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Sustainable Cooking Based on a 3 kW Air-Forced Multifuel Gasification Stove Using Alternative Fuels Obtained from Agricultural Wastes

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Received: 24 July 2020; Accepted: 16 September 2020; Published: 18 September 2020

Abstract: In this research work, a 3 kW stove based on biomass gasification, together with a fuel obtained from agriculture wastes as an alternative to the commonly used charcoal, have been developed looking for sustainable cooking in poor communities. Alternative fuel (BSW) are briquettes obtained by carbonization and densification of agricultural solid wastes. Two laboratory methods, water boil test (WBT) and controlled kitchen test (CCT) were used to analyze the performance of this approach by comparing the proposed improved stove (ICS-G) with the traditional one (TCS), when using both types of fuels: charcoal and BSW. Results indicate that consumption of charcoal decreases by 61% using the improved ICS-G stove instead of the traditional TCS. Similar fuel savings are obtained when using BSW fuels. BSW fuel allows for a carbon monoxide (CO) emission reduction of 41% and 67%, and fine particles (PM) in a 84% and 93%, during the high and low power phases of the tests, respectively. Use of BSW fuel and ICS-G stove instead of the TCS stove with charcoal, provides a cooking time reduction of 18%, savings of \$353.5 per year per family in the purchase of fuel, and an emission reduction of 3.2 t CO_2/year.family.

Keywords: cook stove; alternative fuel; gasification; sustainability

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1. Introduction

In recent decades, the demand for primary energy resources has considerably increased due to the high growths, both in world population and demand, while renewable resources, such as firewood, are often poorly managed in this scenario of increasing demand. Consequently, the proper use of these resources becomes mandatory for sustainable development [1]. Currently, in the world about three billion people depend on solid fuels, such as firewood and charcoal, for cooking food and heating, without having access to clean cooking methods [2–5]. Solid fuels are the main source of energy used for heating and cooking in many urban and suburban communities in sub-Saharan African countries, representing more than 80% of the primary energy supply of these areas [6–8]. The traditional cooking system most used in these communities is based on burning coal or firewood on stoves with the pots placed on top, resulting in a process of very low thermal efficiency and, therefore, in an excessive fuel consumption with the consequent environmental damage [9–11], including excessive CO_2 emissions, thus contributing to global warming and climate change [12]. Significant efforts are in progress to improve cooking stoves and limit the above-mentioned drawbacks. It has been found that fan-assisted cookstoves produce both lower concentrations of flue gases and particulate matter [13]. Positive experience in Rwanda promoting biomass pellets and a fan micro-gasification improved cookstove as a clean cooking alternative to charcoal has been obtained [14]. Gasifier Cookstove using biochar improves energy efficiency and air quality [15] and investigation on the gas production from a gasifier cookstove indicates the importance of primary air to reduce tars and increases combustion [16]. This paper addresses all these aspects: gasifier implementation, energy efficiency, air quality, pellets use, etc., looking for the improvement of cook stove both in the technical and economical aspects, with special emphasis on the use of agriculture wastes to reduce the environmental impact of cooking in under-developed countries.

