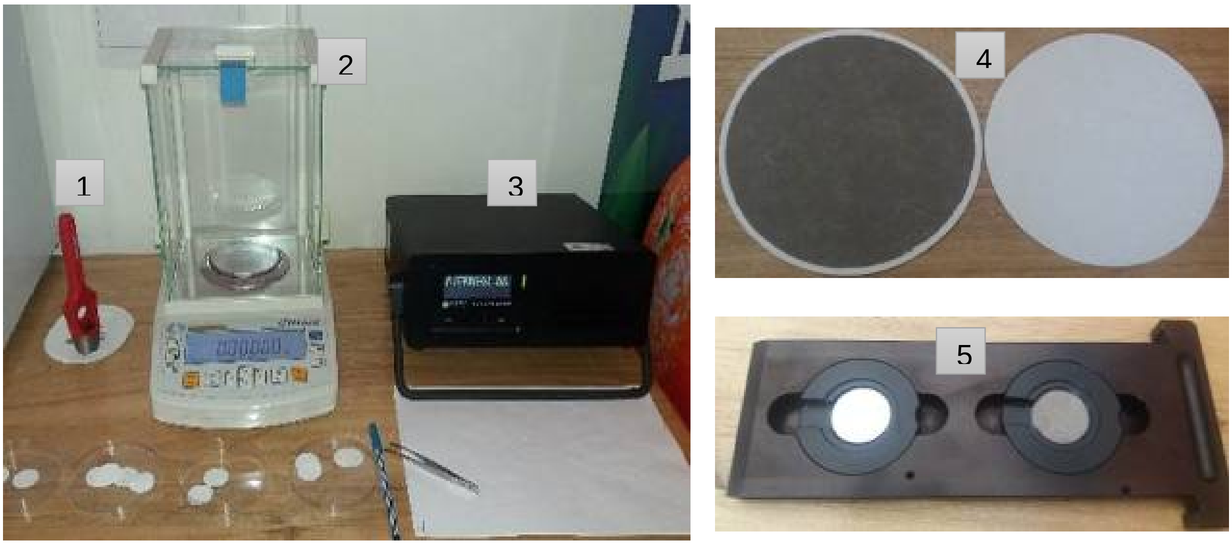

Fig 6: (1) punch for resizing filters for sootscan, (2) microscale for filter weighing, (3) sootscan

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for black carbon, (4) blank and sample quartz filter material, (5) resized blank and sample filter ready for analysis in the sootscan

2.3 Analysis of results

Following the tests, the measured data was checked, verified and the Coefficient of Variation (CoV) done across the three tests for each stove to make sure the results were consistent and were true results obtained from the stove performance tests. The recommended limit for CoV on fuel use / efficiency and bench mark values is 25%.

The test results were summarized using the tiers of performance. The tiers of performance were developed by the International Standards Organization (ISO) / International Workshop Agreement (*IWA 11:2012*)[2]

Table 2: Stove performance indicators and respective metrics

Performance indicator	Metrics	Units
Efficiency/Fuel Use	High power thermal efficiency	%
	Low power specific consumption	MJ/min/l
Emissions	High power CO	g/MJ_d
	Low power CO	g/min/l
	High power PM2.5	mg/MJ_d
	Low power PM2.5	mg/min/l
Indoor emissions	Indoor emissions CO	g/min
	Indoor emissions PM2.5	mg/min
Safety	Points from 10 weighted safety parameters	Points

Basing on the results, the stove fuel combination was categorised under different tiers of performance according to ISO/IWA guidelines, as follows:

Table 3: Tier levels and their explanations

Tier	Explanation
Tier 0	No improvement over open fire / baseline
Tier 1	Measurable improvement over baseline
Tier 2	Substantial improvement over baseline
Tier 3	Currently achievable technology for biomass stoves
Tier 4	Stretch goals for targeting ambitious health and environmental outcomes

(Source: PCIA/GACC, 2012)

[2] Guidelines for Evaluating Cookstove Performance available at http://www.iso.org/iso/catalogue_detail?csnumber=61975

Table 4: Tier values of IWA performance metrics used to categorize stoves

Performance indicator	IWA WBT tiers	Units	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4
Efficiency / fuel Use	High power thermal efficiency	%	<0.15	≥0.15	≥0.25	≥0.35	≥0.45
	Low power specific consumption	MJ/min/l	>0.05	≤0.05	≤0.039	≤0.028	≤0.017
Emissions	High power CO	g/MJd	>16	≤16	≤11	≤9	≤8
	Low power CO	g/min/l	>0.2	≤0.2	≤0.13	≤0.1	≤0.09
	High power PM2.5	mg/MJd	>979	≤979	≤386	≤168	≤41
	Low power PM2.5	mg/min/l	>8	≤8	≤4	≤2	≤1
Indoor emissions	Indoor emissions CO	g/min	>0.97	≤0.97	≤0.62	≤0.49	≤0.42
	Indoor emissions PM2.5	mg/min	>40	≤40	≤17	≤8	≤2

2.4 Quality assurance

The Laboratory Emissions Monitoring System (LEMS) measures harmful emissions from biomass cookstoves. It uses the total capture method to sample and measure particulate matter less than 2.5 microns in aerodynamic diameter, CO, and CO2. All of the metrics are measured once every two seconds (real time measurements). The PM2.5 is additionally sampled separately using a gravimetric filter system for increased accuracy (average measurement). The gravimetric PM2.5 measurement is reported since it is a more accurate measurement. *The sensors that provide the real time emissions measurements are calibrated to report the concentration of the pollutant.*

The average measurement of PM2.5 uses a pump and filter system (gravimetric). Mass is deposited on a filter at a controlled rate based on the amount of air pulled through the filter. The mass on the filter is measured separately using an electronic balance which has an *internal self calibration mechanism done after a couple of measurements.* The mass on the filter is related to the mass emitted from the stove using the volumetric flow rate at the sample location.

All weigh scales and thermometers used in the laboratory are calibrated by the Uganda National Bureau of Standards.

