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Energy performance of biomass cookstoves using fuel briquettes

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ABSTRACT

In this study, the energy performance of an improved cookstove (ICS) is evaluated and compared with the performance of a charcoal stove and the three-stone fire using two biomass fuel – rice husk and sawdust briquettes. The performance of the cookstoves is evaluated based on the standard testing protocol of water boiling test in three phases – cold start, hot start and simmering. The energy performance of the cookstoves is compared using analysis of variance (ANOVA). The results of the study show that the ICS performed better in the cold and hot starts as opposed to the simmering phase. ANOVA shows that the thermal efficiency, firepower, specific fuel consumption, time to boil, burning rate and the turndown ratio of the three cookstoves are significantly different ($p < 0.05$) from one another for each of the fuel types. In the high power phase, the ICS offered superior energy performance over the two conventional cookstoves with the use of rice husk briquette as fuel. However, the performance of the ICS is low compared to that of the two conventional cookstoves in the simmering phase. The ICS offered better thermal efficiency over the traditional cookstoves and some other ICSs in the literatures.

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Introduction

It is a common practice among populations in regions of the world with limited access to quality energy systems powered by either electricity or gas to use solid biomass, particularly fuel wood, inefficiently in traditional cookstoves for household heating, cooking and lighting. The inefficient combustion of solid biomass in traditional stoves such as the open fires and other conventional cookstoves is a major cause of household air pollution that constitutes both health and environmental risks. This is because the pollutant gases emanating from the incomplete combustion of biomass in the cookstoves either escape into the ambient atmosphere or directly into the living houses. Long exposure to these pollutants is one of the major causes of lung-related diseases among rural people. Mothers and young children are the most vulnerable as they spend most of their time within the vicinity of the cooking environment attending to the cookstove. The inefficient use of solid fuel in traditional cookstoves constitutes a first-order public health crisis killing nearly 600,000 Africans annually, and ranks as the second-largest health risk factor resulting in death and disability in Africa [1].

Traditional cookstoves are still popular in about 40%–50% of the present world population, particularly among communities in developing and least developed countries. The number of users of such stoves who rely on traditional fuel wood as the only source of fuel is estimated at about 2.7 billion and the number is on the increase due to population growth and the often availability of the biomass at little or no financial cost [2,3]. The heavy dependent of some communities, particularly rural communities, on the harvesting of fuel wood has been linked to the issues of regional desertification and deforestation, with global climate and health implications [4]. In Africa for example, it is estimated that more than 600 million people rely on forest wood as the primary source of energy for traditional cooking and this number is expected to reach 850–900 million by 2020 [1,2], thus posing a significant threat to the tropical forest areas in Africa. Globally, the concerns with the use of traditional and conventional cookstoves include the indiscriminate harvesting of wood fuel, and the inefficient and incomplete combustion of the biomass in such stoves resulting in harmful emissions with detrimental implications that transcend regions.

Appropriate access to a minimum energy level is a prerequisite to mitigating the problems associated with the use of traditional cookstoves; an added benefit being the promotion of human development. Access to energy has been reported to be strongly positively correlated with human development, particularly the achievement of some of the Millennium Development Goals [5,6]. The first step in the scale-up of energy access for poor rural household populations in developing and least developed countries is the sensitization of the local populace on the benefits of the use of improved cookstoves (ICS) and cleaner fuels.

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This is a step many international organizations, such as the Global Alliance for Clean Cookstoves and Practical Action, have successfully done. In some African countries including Nigeria, Ghana, Senegal and Uganda, the aggressive promotion of the use of ICSs by both local and international organizations has created a positive environment for its uptake. However, the focus has now shifted to the quality testing of ICSs prior to deployment. This is mainly because, even though a number of cookstoves have been developed and deployed as an improved alternative to traditional stoves, many have either failed or underperformed due to the lack of standard testing and quality control of the stoves prior to dissemination to the users [7,8].

To address the problem of deployment of poor performing cookstoves, there is the need for standard testing of ICSs using appropriate biomass fuel prior to dissemination to end-users. In this context, a number of studies have been published in the literatures centred on the evaluation and energy performance improvement of ICSs using the standard testing protocols of water boiling test (WBT), and controlled cooking test. The energy performance of a top-lit updraft (TLUD) cookstove using three different fuel types – wood chips, coconut shell and rice husk briquette was evaluated by [9]. It was reported that the performance of the cookstove was significantly influenced ($p < 0.05$) by fuel type. In the study by [5], two ICSs were compared to the traditional 3-stone fire and a gas stove based on the water boiling and controlled cooking tests. The authors reported significant fuel savings due to the use of the ICSs. A rice-husk-fuelled cookstove was developed in [10], and the authors reported an average thermal efficiency of 18% and a specific fuel consumption (SFC) of 4.2 MJ per kg of cooked food for the stove. With the aim of providing a solution to the energy problem of low-income families in the Indian coastal region, Mehetre et al. [11] developed an ICS and reported a thermal efficiency power rating of 28.8% and 2.65 kW, respectively for the stove. Similarly, some other studies have evaluated the performance of different ICSs in different regions using biomass as fuel [12–16].

Although a number of studies have investigated the performance of different cookstoves, every ICS must be tested for its energy performance prior to its dissemination. This is because a significant underlying factor in the successful design and implementation of any ICS programme is the testing of the cookstove taking into consideration the cooking habits and preferences of the target users, and using available and sustainable fuel sources within the locality of the users. Although the use of multiple fuel types in ICS testing is often not emphasized, it is a core part of the transition from traditional to ICS use. Furthermore, the evaluation of ICSs using different fuel types is critical to understanding the impact of fuel type on the thermal performance of cookstoves. In the light of this, this study investigates the energy performance of a recently developed ICS using rice husk and sawdust briquettes as fuel. The energy performance of the ICS is compared to that of two common conventional cookstoves among the local populace namely, the three-stone fire and the 'charcoal' stove, using the same fuel types. The performance evaluation is carried out using the standard WBT protocol, and the parameters determined are used as a basis for comparison.