Although agriculture and timber industry are considered as mainly responsible for large-scale deforestation, energy supply for food cooking [17] also has an important contribution to deforestation and land degradation. The collection of firewood and the production of charcoal for cooking can have a significant impact on local ecosystems, particularly in overpopulated areas [18,19]. Due to the fight against climate change and the search for energy security, biomass resources are becoming more important than ever, given they can be considered as renewable and sustainable source of energy, neutral for climate impact [20] and socially viable. This is possible if: (i) they are collected in sustainably managed forests, where each cut tree is replanted directly; and, (ii) the wood is burned using appropriate technologies to maximize energy efficiency and minimize harmful emissions inside the house (CO and PM) and to the atmosphere (CO_2) [21]. In sub-Saharan African countries, burning agricultural wastes (including stems, herbs and leaves) is the easiest and most economical way to eliminate the volume of those wastes. Outdoor incineration allows for a fast elimination of previous crops wastes, as well as the pruning and cleaning of the crop area. It is estimated that burning biomass, such as wood, leaves, trees and pastures, including agricultural wastes, is responsible for 40% of carbon dioxide (CO_2), 32% of carbon monoxide (CO), 20% of suspended fine particles (PM) and 8% of other emissions to the atmosphere [22,23] of these areas. These biomass wastes could be instead used in cooking stoves, using a biomass gasification technology, and thus be an important part of solving these emission problems [24,25]. The amount of peanut shell waste produced annually in the Democratic Republic of the Congo is estimated at 114,000 tons and that of rice husk is around 133,200 t/year [26,27]. The province of Bandundu, to which the present study is applied, being a province totally dedicated to agriculture, represents almost 20% of the production of agricultural residues in the Democratic Republic of the Congo (DRC). Using improved gasification stoves, energy efficiencies can easily reach values greater than 60%, compared to 30–40% of the current ones [28,29]. Most of the technologies currently in use consist of enhanced direct combustion ICS with a ceramic combustion chamber. This approach simply involves directing much of the combustion energy to the pot. In this system, it is difficult to improve the quality of combustion because the air supply is naturally ventilated and therefore difficult to regulate, which leads to incomplete combustion with a direct negative consequence on energy efficiency and polluting emissions. In order to reduce the consumption of firewood and CO_2 emissions in cooking activities, a 3 kW power stove has been optimized using the biomass micro-gasification principle. Additionally, to reduce the consumption of forest biomass, an alternative fuel to charcoal consisting of briquettes produced by carbonization and densification of agricultural solid wastes (peanut husk and rice husk, mainly) has been developed. To verify these improvement approaches, two laboratory test methods, the boiling water test (WBT) and the controlled cooking test (CCT), have been applied to the traditional stove (TCS) and the new one we are proposing (ICS-G), using in both cases charcoal and alternative fuel (BSW) briquettes as fuels.

2. Materials and Methods

2.1. Study Case

The study was conducted in the city of Bandundu located 409 km from the DRC capital Kinshasa and in an essentially agricultural region. The population size is estimated at 3,673,000 inhabitants and

90% of the population is considered dependent on biomass-firewood for cooking food. The average family size is six people and the eating habits are such that only one large meal is served daily.

2.2. Fuels

The fuel currently used for food cooking in sub-Saharan African countries is charcoal. We have deduced its main characteristics by application of standards biomass characterization techniques [30]. Obtained results are detailed in Table 1.

Table 1. Thermo-physical characteristics of traditional charcoal.

Bulk Density [kg·m^{-3}]	**Moisture Content**	**Volatile Matter**	**Ash Content**	**Fixed Carbon**	**HHV [MJ·kg^{-1}]**	**LHV [MJ·kg^{-1}]**
365	7%	13%	2%	85%	30.2	29.8

There are many different solid biomass residues from agricultural activities in the Democratic Republic of the Congo (DRC). In this work, we have selected as sources for fuel for cooking activities those with the better thermo-physical properties. The proposed fuel (BSW) for cooking are briquettes with a cylindrical shape of 2 cm in diameter and 3.5 cm in length (Figure 1), so they are well adjusted to the typical cooking stoves. The briquettes are made from solid agricultural wastes, such as peanut shells and rice husks. Manufacturing of briquettes entails the following steps:

(1st) Carbonization: carried out in a traditional furnace composed of a cylindrical metal barrel 80 cm in diameter and 120 cm high. The metal barrel has about 30 vent holes, 3 cm diameter each, at its lower base. The removable upper base has a 10 cm diameter and 100 cm high chimney. Char waste is introduced from the top with a quantity of 20 kg of solid waste (rice husks or peanuts). The fire is lit from the top of this furnace. The carbonization system is endothermic in oxygen, evolving at temperatures between 250–500 °C for 2–3 h. After this, holes in the lower base are covered and the lid is closed until cooled, which can last 3–4 h. The carbonization yield varies between 18–20%.

(2nd) Grinding: the char waste is placed in a mortar with an artisanal pestle to convert the charred waste into a fine powder with a grain size of 1 mm.

(3rd) Binding: the resulting powder, combined with a binder biomass (paper pulp and cassava fibers), is mixed properly to have a good homogenization.

(4th) Densification: this mixture is manually densified to form the briquettes.

(5th) Drying: the briquettes are dried in the sun for three days before their use.