3. Results

3.1 Fuel properties results

Table 5: Fuel properties results for all fuel samples

METRICS	SAMPLE	Charcoal	Agro-char briquettes		FS char briquettes		
		CH	CH-1	CH-2	FS-1	FS-2	FS-3
Moisture content (%)	S1	5.8	7.4	7.4	7.8	7.3	7.3
	S2	6.4	6.9	7.7	7.8	7.8	7.8
	S3	6.4	7.5	7.5	7.4	7.4	7.2
	Average	6.2	7.3	7.5	7.7	7.5	7.4
Volatile matter (%)	S1	9.7	21.8	19.3	25.2	19.3	18.1
	S2	10.5	23.9	22.6	23.3	18.2	18.0
	S3	11.8	22.9	23.7	21.5	19.9	18.7
	Average	10.6	22.9	21.9	23.3	19.1	18.3
Ash content (%)	S1	1.2	19.2	22.9	35.5	25.6	27.1
	S2	1.0	19.5	17.5	34.6	25.8	25.9
	S3	0.9	20.6	21.1	31.2	26.7	26.4
	Average	1.0	19.8	20.5	33.8	26.0	26.5
Fixed carbon (%)	S1	83.4	51.6	50.3	31.5	47.7	47.5
	S2	82.1	49.7	52.1	34.3	48.2	48.2
	S3	81.0	49.0	47.7	40.0	46.0	47.7
	Average	82.1	50.1	50.1	35.2	47.3	47.8
Calorific value (MJ/kg)	S1	30.6	21.1	21.2	18.4	20.1	19.7
	S2	29.7	21.7	22.2	18.9	20.1	19.7
	S3	29.3	22.3	21.2	17.5	20.2	20.7
	Average	29.8	21.7	21.5	18.3	20.1	20.0

3.2 Stove-fuel performance results

The test results are summary results based on three WBT test replicates performed on the BURN Jikokoa stove for each fuel. Detailed results are annexed to this report.

3.2.1 Performance results for Jikokoa stove using CH charcoal

Table 6: IWA performance results for Jikokoa stove using CH charcoal

		Metric		Value	Unit	Sub-tier
Efficiency / fuel use						
Tier	**4**	High power thermal efficiency		53.0%	%	4
		Low power specific consumption		0.0048	MJ/min/l	4
Emissions						
Tier	**1**	High power CO		11.16	g/MJd	1
		Low power CO		0.04	g/min/l	4
		High power PM2.5		116.44	mg/MJd	3
		Low power PM2.5		1.40	mg/min/l	3
Indoor emissions						
Tier	**1**	Indoor emissions CO		0.67	g/min	1
		Indoor emissions PM2.5		6.56	mg/min	3
Black carbon (ug)		Cold start	Hot start	Simmer		
		160.6	5.4	7.1		

Tier 0 → Improving performance → Tier 4

3.2.2 Performance results for Jikokoa stove using CH-1 char briquettes

Table 7: IWA performance results for Jikokoa stove using CH-1 char briquettes

		Metric		Value	Unit	Sub-tier
Efficiency / fuel use						
Tier	**4**	High power thermal efficiency		56.63%	%	4
		Low power specific consumption		0.0048	MJ/min/l	4
Emissions						
Tier	**0**	High power CO		22.43	g/MJd	0
		Low power CO		0.04	g/min/l	4
		High power PM2.5		148.89	mg/MJd	3
		Low power PM2.5		1.49	mg/min/l	3
Indoor emissions						
Tier	**0**	Indoor emissions CO		1.1	g/min	0
		Indoor emissions PM2.5		6.86	mg/min	3
Black carbon (ug)		Cold start	Hot start	Simmer		
		392.9	5.1	7.4		

Tier 0 → Improving performance → Tier 4

3.2.3 Performance results for Jikokoa stove using CH-2 char briquettes

Table 8: IWA performance results for Jikokoa stove using CH-2 char briquettes

		Metric	**Value**	**Unit**	**Sub-tier**
Efficiency / fuel use					
Tier	**4**	High power thermal efficiency	67.8%	%	4
		Low power specific consumption	0.0030	MJ/min/l	4
Emissions					
Tier	**1**	High power CO	13.02	g/MJd	1
		Low power CO	0.05	g/min/l	4
		High power PM2.5	121.65	mg/MJd	3
		Low power PM2.5	1.09	mg/min/l	3
Indoor emissions					
Tier	**2**	Indoor emissions CO	0.6	g/min	2
		Indoor emissions PM2.5	5.17	mg/min	3
Black carbon (ug)		Cold start	Hot start	Simmer	
		135.2	7.1	7.4	

Tier 0 → Improving performance → Tier 4

3.2.4 Performance results for Jikokoa stove using FS-1 briquettes

Table 9: IWA performance results for Jikokoa stove using FS-1 briquettes

		Metric	**Value**	**Unit**	**Sub-tier**
Efficiency / fuel use					
Tier	**4**	High power thermal efficiency	85.8%	%	4
		Low power specific consumption	0.0020	MJ/min/l	4
Emissions					
Tier	**1**	High power CO	11.23	g/MJd	1
		Low power CO	0.03	g/min/l	4
		High power PM2.5	234.75	mg/MJd	2
		Low power PM2.5	2.06	mg/min/l	2
Indoor emissions					
Tier	**2**	Indoor emissions CO	0.5	g/min	2
		Indoor emissions PM2.5	10.24	mg/min	2
Black carbon (ug)		Cold start	Hot start	Simmer	
		68.6	6.6	4.6	

Tier 0 → Improving performance → Tier 4

3.2.5 Performance results for Jikokoa stove using FS-2 briquettes

Table 10: IWA performance results for Jikokoa stove using FS-2 briquettes

		Metric	**Value**	**Unit**	**Sub-tier**
Efficiency / fuel use					
Tier	**4**	High power thermal efficiency	75.9%	%	4
		Low power specific consumption	0.0030	MJ/min/l	4
Emissions					
Tier	**1**	High power CO	9.31	g/MJd	2
		Low power CO	0.05	g/min/l	4
		High power PM2.5	373.80	mg/MJd	2
		Low power PM2.5	4.21	mg/min/l	1
Indoor emissions					
Tier	**1**	Indoor emissions CO	0.5	g/min	3
		Indoor emissions PM2.5	19.70	mg/min	1
Black carbon (ug)		Cold start	Hot start	Simmer	
		338.3	7.1	7.7	