Materials and methods

Description of the cookstoves

The performance of three biomass cookstoves was investigated using rice husk and sawdust briquettes. The cookstoves investigated include the three-stone fire or 'open fire', 'charcoal' stove, and an ICS developed in the Department of Agricultural and Bioresources Engineering, University of Nigeria. The stoves are briefly described below:

Three-stone fire

The three-stone fire, also known as the 'open fire' (Figure 1), is the traditional and primary cookstove type used in Sub-Sahara Africa [14]. It consists of three similar-sized stones on which a cooking pot is balanced over a fire. The arrangement of the stones is such that they can act as a support for the cooking pot. The height of the stones is usually about 15–30 cm depending on the size of the pot. This gives sufficient clearance above the ground for the biomass fuel to be placed beneath the pot. As the fire is lit beneath the pot, combustion in the three-stone fire is incomplete and uncontrolled, generating a great quantity of particles and gases that are emitted directly into the cooking environment [17].

Figure 1. Three-stone fire.

Figure 2. 'Charcoal' stove.

'Charcoal' stove

The 'charcoal' stove is another very common cooking device originally fabricated to utilize charcoal as fuel (Figure 2). However, other biomass fuel types such as wood chips and briquettes have been used in the stove. The cooking pot is positioned as close as possible to the fuel with the air inlet just below the fuel grate. The closeness of the pot to the fuel increases the full utilization of the heat generated from the fuel, reducing the loss of heat to the environment.

The improved cookstove (ICS)

The improved biomass cookstove developed in this study is shown in Figure 3. Figure 3(a) shows the labelled parts of the stove while Figure 3(b) shows the stove in use. The combustion chamber of the cookstove is made of cylindrical-shaped mild steel sheet of 2 mm thickness with the internal and external diameter, and the height of the chamber being 180 mm, 225 mm, and 370 mm, respectively. The vertical cylindrical combustion chamber controls airflow and directs the heated air and gases to the pot, thus increasing the heat transfer. The cookstove has a removable top cover that allows for the feeding of the combustion chamber with appropriate biomass fuel prior to ignition. It also acts as support for the cooking pot. To minimize heat loss from the combustion chamber to the environment, the space between the internal and outer cylinder of the chamber is filled with a mixture of clay and powdered charcoal. This provides a relatively lightweight insulation material readily accessible within the locality of the study. A cylindrical mild steel pipe of 100 mm diameter and 130 mm length equipped with a cover is connected to the combustion chamber through the outer combustion surface at an angle of 30°. The pipe serves as inlet channel for feeding biomass fuel into the chamber during cooking and it is positioned at a distance of 100 mm from the top cover. The stove has two handles welded to the body of the cookstove for the ease of moving the stove. The bottom of the combustion chamber is suspended from the ground surface at a height of 210 mm by means of four iron stands of 20 mm width and 10 mm thickness. A grate made from mild steel of 4 mm thickness that allows for the inflow of air as well as the collection of ashes is fixed to the bottom of the chamber. The size of the grate openings is 15 mm diameter.

To use the cookstove, the combustion chamber is loaded with an appropriate fuel such as biomass briquettes. The fuel is lit from the top, allowed to steady, and the pot is placed on the stove. Depending on the fuel type, a little quantity of kerosene may be used to

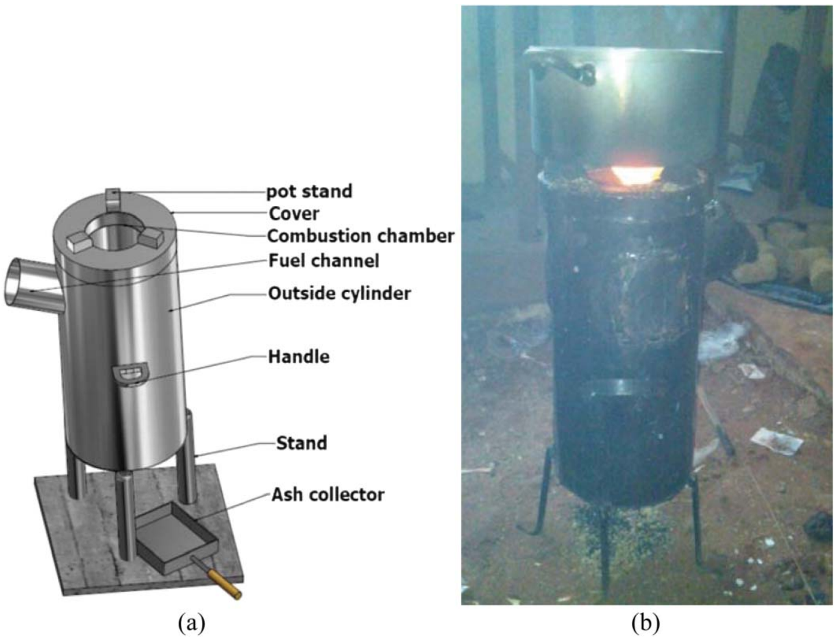

Figure 3. (a) The improved biomass cookstove. (b) The improved biomass cookstove in use.

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start the fire and then allowed to steady. If the need be, the cookstove may be refuelled with the biomass fuel through the fuel inlet channel during the cooking process.

Combustion properties of the fuel briquettes

Prior to the performance evaluation of the cookstoves, the combustion properties of the rice husk and sawdust briquettes which include the proximate analysis – moisture content, volatile matter, fixed carbon and ash contents, the calorific value (higher heating value (HHV) and lower heating value (LHV)) – were determined based on [18]. Based on the proximate analysis, the elemental composition of the briquettes was estimated using the following equations [19]:

$$C = 0.637FC + 0.455VM \quad (1)$$

$$H = 0.052FC + 0.062VM \quad (2)$$

$$O = 0.304FC + 0.476VM \quad (3)$$

subject to the proximate analysis being in this range, fixed carbon (FC): 4.7%–38.4%, volatile matter (VM): 57.2%–90.6%, carbon (C): 36.2%–53.1%, hydrogen (H): 4.36%–8.3% and Oxygen (O): 31.37%–49.5% in wt% on dry basis.