Figure 1. BSW briquettes.

Three types of briquettes were manufactured with the dosages detailed in Table 2. Their elemental composition and the different thermo-physical properties of these briquettes, respectively, are shown at Tables 3 and 4. These values were obtained following current regulations for this type of characterization [30]. From the cooking tests carried out summarized in Table 4, it results that BSW3 structure is the most adequate to be used, given its higher calorific value.

Table 2. Composition of the different types of briquettes [% mass].

Type	E1	E2	E3	E4	E5
BSW 1	50%	-	20%	15%	15%
BSW 2	-	50%	30%	10%	10%
BSW 3	-	20%	50%	15%	15%

(E1 = biochar rice, E2 = biochar peanut, E3 = sawdust, E4 = paper paste, E5 = cassava xilema fiber).

Table 3. Alternative fuel (BSW) elemental composition.

Type	C	H	N	O	S
BSW 1	51.70%	2.40%	0.70%	45.20%	0.00%
BSW 2	52.50%	3.20%	0.70%	43.60%	0.00%
BSW 3	50.70%	2.70%	0.60%	46.00%	0.00%

Table 4. BSW thermo-physical characteristics.

	Bulk Density $[\mathrm{kg \cdot m^{-3}}]$	Moisture Content	Volatile Matter	Ash Content	Fixed Carbon	HHV $[\mathrm{MJ \cdot kg^{-1}}]$	LHV $[\mathrm{MJ \cdot kg^{-1}}]$
BSW 1	520	7.50%	34.30%	24.50%	33.70%	18.2	17.7
BSW 2	550	10.20%	36.00%	25.80%	28.00%	18.4	17.7
BSW 3	560	10.30%	38.80%	19.00%	32.90%	19	18.3