Tier 0 → Improving performance → Tier 4

3.2.6 Performance results for Jikokoa stove using FS-3 briquettes

Table 11: IWA performance results for Jikokoa stove using FS-3 briquettes

		Metric	**Value**	**Unit**	**Sub-Tier**
Efficiency / fuel use					
Tier	**4**	High power thermal efficiency	82.6%	%	4
		Low power specific consumption	0.0027	MJ/min/l	4
Emissions					
Tier	**3**	High power CO	8.69	g/MJd	3
		Low power CO	0.05	g/min/l	4
		High power PM2.5	122.76	mg/MJd	3
		Low power PM2.5	1.12	mg/min/l	3
Indoor emissions					
Tier	**3**	Indoor emissions CO	0.4	g/min	4
		Indoor emissions PM2.5	5.74	mg/min	3
Black carbon (ug)		Cold start	Hot start	Simmer	
		284.9	6.6	5.4	

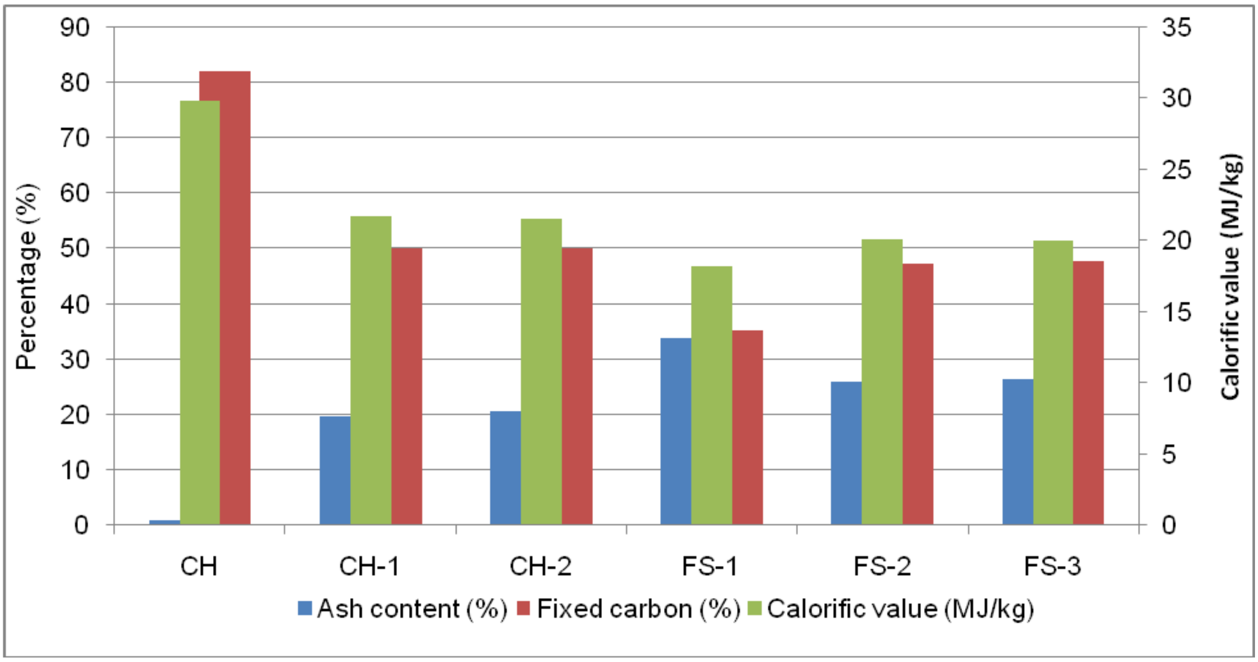
Tier 0 → Improving performance → Tier 4

4. Results analysis and discussion

The sections below show graphical presentations of the results and provide an analysis of the performance comparison between the different fuel types.

4.1 Fuel properties analysis for all analyzed fuels

4.1.1 Calorific value, fixed carbon and ash content for all fuels



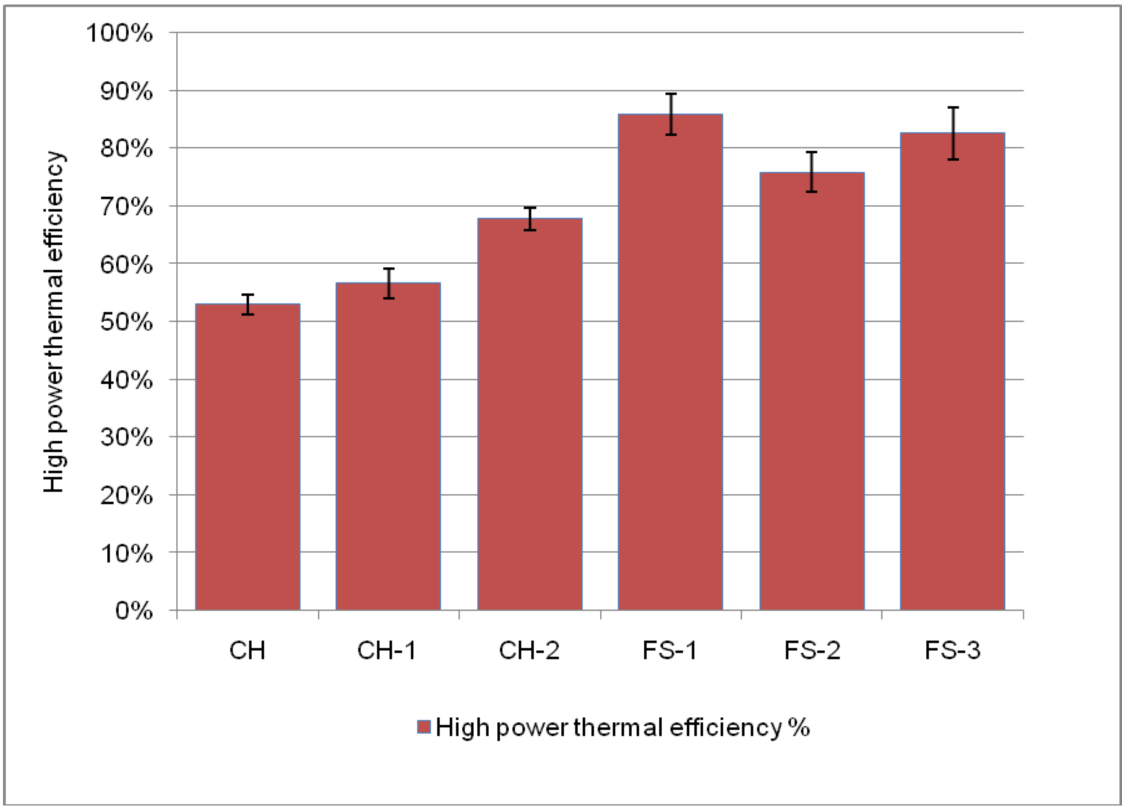
As shown in the graph above, charcoal (Ch) has the highest calorific value followed by the agro-char briquettes (Ch-1 and Ch-2)) and the FS briquettes (FS-1, FS-2 and FS-3) which have a lower calorific value.