Performance evaluation of the cookstoves

The performance of the cookstoves, that is, the improved biomass cookstove, the 'charcoal' stove and the three-stone fire, was evaluated using the WBT and then statistically compared to quantify the performance of the ICS relative to the two conventional cookstoves. The WBT is a simplified simulation of cooking process. It is intended to measure how efficiently a stove uses fuel to heat water in a cooking pot. In the WBT, a known quantity of water is heated on the cookstove. No lid is used to cover the vessel so that evaporated water freely escapes from the vessel. The quantity of water evaporated after the complete burning of the fuel is determined to calculate the efficiency. Stove developers around the world have developed a standardized WBT to help them in their work [20]. The WBT consists of three phases:

- High power phase with cold start
- High power phase with hot start
- Low power phase with simmering

The WBT for each of the cookstoves begins with the cold start high power phase. The tester begins with the cookstove at room temperature and uses biomass fuel from a pre-weighed bundle to boil a measured quantity of water in a standard pot. The tester then replaces the boiled water with a fresh pot with ambient-temperature water to perform the second phase. The hot-start high power phase is conducted after the cold-start high power phase while the stove is still hot. Again, the tester uses biomass fuel from a pre-weighed bundle to boil a measured quantity of water in a standard pot. Repeating the test with a hot stove helps to identify differences in the performance between a cookstove when it is cold and when it is hot. This is particularly important for stoves with high thermal mass, since these stoves may be kept warm in practice. The final stage of the WBT is the simmer phase that provides an indication of the amount of biomass fuel required to simmer a measured quantity of water at just below the boiling point for 45 min. This step simulates the long cooking of legumes or pulses that are common throughout the world. Since the energy performance of the cookstoves is evaluated using two biomass fuel types, the stoves were allowed to cool to ambient temperature for about 7 h after the testing with the first biomass fuel. Testing of the cookstoves using the second fuel type was initiated afterwards, thus ensuring that the cookstoves were at ambient temperature for the start of the cold start phase of the WBT.

The WBT yields numerous indicators for assessing cookstove performance, but only six widely used performance indices that are of importance to end-users and stove designers are considered namely, the thermal efficiency (H), firepower (P), SFC of the stove per unit of water boiled, burning rate, turn-down ratio and the time to boil a fixed quantity of water [9,21].

Thermal efficiency (H) is the ratio of the work done by heating and evaporating water to the energy consumed by burning fuel [20,22,23]; mathematically,

$$H = \frac{4.186\,\frac{\mathrm{J}}{\mathrm{g}\,^{\circ}\mathrm{C}} \times W_{\mathrm{w}} \times (T_{\mathrm{f}} - T_{\mathrm{i}}) + 2260\,\frac{\mathrm{kJ}}{\mathrm{kg}} \times W_{\mathrm{v}}}{f_d \times \mathrm{LHV}}, \quad (4)$$

where W_{w} is the mass of water in the pot (g), specific heat of water is 4.186 J/g °C, $(T_{\mathrm{f}} - T_{\mathrm{i}})$ is the change in water temperature measured in °C (T_{f} – final water temperature in °C, T_{i} – initial water temperature in °C), W_{v} is the mass of water evaporated from the pot measured in g, and the latent heat of evaporation of water is 2260 kJ/kg. The dry-fuel equivalent consumed during each phase of the test (g) is represented by f_d, and LHV is the lower heating value (also called net calorific value) and is measured in kJ/kg.

$$f_d = f_m \times [1 - (1.12 \times mc)] - 1.5 \times \Delta c, \quad (5)$$

where f_m (in g) is the mass of the biomass fuel used to bring the water to boiling point, and it is calculated by taking the difference between the mass of pre-weighed bundle of the fuel and the mass of the fuel remaining at the end of each test phase; mc is the moisture content of the biomass fuel measured in %

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wet basis; Δc is the net change in char during test and is measured in g.

Firepower, P, is the ratio of the fuel energy consumed by the cookstove per unit time (measured in Watts) during each phase of the test; mathematically,

$$P = \frac{f_d \times \text{LHV}}{60\ (t_f - t_i)}\ , \tag{6}$$

where $(t_f - t_i)$ is the duration of the specific test phase in min; t_i – time at the start of the test phase (min), t_f – time at the end of the test phase (min).

SFC (g/l), is the amount of biomass fuel required to produce a unit output [22]. It is the ratio of the amount of biomass fuel consumed to the amount of water remaining at the end of the trial, i.e. it can be defined for any number of cooking tasks whether the output is boiled water or cooked food. In this case, SFC refers to a measure of the amount of biomass fuel required to bring 1 L (or kilo) of water to boiling point. Mathematically, SFC is calculated as follows:

$$\text{SFC} = \frac{f_d}{W_{wf}} \tag{7}$$

where W_{wf} is the amount of water remaining in the pot after boiling (L), and f_d is the dry-fuel equivalent consumed during the test (g) as earlier defined.

Time to boil a given quantity of water is determined for each phase of the WBT. The time taken to boil water is straightforward. The only complication arises in stoves that can accommodate multiple cooking pots in which case the time required to boil water in the primary pot is defined as the end-point and the other pots are ignored [24]. However, in this study, none of the stoves investigated accommodates more of than one pot at a time.