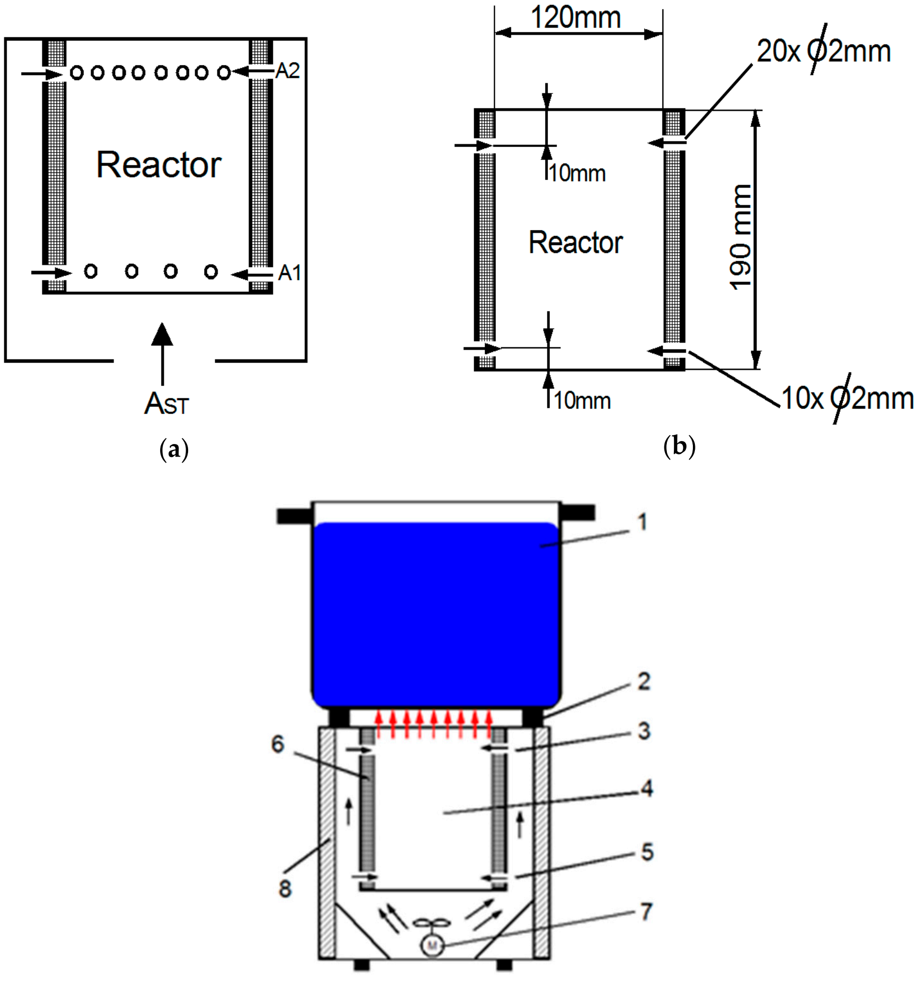
2.3. *Stoves*

Figure 2a illustrates the traditional stove (TCS), currently used in DRC, taken as the reference for our study. It consists of a cylindrical combustion chamber, 100 mm deep and 280 mm in diameter, with holes, 10 to 12 mm in diameter, both in the base and the lateral side [31].

(**a**) (**b**)

Figure 2. Cooking stoves. (**a**) Traditional cookstove, TCS. (**b**) Improved Cookstove Gasifier, ICS-G.

Our improved gasification stove (ICS-G), shown in Figure 2b, generates combustion through two consecutive stages with a stoichiometric proportion of 6 kg of air per 1 kg of biomass to ensure total biomass combustion. The fraction of air that is introduced into the lower part of the reactor (ε), in respect to the total one used by the stove, is fixed to 0.3–0.4, with the purpose to gasify solid biomass into a gaseous element (syngas). The remaining quantity of air, known as secondary air, is introduced at the top of the reactor, and has the function to ensure a complete combustion of the biomass. The number of holes and, therefore, the primary and secondary air inlet sections, are such that they ensure these air proportions. The different components of this ICS-G are shown at the diagrams in the Figure 3.



(**a**)

(**b**)

(**c**)

Figure 3. Improved Cookstove Gasifier, ICS-G. (**a**): air flows; (**b**): dimensions; (**c**): components.

Calculation of the improved ICS-G stove dimensions takes into account different aspects [32–36]; in particular, the amount of energy needed to cook a meal for a six-person household was estimated to be around Q = 15.8 MJ [28,32,33]. Therefore, the minimum power requirement to cook food for a meal for a family of six persons with a burning time in the range 1.0–1.5 h [34] is about 3 kW. The rest of this stove design parameters are detailed in Table 5.

Table 5. Improved gasification stove (ICS-G) design parameters.

Parameter	Symbol	Value
Power	P	3 kW
Stoichiometric air	SA	6 kg air/kg biomass
Equivalence ratio	ε	0.33
Air density	ρ_a	1.25 kg·m^{-3}
Thermal efficiency	η_{th}	60%
Cooking time	Δt	1 h
Specific biomass weight	ρ_f	560 kg.m^{-3}
Air holes diameter	d_e	2 mm
Specific gasification rate	SGR	110 kg·m^{-2}·h^{-1}

The following ICS-G characteristics are deduced:

(a) Fuel Consumption Rate (FCR): amount of biomass fuel to be used by the stove to provide the required energy, it is deduced by using the relationship (1).

$$FCR = \frac{P * 3600}{LCV * \eta_{th}} \tag{1}$$

where LCV represents the fuel low specific calorific power, η_{th} accounts for the gasifier thermal efficiency and P is the power reactor. For this gasifier, the thermal efficiency was initially assumed as 60–70% [28,33,35].

(b) Reactor Diameter [32,34–36].

The reactor diameter is a function of the fuel consumption rate and the specific gasification rate (SGR), this one defined as the amount of fuel used per unit of time and per unit of area in the reactor. (110–210 kg·m^{-2}·h^{-1}) The diameter can be determined using expression (2).

$$D = \left(\frac{4 \ * \ FCR}{SGR \ * \ \pi}\right)^{0.5} \tag{2}$$

(c) Reactor Height: the height of the reactor determines the operation time of the combustion chamber once the fuel is loaded. It is deduced by using Equation (3) [32,34–36].

$$H = \frac{SGR \ * \ \Delta t}{\rho_f} \tag{3}$$

where, SGR is the specific gasification rate, Δt is the estimated reactor operation time and ρ_f is the fuel density.