The amount of fixed carbon also varies proportionally as the calorific value. The graph also shows that charcoal has minimal ash content, as compared to the FS briquettes. Pure FS char briquettes have the highest amount of ash content.

The lower the ash content, the higher the amount of fixed carbon and as such a higher calorific value.

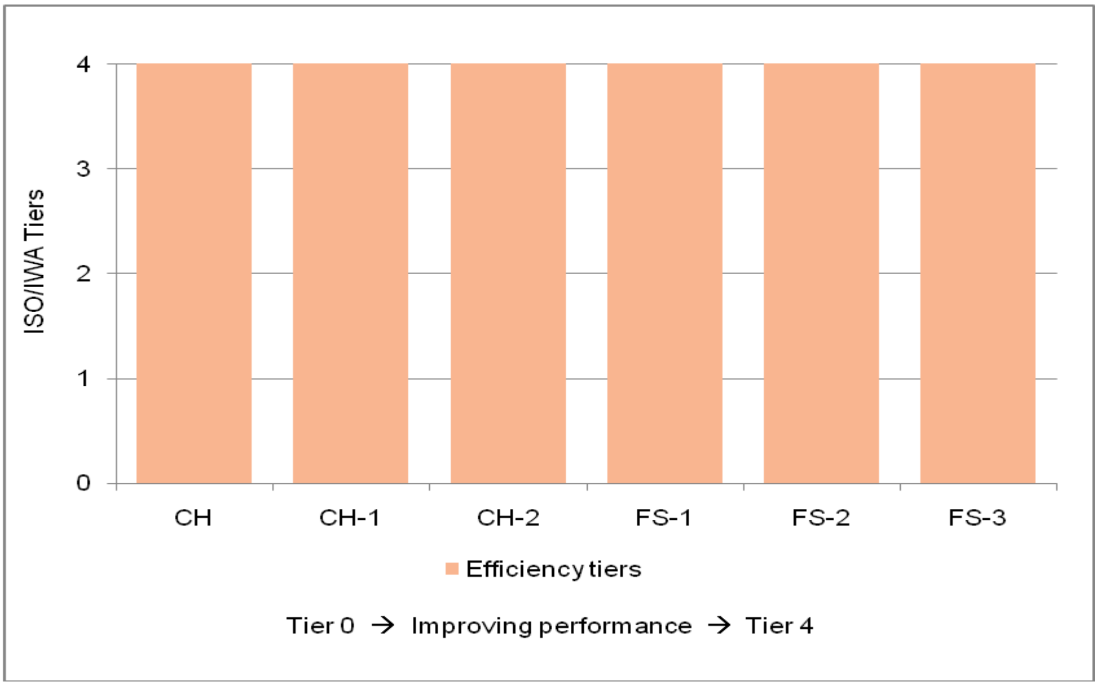
4.2 Stove performance results for all analyzed fuels

4.2.1 High power thermal efficiency of all fuels



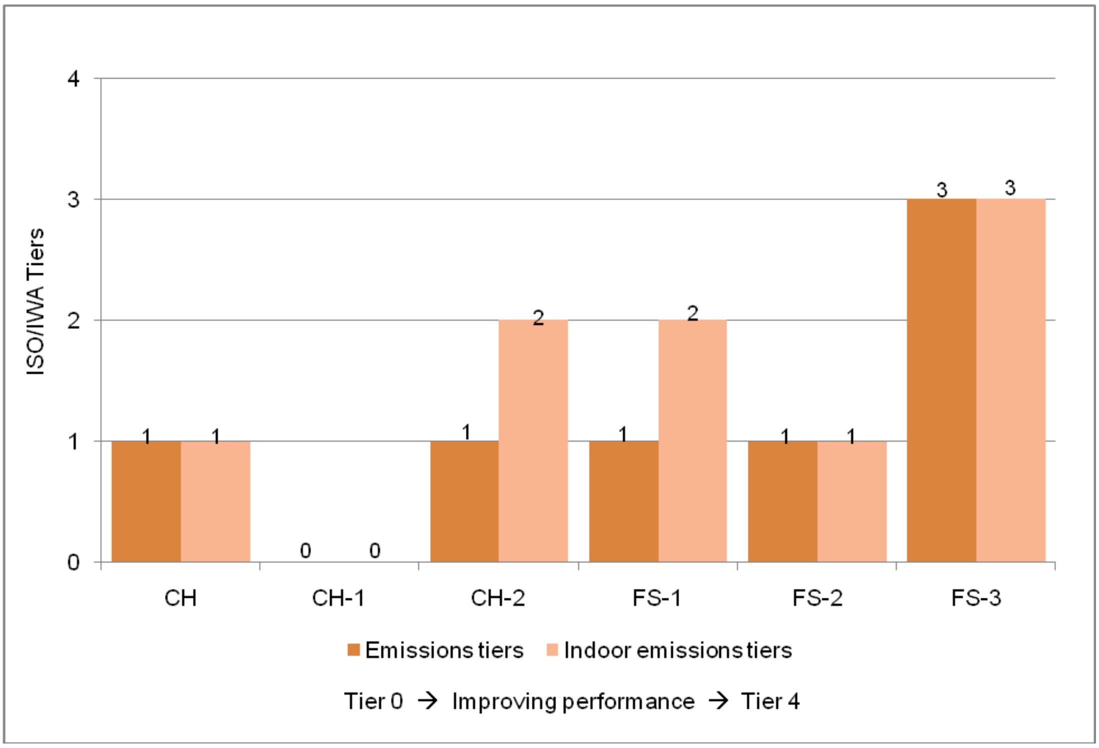
The graph above shows the high power thermal efficiency for the jikokoa cookstove whilst using the different fuel types. The efficiency was highest when the cookstove was using the FS briquettes as fuel. The high efficiency when using the FS briquettes for this particular cookstove could be attributed to the fuel burning with low firepower with much of the heat being absorbed by the pot thus higher efficiency.