Burning rate, r_{cb} (g/min), is a measure of the rate of fuel consumption while bringing water to a boil. It is calculated by dividing the equivalent dry-fuel consumed (f_d) measured in g by the duration of the test phase (min) as shown in Equation (8):

$$r_{cb} = \frac{f_d}{t_f - t_i}. \tag{8}$$

Turndown ratio, TDR, is the ratio of the stove's high power output to its low power output; it indicates the degree to which power output from the stove can be controlled by the user [20]. Mathematically, it is expressed as

$$\text{TDR} = \frac{P_h}{P_s}, \tag{9}$$

where P_h is the firepower in the hot start phase (W), and P_s is the firepower in the simmering phase (W). P_h and P_s are calculated using the firepower (P) equation described in Equation (6). The subscripts 'h' (hot start) and 's' (simmering) denote the phase of the WBT for which the fire power is calculated.

Comparison of the performance of the cookstoves

The parameters obtained from the WBT were used to compare the performance of the stoves with respect to the fuel used. Descriptive statistics were used, and analysis of variance (ANOVA) carried out at 5% significance level ($p < 0.05$) to determine any significant difference in the performance parameters among the three cookstoves. Where significant difference was observed, the means were separated using Fisher's least significant difference (FLSD) at 5% level of significance. The experiment was replicated five times.

Results and discussions

Fuel properties

The result of the proximate and ultimate analysis of the fuel briquettes used as fuel in this study is shown in Table 1. The rice husk and sawdust briquettes are about 65 mm in diameter and 95 mm in height (Figure 4).

Performance evaluation of the cookstoves

The performance evaluation of the cookstoves was carried out using two biomass briquette fuel (rice husk and sawdust briquettes) and then compared. WBT was used as the basis for the performance evaluation of the stoves as had been used by other researchers [9,12,24–26].

Performance evaluation using rice husk briquette

The results of the performance evaluation of the ICS, charcoal stove and the three-stone fire using rice husk briquette as fuel in the cold start, hot start and the simmer phases of the WBT are presented in Tables 2–4, respectively. The ANOVA test carried out at 5%

Table 1. Proximate and ultimate analysis of the fuel briquettes.

Fuel		Rice husk briquette	Sawdust briquette
Proximate analysis (% wet basis)	Moisture content	12.3	13.6
	Volatile matter	82.86	90.02
	Ash content	11.23	5.08
	Fixed carbon	5.91	4.90
	Higher heating value (MJ/kg)	30.12	33.02
	Lower heating value (MJ/kg)	17.38	17.57
Ultimate analysis (% wet basis)	Carbon	41.46	41.2
	Hydrogen	5.44	5.84
	Oxygen	41.23	44.34

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Figure 4. Rice husk and sawdust briquettes.

significant level shows that the thermal efficiency, fire power, SFC, time to boil, burning rate and the turndown ratio of the cookstoves are significantly different ($p < 0.05$) from one another. The thermal efficiency of the cookstoves is used as an indicator of the stove performance and fuel savings [9,22]. In comparison to the other two stoves, the ICS has higher thermal efficiency in the high power phase but lower thermal efficiency in the low power phase. The higher thermal efficiency of the ICS in the high power phase of the WBT could be attributed to the insulated combustion chamber of the ICS achieved using a mix of clay and powdered charcoal. The insulation helps to improve the retention of the heat generated within the chamber with minimal loss to the surrounding environment. In addition, the vertical elongated shape of the combustion chamber of the ICS has been reported to significantly improve airflow and mixing for combustion within the

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Table 2. Energy performance of the ICS, charcoal stove and three-stone fire using rice husk briquette in the cold start phase of the water boiling test (±standard deviations).

Performance parameters in the cold start phase	Cookstoves Improved cookstove	Charcoal stove	Three-stone fire	FLSD
Thermal efficiency (%)	32.56 ± 0.99a	14.71 ± 1.04b	14.63 ± 1.03b	2.04
Fire power (Watts)	5037.17 ± 0.54a	11,144.45 ± 5.02b	9050.57 ± 10.01c	12.94
Specific fuel consumption (g/l)	0.21 ± 0.00a	0.24 ± 0.07a	0.25 ± 0.08a	0.12
Time to boil (min)	23 ± 1a	13 ± 1b	16 ± 1c	2
Burning rate (g/min)	17.72 ± 1.14a	38.52 ± 1.22b	31.38 ± 0.44c	1.99

Mean values of the performance parameters of the cookstoves in a row having different letters are significantly different from one another at $p < 0.05$. Means with the same letter are not significantly different from one another ($p > 0.05$). FLSD means Fisher's least significant difference.

Table 3. Energy performance of the ICS, charcoal stove and three-stone fire using rice husk briquette in the hot start phase of the water boiling test (±standard deviations).

Performance parameters in the hot start phase	Cookstoves Improved cookstove	Charcoal stove	Three-stone fire	FLSD
Thermal efficiency (%)	36.62 ± 1.19a	8.38 ± 0.31b	10.49 ± 1.07c	1.88
Fire power (Watts)	7240.49 ± 0.50a	14,472.69 ± 6.95b	16,894.42 ± 3.97c	9.25
Specific fuel consumption (g/l)	0.19 ± 0.00a	0.29 ± 0.01a,b	0.34 ± 0.09b	0.10
Time to boil (min)	14 ± 1a	14 ± 1a	12 ± 1b	2
Burning rate (g/min)	25.17 ± 0.76a	50 ± 1.00b	58.42 ± 0.92c	1.8
Turndown ratio	1.41 ± 0.10a	2.83 ± 0.13b	0.94 ± 0.01c	0.2

Mean values of the performance parameters of the cookstoves in a row having different letters are significantly different from one another at $p < 0.05$. Means with the same letter are not significantly different from one another ($p > 0.05$). FLSD means Fisher's least significant difference.

Table 4. Energy performance of the ICS, charcoal stove and three-stone fire using rice husk briquette in the simmer phase of the water boiling test (±standard deviations).