(d) Amount of air needed for gasification (Q_{PA}): this magnitude refers to the air flow rate needed to gasify the fuel and it is given by Equation (4).

$$Q_{PA} = \frac{\varepsilon * FCR * SA}{\rho_a} \tag{4}$$

where, Q_{PA} is the airflow rate, ε is the gasification equivalence ratio (0.3 to 0.4), FCR is the fuel consumption rate, SA is the stoichiometric amount of air required by unit of biomass (6 kg air per kg biomass) [33] and ρ_a is the air density.

The total amount of air needed for total combustion in the stove is deduced from the above-mentioned Q_{PA}, by dividing it by the equivalence ratio ε.

The parameters of a 3 kW stove are deduced using the abovementioned equations and are detailed in Table 6.

Table 6. Parameters of a 3 kW reactor.

D [cm]	H [cm]	FCR [kg·h^{-1}]	Q_{PA} [m^3·h^{-1}]	QAT [m^3·h^{-1}]
12	19	0.906	1.304	4.34

Air is introduced in the combustion chamber (Figure 3a) through the inputs A1 (primary air for gasification) and A2 (secondary air for total combustion). The total air flux A_{ST} is guaranteed by a 3 W fan at 12 V DC. A small speed controller allows for the regulation of the airflow in the reactor. A lithium-ion battery (12 V; 9 Ah) and a solar panel (5 W) provide the necessary power for the system. The primary air enters through 10 small holes of 2 mm in diameter located 10 mm from the bottom of the reactor. The secondary air enters the reactor through 20 small holes 2 mm in diameter at the top of the stove (Figure 3b).

ICS-G stove includes the following components (Figure 3c):

a. Reactor: it is cylindrical, 12 cm internal diameter and 19 cm deep, and surrounded by a 1 cm layer of clay.
b. Secondary Air Duct Tunnel: a second, 16 cm cylinder surrounds the reactor, so a 1 mm gap allows secondary air to rise, sweeping through the reactor body. This allows preheating of the secondary air.
c. Thermal insulation: a 4 cm layer of rock wool
d. Fan: a small 3 W-12 V DC motor provides the primary and secondary air supply.
e. Power supply: a small 5 W solar panel that charges a 9 Ah-12 V lithium battery.
f. Regulation: a potentiometric circuit allows varying the supply voltage of the small motor, to control the primary and secondary airflows.
g. Outer shell: it is a 24 cm cube made of 1 mm thick sheet metal. The lower base is perforated to allow the motor to inject ambient air.

2.4. Instrumentation

The equipment used to characterize the proposed fuel and stove include:

- Balance OHAUS V11 P6 with a 6 kg capacity and 0.1 g accuracy. Used to determine the amount of fuel used in the WBT and CCT test.
- Balance OHAUS NVL 20,000/2 with a 20 kg capacity and 1 g accuracy. This scale was used to measure the amount of water to boil during the WBT test and the amount of dry and cooked meal during the CCT test.
- Balance Mettler AB304-S/FACT with a 320 g capacity and 0.1 mg accuracy. It was used for the characterization of briquettes
- Select Muffle Furnace SELECT-HORN, Capacity 9 L. Power 3000 W. Maximum temperature 1100 °C. This muffle was used for the thermo-physical characterization of briquettes
- Combustion calorimeter CAL2 K/1. Resolution 0.001 MJ/kg and 0.000001 °C. To allow for the determination of the calorific value of the briquettes

A Portable Emission Monitoring System (PEMS) was used for the determination of the polluting emissions of CO and PM during the Water Boiling Test, WBT (Figure 4). This system consists of a bell (a1), inside which the stove to be tested (a2) is placed; an extractor (a3) absorbs all the polluting emissions and takes a sample of the emission gases to take them to the sensor box (a4). Finally, an interface with a data acquisition system allows for the data storage in a computer (a5).

Figure 4. Portable Emission Monitoring System (PEMS).