4.2.2 Efficiency performance in tiers for all fuels



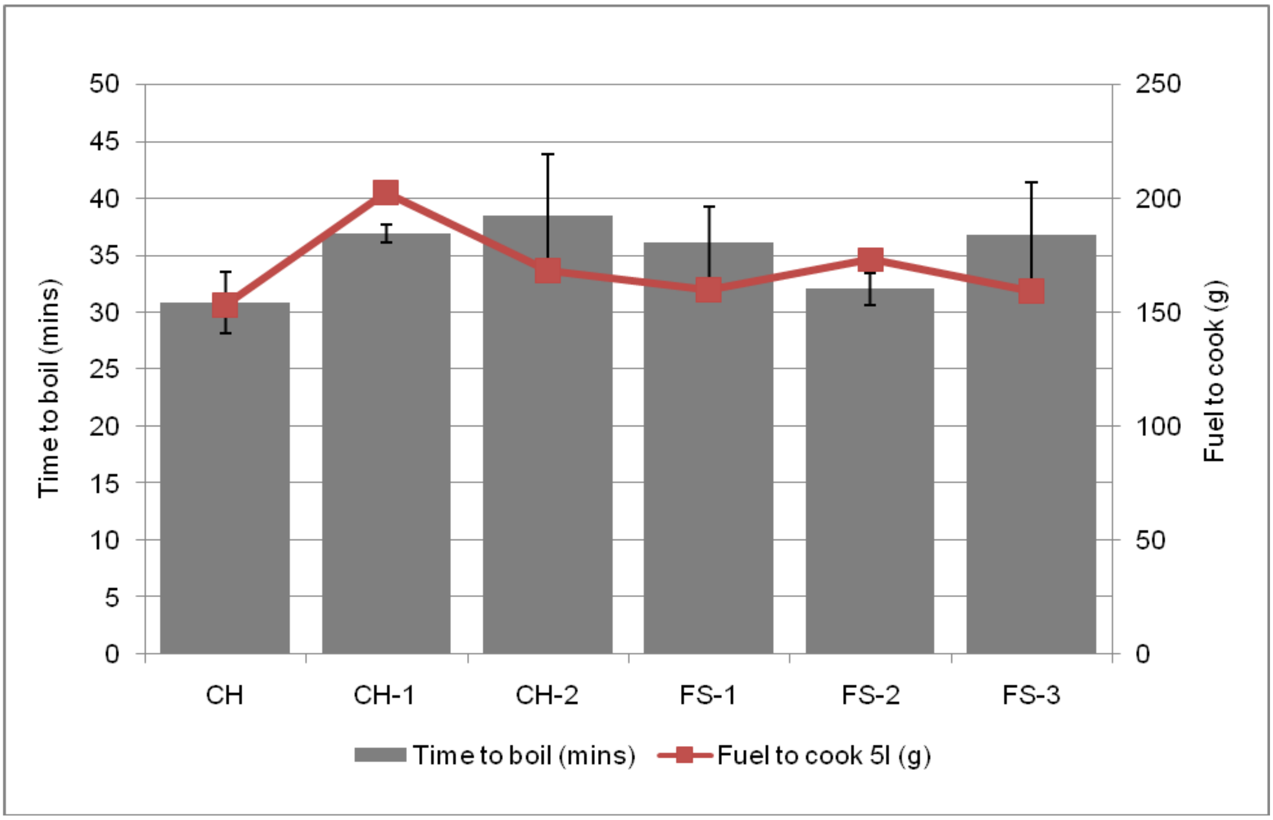
The graph above shows efficiency tier performance of the cookstove when using different fuel types. The Jikokoa cookstove performance when using all the study fuels was in tier 4 indicating "stretch goals for targeting ambitious health and environmental outcomes"

4.2.3 Emissions performance in tiers for all fuels



The graph shows emissions tier performance of the cookstove when using different fuel types. The FS-3 faecal sludge briquettes performed best with tier 3 performance for both total emissions and indoor emissions; while the CH-1 char briquettes rated at tier 0 performance for both total emissions and indoor emissions, this is attributed to high CO levels as seen in the results section.

4.2.4 Time to boil and fuel to cook 5 litres for all fuels



The grey data series (bar graph) on the graph show that charcoal CH had a shorter / faster time to boil as compared to the agro-char briquettes (CH-1, CH-2) and the faecal sludge briquettes (FS-1, FS-2, FS-3) which averagely took longer to boil 5 litres of water.

The same graph has red data series (line graph) that show the amount of fuel used to cook 5 litres of water. CH-1 char briquettes used the most fuel to cook 5 litres of water than other fuels while CH charcoal used the least fuel.

5. Summary findings

- Faecal sludge briquettes are technically viable as a cooking fuel when blended with other char from agro waste or char dust. However, they cannot be used as 100% faecal sludge given the low calorific value (Byrne et al., 2016).
- The cookstove type and fuel contribute to optimum performance of the cookstove in terms of efficiency and emissions.

6. Recommendations

- Real-life cooking experiments should be performed for more conclusive results.