Performance parameters in the simmer phase	Cookstoves Improved cookstove	Charcoal stove	Three-stone fire	FLSD
Thermal efficiency (%)	3.46 ± 0.09a	19.51 ± 1.15b	9.67 ± 0.74c	1.58
Fire power (Watts)	5148.66 ± 0.52a	5149.49 ± 3.99a	9653.68 ± 3.11b	5.87
Specific fuel consumption (g/l)	0.48 ± 0.00a	0.65 ± 0.08b	1.25 ± 0.03c	0.09
Burning rate (g/min)	17.32 ± 1.04a	17.61 ± 0.971b	33.52 ± 1.16c	2.12

Mean values of the performance parameters of the cookstoves in a row having different letters are significantly different from one another at $p < 0.05$. Means with the same letter are not significantly different from one another ($p > 0.05$). FLSD means Fisher's least significant difference.

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chamber, and also helps to direct the heated air to the pot thus increasing heat transfer [9]. This is in contrast to the design of the two conventional stoves whose performance is evaluated in this study.

The low thermal efficiency of the ICS in the simmering stage of the low power phase compared to the other two cookstoves suggests that in its present design, it may not be the most appropriate cookstove for long-time slow cooking. The low thermal efficiency could be attributed to the lack of a mechanism to control the inflow of air into the combustion chamber which is needed to achieve a steady low heat for simmering. The thermal efficiency of the ICS in the hot start of the high power phase, 36.62 $\pm$ 1.19% (Table 3), is observed to be higher than its thermal efficiency in the cold start, 32.56 $\pm$ 0.99% (Table 2). This is a common trend in the performance of ICSs attributable to the already charged state – heated stove and fuel – of the cookstove in the hot start phase of the WBT. In the cold start phase, some energy is expended in heating up the biomass fuel and the combustion chamber of the cookstove, whereas in the hot start phase, the cookstove and the fuel are already heated up thus improving the thermal efficiency of the stove in this phase.

The highest thermal efficiency of 19.51 $\pm$ 1.15% is recorded for the charcoal stove in the simmering of the low power phase. The thermal efficiency of the three-stone fire (14.63 $\pm$ 1.03%) and the charcoal stove (14.71 $\pm$ 1.04%) in the cold start of the high power phase is not significantly different from one another ($p > 0.05$). The reported thermal efficiency ratings are within the range previously reported [22]. The fire power of the cookstoves in the cold start, hot start, and simmering phases range from 5037.17 $\pm$ 0.54 to 11,144.45 $\pm$ 5.02, 7240.49 $\pm$ 0.50 to 16,894.42 $\pm$ 3.97, and 5148.66 $\pm$ 0.52 to 9653.68 $\pm$ 3.11 Watts, respectively. In all the water boing test phases, the ICS has the lowest firepower; however, in the simmering phase, the mean firepower value recorded (5148.66 $\pm$ 0.52 W) for the ICS is not significantly different from that recorded for the charcoal stove (5149.49 $\pm$ 3.99 W). The low fire power of the ICS suggests that the flame from the cookstove during use is consistent and stable. This contributes to minimal loss of heat to the environment as opposed to the case of unstable and inconsistent flame which is a common feature in the use of the three-stone fire and the charcoal stove. The consistent and stable flame in the ICS could be attributed to the improved airflow and mixing in the vertical elongated combustion chamber of the stove.

The SFC of the ICS measured in g/l of the boiled water is determined to be lowest in high power and low power phases of the WBT compared to the SFC of the other two cookstoves. The determined SFC of the ICS is 0.21, 0.19, and 0.48 g/l in the cold start, hot start and the simmering stages, respectively. Although these values are numerically lower than the values determined for the charcoal stove and three-stone fire in each phase of the test, they are not statistically significantly different from the values determined for the other stoves ($p < 0.05$) except in the simmering phase. This shows that the ICS offers better fuel savings relative to the other two stoves particularly in the low power phase which accounts for much of the fuel and energy requirements for cooking [22]. In a region where fuel scarcity is a serious problem, biomass fuel savings using the ICS can have a significant impact. The low SFC of the ICS is reflected in its time to boil 2.5 kg of water which was highest in the cold start (23 $\pm$ 1 min) but shared the same mean value with the charcoal stove in the hot start of the high power phase (14 $\pm$ 1 min). The charcoal stove has the lowest time to boil 2.5 kg of water (13 $\pm$ 1 min) in the cold start phase while the lowest time of 12 $\pm$ 1 min is observed for the three-stone fire in the hot start phase. The lowest time to boil 2.5 kg of water observed for the charcoal stove and the three-stone fire in the cold start (Table 2) and hot start (Table 3) of the high power phases, respectively, could be due to the high burning rates observed for the two stoves in the high power phases. The burning rates are determined to be 38.52 $\pm$ 1.22 and 58.42 $\pm$ 0.92 g/min for the charcoal stove and the three-stone fire, respectively. In all the WBT phases, the ICS gave the lowest burning rate which is significantly different ($p < 0.05$) from the values determined for the charcoal stove and the three-stone fire. This is a reflection of the low SFC earlier reported for the ICS. The turndown ratio which represents the degree to which the firepower of the stove can be controlled by the user [20] is observed to be highest for the charcoal stove (2.83 $\pm$ 0.13) followed by the ICS (1.41 $\pm$ 0.10) and then the three-stone fire (0.94 $\pm$ 0.01).

Performance evaluation using sawdust briquette

The result of the performance evaluation of the ICS, charcoal stove and the three-stone fire using sawdust briquette as fuel in the cold start, hot start and simmering phases of the WBT is presented in Tables 5–7, respectively. It is observed, based on the ANOVA test carried out at 5% significant level, that the performance parameters of the three stoves obtained in the WBT, that is, the thermal efficiency, firepower, SFC, time to boil, burning rate and the turndown ratio, varied significantly from one another ($p < 0.05$). The thermal efficiency of the ICS and the three-stone fire determined using sawdust as fuel is not significantly different ($p > 0.05$) in the cold start (12.71 $\pm$ 1.06 and 12.70 $\pm$ 0.96%), hot start (17.57 $\pm$ 1.07 and 17.76 $\pm$ 1.00%) and the simmering (9.48 $\pm$ 0.84 and 9.4 $\pm$ 0.4%) stages, respectively. The thermal efficiency recorded for the charcoal stove in the cold start (17.66 $\pm$ 0.85%), hot start (20.66 $\pm$ 0.58%) and the

Table 5. Energy performance of the ICS, charcoal stove and three-stone fire using sawdust briquette in the cold start phase of the water boiling test (±standard deviations).