2.5. Methods

(a) Laboratory tests

Performance of the ICS-G and the TCS stoves were evaluated by using the WBT 4.2.3 [37] and CCT v.2 [38] laboratory methods. WBT 4.2.3 protocol is a laboratory simulation of the energy efficiency of the cooking process using water in three sequential phases, as detailed in Figure 5. The first phase, High Power Cold Start (HPCS), begins by heating the stove, filled with water from room temperature, until the water reaches boiling point. In the second phase, High Power High Start (HPHS), with the stove already hot from the previous phase, a new refill with fresh water is made and heating starts to reach again the water boiling temperature. In the third phase, Low Power (LP), the water is maintained for 45 min at a temperature close to the boiling point. In the three phases, the amount of fuel used for each process is carefully measured. Performance analyses were performed in order to compare the traditional stove TCS with the improved ICS-G stove using the new BSW3 fuel. The performance indicators used to compare the stoves are those officially recognized by the International Workshop Agreement (IWA), in order to ensure consistency of the selection with the ISO/IWA11:2012 guidelines [39].

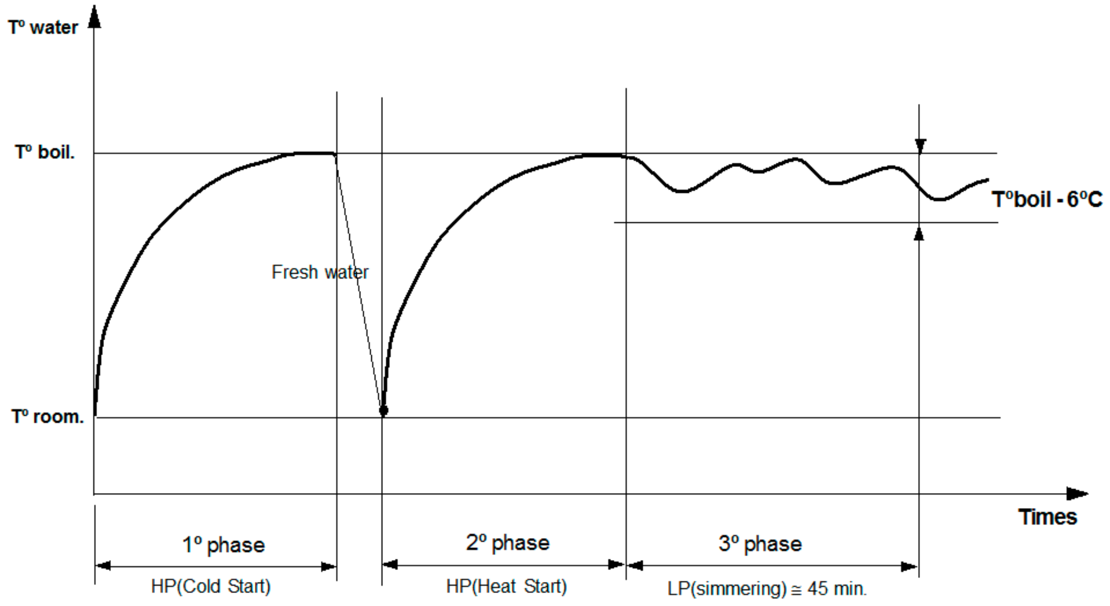


Figure 5. Sequential steps in the Water Boil Test (WBT) Protocol [40].

Many studies and researchers suggest that WBT laboratory tests do not necessarily predict the performance of stoves in real domestic kitchens [40–44]. For these reasons, in this investigation the WBT tests were complemented by the CCT tests, in which real meals were prepared. In these CCT tests the cooking of a real meal commonly consumed by the population of the area under study is carried out under strict controlled conditions. During the CCT process, three cooks prepared the same meal under identical conditions and with the same amounts of ingredients and water. Total needed time and the amount of fuel used for the food cooking were measured. To allow for the reproducibility of the results and to minimize the margin of error, all the pots used for these tests have the same characteristics and dimensions [45–47], and the cooks prepared six times the same amount of food (n = 6). The ingredients used in the tests are shown in Table 7. Each test is based on a total of 12.45 kg of raw material, including cooking water. Final weight after cooking should be 6.58 kg (Standard deviation, SD = 0.10).

Table 7. Raw material for a controlled kitchen test (CCT).