7. References

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8. Appendix

Appendix 1: Detailed stove performance results

Stove type/model		Burn Jikokoa cookstove						Burn Jikokoa cookstove						Burn Jikokoa cookstove					
Fuel species		**CH: Wood charcoal**						**CH-2: Agro-char briquettes, Briketi**						**CH-1: Agro-char briquettes, Green Heat**					
IWA Performance Metrics	**units**	Test 1	Test 2	Test 3	**Average**	STDeV	CoV	Test 1	Test 2	Test 3	**Average**	STDeV	CoV	Test 1	Test 2	Test 3	**Average**	STDev	CoV
High Power Thermal Efficiency	%	54.6%	51.2%	53.2%	**53.0%**	0.02	3%	66.1%	70.0%	67.3%	**67.8%**	0.02	3%	55.9%	54.4%	59.5%	**56.63%**	0.03	5%
Low Power Specific Consumption Rate	MJ/min/L	0.005	0.005	0.005	**0.0048**	0.00	3%	0.003	0.003	0.003	**0.0030**	0.00	8%	0.008	0.001	0.002	**0.0036**	0.00	107%
High Power CO	g/MJd	9.20	11.96	12.32	**11.16**	1.70	15%	13.89	11.87	13.31	**13.02**	1.04	8%	20.06	27.02	20.20	**22.43**	3.98	18%
Low Power CO	g/min/L	0.03	0.04	0.04	**0.04**	0.00	13%	0.05	0.05	0.07	**0.05**	0.01	18%	0.08	0.03	0.03	**0.04**	0.03	67%
High Power PM	mg/MJd	111.0	78.4	159.9	**116.44**	41.02	35%	86.9	108.6	169.5	**121.65**	42.79	35%	133.5	144.9	168.2	**148.89**	17.68	12%
Low Power PM	mg/min/L	1.23	0.95	2.03	**1.40**	0.56	40%	0.88	1.08	1.31	**1.09**	0.22	20%	1.51	1.36	1.59	**1.49**	0.12	8%
Indoor Emissions CO	g/min	0.55	0.73	0.74	**0.67**	0.11	16%	0.66	0.54	0.50	**0.57**	0.08	15%	0.97	1.30	0.96	**1.07**	0.19	18%
Indoor Emissions PM	mg/min	5.7	4.5	9.5	**6.56**	2.61	40%	4.2	5.1	6.3	**5.17**	1.06	20%	6.4	6.6	7.6	**6.86**	0.68	10%
Safety	Index																		
		Test 1	Test 2	Test 3	**Sub Tier**	Tier		Test 1	Test 2	Test 3	**Sub Tier**	Tier		Test 1	Test 2	Test 3	**Sub Tier**	Tier	
High Power Thermal Efficiency		4.1	4.1	4.1	**4**	4		4.3	4.4	4.4	**4**	4		4.1	4.1	4.2	**4**	4	
Low Power Specific Consumption Rate		4.7	4.7	4.7	**4**			4.8	4.8	4.8	**4**			4.5	4.9	4.9	**4**		
High Power CO		2.8	1.8	1.7	**1**	1		1.4	1.8	1.5	**1**	1		0.7	0.5	0.7	**0**	0	
Low Power CO		4.6	4.5	4.5	**4**			4.4	4.4	4.2	**4**			4.1	4.6	4.7	**4**		
High Power PM		3.4	3.7	3.0	**3**			3.6	3.4	2.9	**3**			3.2	3.1	2.9	**3**		
Low Power PM		3.7	4.0	2.9	**3**			4.1	3.9	3.6	**3**			3.4	3.6	3.4	**3**		
Indoor Emissions CO		2.5	1.6	1.6	**1**	1		1.8	2.6	2.9	**2**	2		0.9	0.7	1.0	**0**	0	
Indoor Emissions PM		3.3	3.5	2.8	**3**			3.6	3.4	3.2	**3**			3.2	3.2	3.0	**3**		
Standard Performance Measures																			
Fuel to Cook 5L (850/1500)	g	152.8	155.3	151.0	**153.02**	2.17	1%	172.0	167.0	165.2	**168.08**	3.55	2%	254.1	177.1	176.2	**202.46**	44.76	22%
CO to Cook 5L (20)	g	22.5	27.8	29.8	**26.70**	3.78	14%	34.4	30.2	35.7	**33.40**	2.85	9%	51.9	51.8	39.5	**47.74**	7.17	15%
PM to Cook 5L (1500)	mg	459.6	339.7	721.4	**506.91**	195.22	39%	342.6	422.1	561.5	**442.05**	110.81	25%	566.6	551.1	640.1	**585.92**	47.55	8%
Energy to Cook 5L (15,000/25,000)	kJ	4,360	4,430	4,307	**4365.60**	61.78	1%	3,477	3,375	3,339	**3396.82**	71.66	2%	5,182	3,610	3,592	**4128.07**	912.69	22%
Time to Boil	min	33.9	29.5	29.0	**30.80**	2.69	9%	35.5	35.1	44.7	**38.46**	5.43	14%	36.0	37.6	36.9	**36.84**	0.79	2%
CO2 to Cook 5L	g	340.0	202.0	443.5	**328.53**	121.14	37%	389.9	388.7	305.7	**361.46**	48.25	13%	454.3	351.7	418.4	**408.13**	52.06	13%
Basic Operation	units																		
COLD START																			
Time to boil Pot # 1	min	49	38	36	**40.61**	6.95	17%	40	45	51	**45.33**	5.09	11%	44	47	49	**46.58**	2.48	5%
Burning rate	g/min	2.80	3.66	3.57	**3.34**	0.47	14%	4.44	3.89	3.29	**3.87**	0.57	15%	4.88	4.44	4.45	**4.59**	0.25	5%
Thermal efficiency	--	42%	40%	45%	**0.43**	0.02	5%	47%	47%	46%	**0.47**	0.00	1%	39%	40%	38%	**0.39**	0.01	3%
Specific fuel consumption	g/liter	27.46	27.72	25.77	**26.98**	1.06	4%	36.28	35.19	33.53	**35.00**	1.38	4%	43.29	42.29	43.64	**43.07**	0.70	2%
Temp-corrected specific consumption	g/liter	27.8	28.8	26.1	**27.58**	1.39	5%	36.2	35.0	35.4	**35.52**	0.60	2%	43.3	41.7	43.3	**42.77**	0.95	2%
Firepower	watts	1,333	1,738	1,699	**1589.96**	223.52	14%	1,494	1,310	1,109	**1304.37**	192.81	15%	1,658	1,509	1,511	**1559.37**	85.00	5%
Equivalent Dry Fuel Consumed	g	136.1	137.1	127.7	**133.65**	5.14	4%	179.4	174.8	166.6	**173.59**	6.49	4%	214.0	209.4	216.7	**213.34**	3.71	2%
HOT START																			
Time to boil Pot # 1	min	18	19	22	**19.76**	1.74	9%	30	25	35	**29.94**	4.58	15%	28	28	25	**27.12**	1.48	5%
Burning rate	g/min	4.70	4.58	4.35	**4.54**	0.18	4%	3.09	3.39	2.54	**3.01**	0.43	14%	4.00	4.11	3.94	**4.02**	0.09	2%
Thermal efficiency	--	67%	62%	62%	**0.63**	0.03	5%	85%	93%	88%	**0.89**	0.04	5%	73%	69%	82%	**0.74**	0.06	9%
Specific fuel consumption	g/liter	17.38	17.89	19.07	**18.11**	0.87	5%	18.59	17.30	17.67	**17.86**	0.66	4%	22.61	23.13	20.22	**21.99**	1.55	7%
Temp-corrected specific consumption	g/liter	17.7	18.6	19.2	**18.46**	0.75	4%	19.1	17.4	18.5	**18.33**	0.82	4%	22.7	23.8	20.2	**22.25**	1.84	8%
Firepower	watts	2,233	2,179	2,067	**2159.46**	84.78	4%	1,041	1,142	857	**1013.37**	144.64	14%	1,359	1,396	1,338	**1364.49**	29.49	2%
Equivalent Dry Fuel Consumed	g	85.8	88.6	94.2	**89.51**	4.27	5%	92.4	86.0	87.9	**88.78**	3.30	4%	112.0	114.8	100.1	**108.96**	7.81	7%
SIMMER																			
Burning rate	g/min	0.81	0.77	0.79	**0.79**	0.02	3%	0.71	0.75	0.65	**0.71**	0.05	7%	1.67	0.29	0.37	**0.78**	0.78	100%
Thermal efficiency	--	67%	64%	63%	**0.65**	0.02	3%	87%	84%	73%	**0.81**	0.07	9%	107%	127%	112%	**1.15**	0.10	9%
Specific fuel consumption 45 min	g/liter	7.8	7.3	7.6	**7.58**	0.24	3%	6.8	7.2	6.1	**6.69**	0.53	8%	17.8	2.7	3.5	**7.98**	8.53	107%
Firepower	watts	384	365	374	**374.40**	9.85	3%	240	253	219	**237.49**	17.24	7%	569	97	125	**263.51**	264.61	100%
Turn down ratio	--	4.64	5.37	5.03	**5.01**	0.37	7%	5.29	4.84	4.48	**4.87**	0.40	8%	2.65	14.97	11.41	**9.68**	6.34	65%
Equivalent Dry Fuel Consumed	g	36.4	34.5	35.4	**35.43**	0.93	3%	32.0	33.9	29.3	**31.73**	2.30	7%	75.3	12.9	16.5	**34.89**	35.04	100%