Performance parameters in the cold start phase	Cookstoves Improved cookstove	Charcoal stove	Three-stone fire	FLSD
Thermal efficiency (%)	12.71 ± 1.06a	17.66 ± 0.85b	12.70 ± 0.96a	1.92
Fire power (Watts)	7810.28 ± 10.00a	10,648.15 ± 10.40b	9151.56 ± 1.77c	16.77
Specific fuel consumption (g/l)	0.17 ± 0.00a	0.18 ± 0.08a	0.23 ± 0.06a	0.11
Time to boil (min)	15 ± 1a	11 ± 1b	16 ± 1a	2
Burning rate (g/min)	26.71 ± 0.72a	36.70 ± 1.04b	31.48 ± 1.18c	2

Mean values of the performance parameters of the cookstoves in a row having different letters are significantly different from one another at $p < 0.05$. Means with the same letter are not significantly different from one another ($p > 0.05$). FLSD means Fisher's least significant difference.

simmering (14.82 ± 1.07) stages is significantly ($p < 0.05$) higher than that reported for the ICS and the three-stone fire.

The firepower of the ICS determined using sawdust briquette as fuel is lowest and significantly different ($p < 0.05$) in the high power and low power phases compared to the other two cooking devices. High firepower leads to maximum heat loss and unstable flame in the burning of biomass fuel in cooking devices which in turn leads to low thermal efficiency of the device as earlier stated. The SFC which provides more information about the performance of a stove followed the same trend as the firepower for the ICS. However, the value recorded in the cold start (0.17 ± 0.00 g/l) is not significantly different ($p > 0.05$) from the values recorded for the charcoal stove (0.18 ± 0.08 g/l) and the three-stone fire (0.23 ± 0.06 g/l). The ICS offers better fuel savings relative to the other two stoves using sawdust briquette as the fuel. This could be attributed to the relatively efficient use of the heat generated within the combustion chamber of the ICS for boiling.

The time recorded as the time to boil 2.5 kg of water in the cold start for the ICS (15 ± 1 min) and the three-stone fire (16 ± 1 min) is not significantly different ($p > 0.05$) as shown in Table 5, but significantly ($p < 0.05$) higher than that recorded for the charcoal stove (11 ± 1, min). Even though the charcoal stove has the lowest time to boil in the cold start, its burning rate is highest in the cold start (36.70 ± 1.04 g/min). In all the water boiling phases, the ICS has the lowest burning rate and is significantly different ($p < 0.05$) from the burning rate recorded for charcoal stove and the three-stone fire. This is a reflection of the low SFC recorded for the ICS in the WBT phases. The turndown ratio, which indicates the degree to which the power output from the stove can be controlled by the user, increased from 1.93 ± 0.03 for the three-stone fire to 3.53 ± 0.31 for the ICS using sawdust briquette as fuel. This value reflects only the amount of power control that was actually used.

Rice husk briquette vs. sawdust briquette for the ICS

From the result of the comparative performance evaluation of the three cookstoves, it is obvious that the ICS offered better performance in most of the parameters investigated, particularly with the use of rice husk briquette as fuel. The success of an improved cookstove programme is defined by the number of stoves in actual use in communities and the extent of multiple fuels and stove usage, rather than simply the number of stoves that are disseminated [22]. The performance of the ICS investigated in this study using two biomass

Table 6. Energy performance of the ICS, charcoal stove and three-stone fire using sawdust briquette in the hot start phase of the water boiling test (±standard deviations).

Performance parameters in the hot start phase	Cookstoves Improved cookstove	Charcoal stove	Three-stone fire	FLSD
Thermal efficiency (%)	17.57 ± 1.07a	20.66 ± 0.58b	17.76 ± 1.00a	1.81
Fire power (Watts)	8543.37 ± 4.04a	9762.48 ± 0.87b	10,649.74 ± 9.01c	11.44
Specific fuel consumption (g/l)	0.15 ± 0.003a	0.18 ± 0.01b	0.17 ± 0.00b	0.01
Time to boil (min)	12 ± 1a	12 ± 1a	11 ± 1a	2
Burning rate (g/min)	29.28 ± 0.67a	33.50 ± 1.41b	36.34 ± 0.69c	1.97
Turndown ratio	3.53 ± 0.31a	2.24 ± 1.05b	1.93 ± 0.028b	1.26

Mean values of the performance parameters of the cookstoves in a row having different letters are significantly different from one another at $p < 0.05$. Means with the same letter are not significantly different from one another ($p > 0.05$). FLSD means Fisher's least significant difference.

Table 7. Energy performance of the ICS, charcoal stove and three-stone fire using sawdust briquette in the simmer phase of the water boiling test (±standard deviations).

Performance parameters in the simmer phase	Cookstoves Improved cookstove	Charcoal stove	Three-stone fire	FLSD
Thermal efficiency (%)	9.48 ± 0.84a	14.82 ± 1.07b	9.4 ± 0.4a	1.64
Fire power (Watts)	2410.01 ± 8.52a	4555.67 ± 1.94b	5532.48 ± 2.09c	10.36
Specific fuel consumption (g/l)	0.24 ± 0.01a	0.5 ± 0.10b	0.5 ± 0.10b	0.16
Burning rate (g/min)	8.66 ± 0.96a	15.73 ± 1.06b	18.59 ± 1.03c	2.04

Mean values of the performance parameters of the cookstoves in a row having different letters are significantly different from one another at $p < 0.05$. Means with the same letter are not significantly different from one another ($p > 0.05$). FLSD means Fisher's least significant difference.