Stove type/model		Burn Jikokoa cookstove						Burn Jikokoa cookstove							Burn Jikokoa cookstove						
Fuel species		**FS-3: Faecal sludge briquettes, CAPIDA**						**FS-2: Faecal sludge briquettes, Sanivation**							**FS-1: Faecal sludge briquettes, Strong youth**						
IWA Performance Metrics	**units**	Test 1	Test 3	Test 4	**Average**	STDeV	CoV	Test 1	Test 2	Test 3	Test 4	**Average**	STDeV	CoV	Test 1	Test 2	Test 3	Test 4	**Average**	STDeV	CoV
High Power Thermal Efficiency	%	87.7%	81.1%	78.9%	**82.6%**	0.05	6%	72.7%	78.2%	79.5%	73.0%	**75.9%**	0.04	5%	84.6%	89.5%	82.5%	86.6%	**85.8%**	0.03	3%
Low Power Specific Consumption Rate	MJ/min/L	0.003	0.002	0.002	**0.0027**	0.00	18%	0.003	0.003	0.003	0.003	**0.0030**	0.00	4%	0.002	0.002	0.002	0.001	**0.0020**	0.00	27%
High Power CO	g/MJd	7.63	11.31	7.13	**8.69**	2.28	26%	9.48	8.59	10.45	8.72	**9.31**	0.85	9%	14.53	11.08	11.14	8.17	**11.23**	2.60	23%
Low Power CO	g/min/L	0.05	0.04	0.05	**0.05**	0.01	12%	0.05	0.04	0.04	0.06	**0.05**	0.01	20%	0.03	0.03	0.04	0.02	**0.03**	0.01	21%
High Power PM	mg/MJd	88.0	131.8	148.5	**122.76**	31.23	25%	372.1	376.7	378.5	367.9	**373.80**	4.80	1%	99.7	685.9	96.5	56.9	**234.75**	301.41	128%
Low Power PM	mg/min/L	0.86	1.29	1.20	**1.12**	0.23	21%	4.34	4.32	4.10	4.07	**4.21**	0.14	3%	0.85	5.79	0.95	0.63	**2.06**	2.49	121%
Indoor Emissions CO	g/min	0.31	0.50	0.34	**0.38**	0.10	27%	0.51	0.43	0.50	0.45	**0.47**	0.04	9%	0.58	0.46	0.52	0.41	**0.49**	0.07	15%
Indoor Emissions PM	mg/min	4.0	6.2	7.0	**5.74**	1.56	27%	20.3	20.1	19.2	19.1	**19.70**	0.62	3%	4.0	29.3	4.5	3.1	**10.24**	12.75	124%
Safety	Index																				
		Test 1	Test 3	Test 4	**Sub Tier**	Tier		Test 1	Test 2	Test 3	Test 4	**Sub Tier**	Tier		Test 1	Test 2	Test 3	Test 4	**Sub Tier**	Tier	
High Power Thermal Efficiency		4.7	4.6	4.6	**4**	4		4.5	4.6	4.6	4.5	**4**	4		4.7	4.8	4.6	4.7	**4**	4	
Low Power Specific Consumption Rate		4.8	4.8	4.8	**4**			4.8	4.8	4.8	4.8	**4**			4.8	4.9	4.8	4.9	**4**		
High Power CO		4.0	1.9	4.1	**3**	3		2.7	3.4	2.2	3.2	**2**	1		1.2	1.9	1.9	3.8	**1**	1	
Low Power CO		4.4	4.5	4.4	**4**			4.4	4.5	4.5	4.3	**4**			4.6	4.6	4.5	4.7	**4**		
High Power PM		3.6	3.2	3.1	**3**			2.0	2.0	2.0	2.0	**2**			3.5	1.4	3.5	3.8	**2**		
Low Power PM		4.1	3.7	3.7	**3**			1.9	1.9	1.9	1.9	**1**			4.1	1.5	4.0	4.3	**2**		
Indoor Emissions CO		4.2	2.9	4.1	**4**	3		2.8	3.9	2.9	3.5	**3**	1		2.3	3.3	2.7	4.0	**2**	2	
Indoor Emissions PM		3.6	3.3	3.1	**3**			1.8	1.8	1.9	1.9	**1**			3.6	1.4	3.5	3.8	**2**		
Standard Performance Measures																					
Fuel to Cook 5L (850/1500)	g	168.8	154.5	154.1	**159.14**	8.39	5%	175.1	169.3	170.3	177.2	**172.99**	3.80	2%	172.0	151.4	165.6	150.4	**159.86**	10.64	7%
CO to Cook 5L (20)	g	25.0	27.7	22.9	**25.21**	2.42	10%	26.3	22.7	26.8	28.3	**26.01**	2.39	9%	30.8	24.6	27.2	18.9	**25.38**	4.99	20%
PM to Cook 5L (1500)	mg	345.0	504.9	515.6	**455.20**	95.55	21%	1582.7	1595.1	1548.0	1550.8	**1569.14**	23.36	1%	348.3	2284.9	374.0	238.9	**811.52**	984.02	121%
Energy to Cook 5L (15,000/25,000)	kJ	3,161	2,892	2,885	**2979.14**	157.15	5%	3,295	3,185	3,203	3,333	**3253.87**	71.41	2%	2,914	2,565	2,805	2,548	**2708.09**	180.30	7%