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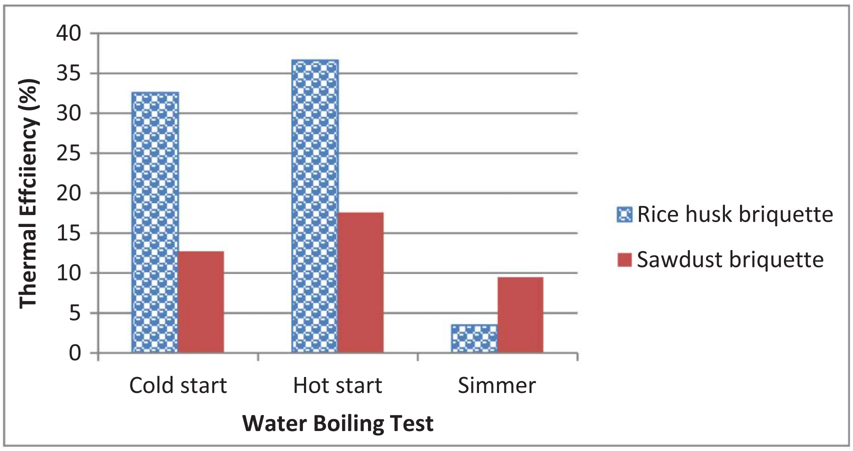

Figure 5. Thermal efficiencies of the ICS using two fuel sources.

fuel, rice husk and sawdust briquettes, is compared. The result of the thermal efficiency, firepower, SFC, time to boil, burning rate, and turndown ratio is observed to be significantly different from each other ($p < 0.05$) in the cold start, hot start and simmering phases of the WBT. In the cold start and hot start, the thermal efficiency of the ICS using rice husk briquette is observed to be higher than the efficiency of the stove using sawdust briquette as fuel (Figure 5). The reverse is, however, the case in the simmering phase. For the firepower, the mean value in the cold and hot starts recorded for the ICS using sawdust briquette is 7810.28 and 8543.37 Watts, respectively, and is higher than the corresponding values determined using rice husk briquette (Figure 6). The SFC of the ICS is lower in all the WBT phases using sawdust briquette as well as the time to boil 2.5 kg of water to boiling point (100 °C) in the high power phase (Figures 7 and 8). The burning rate is observed to be lower for rice husk briquette in the high power phase but higher in the simmer stage (Figure 9). The burning rate of the briquettes could be influenced by the relaxed density of the briquette. The turndown ratio of the ICS using rice husk briquette is lower (1.41 ± 0.10) when compared to that obtained using sawdust briquette (3.53 ± 0.31).

The above results suggest that the energy performance of a stove for heating tasks could be dependent on the type of fuel used, as has been reported in a previous study [9]. Similarly, CO and particulate matter emissions from cookstoves have also been reported to be substantially influenced by the fuel type [27]. A number of characteristic features of the biomass fuel could be responsible for the difference in the performance of the ICS including the physical, chemical and mechanical properties of the fuel. In the case of the biomass briquettes for example, the compaction of the briquettes and the particle size distribution of the biomass fuel could potentially influence the burning rate. This presents an important line of study that requires further research efforts for a better understanding of the characteristics of biomass fuel that influence the performance of cookstoves. In addition, efforts should be made by stakeholders in developing robust ICSs capable of maintaining consistent energy performance irrespective of the type of biomass fuel used.

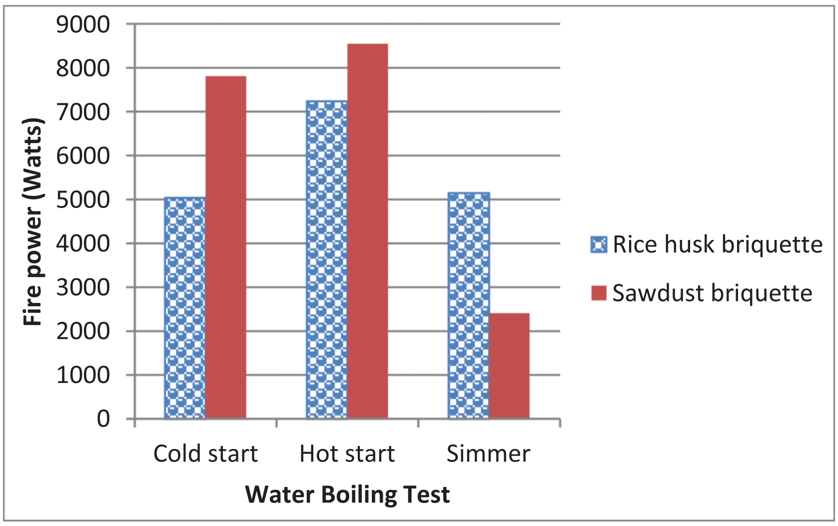

Figure 6. Fire power of the ICS using two fuel sources.

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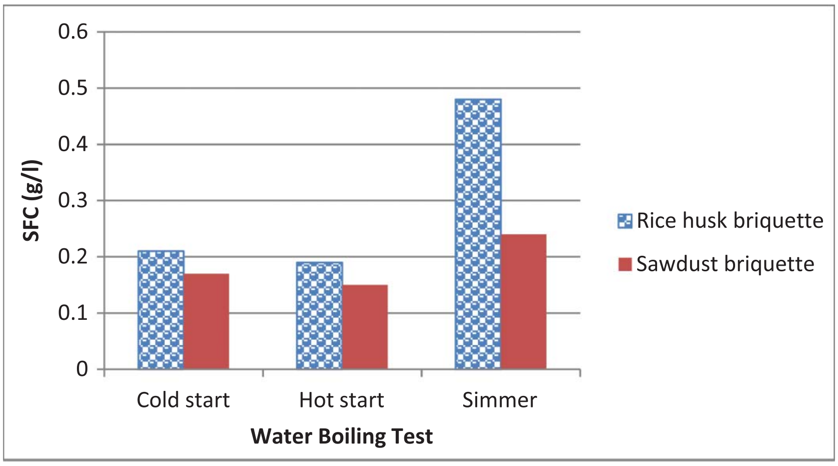

Figure 7. Specific fuel consumption (SFC) of the ICS using two fuel sources.