Time to Boil	min	41.8	35.7	32.8	**36.78**	4.61	13%	30.7	30.9	32.9	33.6	**32.01**	1.46	5%	40.4	37.5	35.0	31.3	**36.06**	3.86	11%
CO2 to Cook 5L	g	399.8	469.1	106.3	**325.05**	192.63	59%	419.5	226.3	441.3	457.3	**386.10**	107.67	28%	240.7	270.0	441.9	255.9	**302.15**	93.95	31%
Basic Operation	units																				
COLD START																					
Time to boil Pot # 1	min	57	44	43	**47.83**	7.80	16%	37	42	42	40	**40.17**	2.06	5%	55	51	41	42	**47.29**	6.70	14%
Burning rate	g/min	3.08	3.82	3.84	**3.58**	0.44	12%	4.98	4.35	4.48	4.51	**4.58**	0.28	6%	3.50	3.63	4.58	4.31	**4.00**	0.52	13%
Thermal efficiency	--	54%	52%	53%	**0.53**	0.01	1%	46%	48%	47%	51%	**0.48**	0.02	4%	49%	53%	53%	54%	**0.52**	0.02	4%
Specific fuel consumption	g/liter	35.74	33.58	33.37	**34.23**	1.32	4%	37.37	36.47	37.64	36.68	**37.04**	0.55	1%	38.53	37.23	37.62	37.05	**37.61**	0.66	2%
Temp-corrected specific consumption	g/liter	37.1	34.2	33.5	**34.93**	1.93	6%	37.9	36.6	38.1	36.3	**37.22**	0.92	2%	39.6	36.9	36.8	36.3	**37.40**	1.52	4%
Firepower	watts	960	1,193	1,199	**1117.31**	136.48	12%	1,563	1,365	1,404	1,413	**1436.35**	86.77	6%	987	1,024	1,292	1,218	**1130.12**	147.94	13%
Equivalent Dry Fuel Consumed	g	174.8	166.6	165.7	**169.02**	5.05	3%	185.7	181.1	186.6	181.1	**183.62**	2.94	2%	191.5	185.1	186.9	183.3	**186.69**	3.52	2%
HOT START																					
Time to boil Pot # 1	min	23	27	22	**24.14**	2.28	9%	23	20	23	27	**23.17**	2.81	12%	23	24	30	21	**24.57**	3.65	15%
Burning rate	g/min	2.96	2.92	3.70	**3.19**	0.44	14%	3.80	4.02	3.35	3.47	**3.66**	0.31	8%	3.25	3.09	2.85	3.84	**3.26**	0.42	13%
Thermal efficiency	--	122%	110%	105%	**1.12**	0.09	8%	99%	108%	112%	95%	**1.04**	0.08	8%	120%	126%	112%	119%	**1.19**	0.06	5%
Specific fuel consumption	g/liter	14.03	15.62	16.56	**15.40**	1.28	8%	17.58	16.20	15.54	18.97	**17.07**	1.52	9%	15.01	15.02	17.04	16.60	**15.92**	1.06	7%
Temp-corrected specific consumption	g/liter	14.7	15.8	16.6	**15.72**	0.96	6%	18.1	16.2	16.0	19.4	**17.43**	1.62	9%	15.9	15.2	17.2	16.3	**16.18**	0.83	5%
Firepower	watts	925	910	1,153	**995.97**	136.51	14%	1,191	1,261	1,050	1,089	**1147.70**	95.95	8%	918	873	804	1,084	**919.95**	119.12	13%
Equivalent Dry Fuel Consumed	g	69.6	77.8	82.4	**76.58**	6.49	8%	86.9	80.5	76.8	93.3	**84.38**	7.25	9%	74.8	74.8	84.8	82.1	**79.10**	5.12	6%
SIMMER																					
Burning rate	g/min	0.81	0.63	0.61	**0.68**	0.11	16%	0.73	0.77	0.73	0.79	**0.76**	0.03	4%	0.69	0.46	0.65	0.41	**0.55**	0.14	25%
Thermal efficiency	--	95%	77%	88%	**0.87**	0.09	10%	98%	107%	99%	80%	**0.96**	0.11	12%	123%	87%	93%	117%	**1.05**	0.18	17%
Specific fuel consumption 45 min	g/liter	7.8	5.9	5.8	**6.50**	1.16	18%	7.0	7.5	7.0	7.6	**7.27**	0.29	4%	6.6	4.2	6.1	3.8	**5.19**	1.38	27%
Firepower	watts	254	197	190	**213.65**	34.96	16%	229	242	229	249	**237.36**	9.55	4%	195	129	183	114	**155.17**	39.52	25%
Turn down ratio	--	3.71	5.34	6.18	**5.08**	1.25	25%	6.00	5.42	5.35	5.03	**5.45**	0.40	7%	4.90	7.37	5.73	10.06	**7.01**	2.28	32%
Equivalent Dry Fuel Consumed	g	36.6	28.4	27.5	**30.81**	5.04	16%	32.9	34.8	32.9	35.7	**34.07**	1.37	4%	31.0	18.2	29.2	18.2	**24.16**	6.88	28%