The performance of the ICS developed in the present study is compared with that of some ICSs in the literatures based on their energy performance in the hot start of the high power phase (Table 8). Five natural draft and one forced draft mode cookstoves are considered. Based on available data as presented in Table 8, the ICS developed in this study performed relatively better in terms of the thermal efficiency. Its thermal efficiency is higher than that of all the natural draft mode cookstoves considered in the comparison. However, its thermal efficiency is lower than that of the forced draft cookstove. The forced draft mode of the cookstove is powered by a thermos-electric generator to which a blower is connected to increase the air flow into the combustion chamber of the stove. The SFC of the ICS of the present study (0.19 g/l) which is

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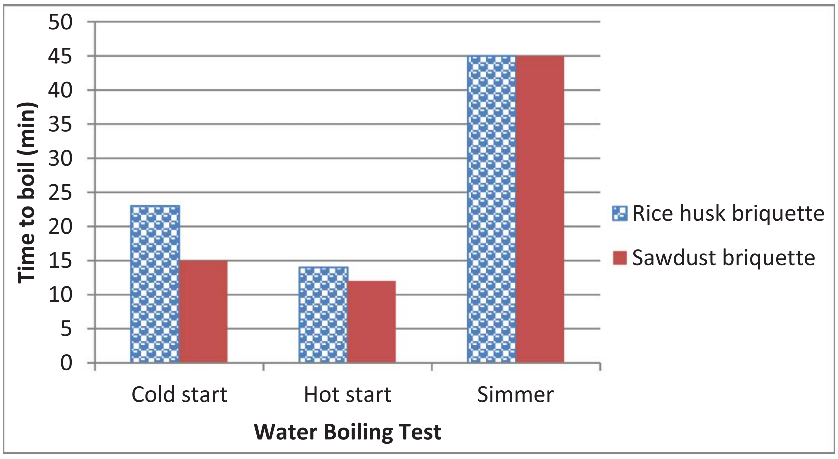

Figure 8. Time to boil water for the ICS using two fuel sources.

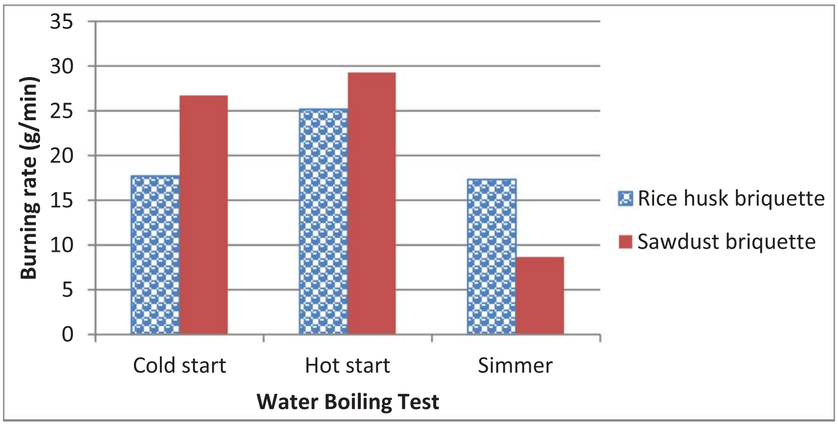

Figure 9. Burning rate of the ICS using two fuel sources.

Table 8. Comparison of the performance of various improved cookstoves in the hot start phase of the water boiling test.

Performance parameters	Improved cookstoves: Cookstove (present study)	Centrafricain stove [5]	Rice husk stove [10]	Ceramic stove [5]	Top-lit updraft [9]	Patsari stove [22]	Forced draft stove [28]
Fuel	Rice husk	Wood	Rice husk	Wood	Wood chips	Wood	Wood
Thermal efficiency (%)	37	17	18	16	14.2	17	47
Fire power (Watts)	7241	12,470	4100	13,641	1497	4400	3970
Specific fuel consumption (g/l)	0.19	153	331 g/kg	161	0.17	0.18 kg/kg	108.4
Time to boil (min)	14	18	27	19	5	–	18
Burning rate (g/min)	25	40	18	44	79.8	–	–
Turndown ratio	1.4	2.7		2.7	0.25	–	3.6

an indication of the potential fuel savings of the stove is comparable to that of the TLUD cookstove (0.17 g/l). The TLUD cookstove presented the shortest time to boil of 5 min while the ICS of this study has a time to boil of 14 min and it is lower than that of the other stoves including the forced draft cookstove. Although the biomass used in the testing of the cookstoves in Table 8 are not all rice husk briquette, the ICS developed and evaluated in this study generally outperformed all the natural draft cookstoves on the basis of their thermal efficiency.

Conclusions

WBT was carried out on three cooking devices – an improved biomass cookstove, charcoal stove, and the three-stone fire – using rice husk and sawdust briquettes, and their performances were compared. It was observed that mean values determined for the thermal efficiency, firepower, SFC, time to boil, burning rate, and turndown ratio of the three cookstove using rice husk and sawdust briquettes were significantly different from each other ($p < 0.05$). The ICS demonstrated clear superiority over the charcoal stove and the traditional three-stone fire based on their thermal efficiency in the high power phase of the WBT. Additional work is, however, needed to improve the thermal efficiency of the ICS in the low-power simmering phase. In comparing the performance of the ICS using two fuel sources, rice husk and sawdust briquettes, no clear trend was observed; however, the performance of the cookstove could have been dependent on the type of fuel used. Based on the results of the study, the improved biomass cookstove offered better performance relative to the two conventional cookstoves and some other improved natural draft mode cookstoves available in the literatures.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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