	Quantity [g]
Fish (6)	1.370
Flour (corn + cassava)	2.010
Peanut paste	180
Vegetables	1.150
Other ingredients (tomatoes, salt, onion, garlic)	390
Olive oil	350
Water	7.000

This test provides reliable performance indicators of the behavior of the cooking stove when used on the field. These performance indicators are the specific fuel consumption (SFC) and the total cooking time. SFC represents the amount of fuel needed to cook the quantity of food needed for usual meal and it is calculated by:

$$SFC = \frac{W_{fuel}}{W_f} \tag{5}$$

where, W_{fuel} is the mass of fuel used for cooking the meal and W_f is the cooked meal mass.

(b) Estimates of CO_2 Emission Reduction (ER-CO_2) for the ICS-G stove.

The calculations of the ER-CO_2 resulting from the use of non-renewable wood in kitchens are carried out using the AMS-II methodology [48] according to the United Nations Convention on Climate Change (UNFCC). These emissions savings are given by:

$$ER = B_{Savings} * f_{NRB} * NCV_{biomass} * EF \tag{6}$$

where, $B_{Savings}$ is the amount of woody biomass, in tons, used by the ICS-G during the year; f_{NBR} is the fraction of non-renewable biomass (it can be obtained from some study results or government data, default value for DRC is 90%); $NCV_{biomass}$ is the low specific heat value of the non-renewable woody biomass that has been replaced (in the case of wood, this value is 0.015 TJ/t, using the gross weight of the air dried wood); and EF is the fossil fuel emission factor that is expected to be used for the replacement of non-renewable woody biomass with other commonly available fossil fuels, its value is 63.7 t CO_2/TJ. When charcoal is used as fuel by the reference TCS stove or by the new ICS-G stove, the amount of woody biomass is determined using a conversion factor of 5 kg of wood (wet) per 1 kg of charcoal (dry base). All these values are obtained from [48].

$B_{Savings}$ can be determined from the results of the CCT tests by using the following relationship:

$$B_{savings} = B_{olds} * \left(1 - \frac{SFC_{New}}{SFC_{olds}}\right) \tag{7}$$

where, SFC_{olds} and SFC_{new} are the specific fuel consumption for the TCS and the ICS-G stoves, respectively.

3. Results and Discussion

3.1. Performance Analysis Using the WBT Method

Table 8 shows the results from the WBT tests for both types of stoves when using charcoal as a fuel. Table 9 details the results when the used fuel is BSW3. All these values have been obtained directly from the PEMS system. In both cases, a significant improvement in energy efficiency of 134% and 153%, respectively, is obtained by using the ICS-G stove, together with a very significant reduction of CO and PM emissions. Comparing the TCS stove using charcoal with the new ICS-G stove using BSW3 briquettes, (Table 10), there was a 150% increase in energy efficiency, savings in fuel of about 67% and CO emission reductions of 41% and 67% during the high and low power test phases, respectively, while PM particle emission reduction reached 84% and 93%, respectively. Therefore, a significant decrease of pollutants and an increase in performance due mainly to the new design of the stove and the new fuel was observed. In a recent study done in a Kenyan village on the impact of a gasifier on improving energy efficiency and reducing polluting emissions, Gitau, J.K. et al. [15] underlines a reduction in CO and PM emissions of 57% and 79%, respectively, when compared with the traditional model. Our improved performance of the ICS-G is mainly due to the improved combustion quality due to the adjustment of the stoichiometric air quantity, which leads to an almost complete combustion of the solid biomass. Forced ventilation (ICS-G) always results in better combustion than natural ventilation (TCS), all other things being equal. In addition, the ICS-G combustion chamber is thermally insulated; this prevents heat loss on the sides of the ICS-G stove and therefore concentrates all the heat produced and directs it towards the pot with the movement of forced air. Natural ventilation does not ensure perfect combustion because of its random nature and high dependence on the external atmospheric conditions, as the combustion chamber is not closed, and heat losses are uncontrolled and widespread.

Table 8. Results from WBT test using charcoal as fuel.

IWA PERFORMANCE METRICS	UNITS	TCS	ICS-G	ICS-G. vs. TCS (%)
High Power Thermal efficiency	%	22 ± 1.0	51.6 ± 1.5	134 ± 13
Low Power Specific Fuel Consumption	kJ/(s.l)	0.64 ± 0.05	0.32 ± 0.07	−50.0 ± 11.6
High Power CO emissions	g/MJ	16.3 ± 3.8	5.1 ± 0.2	−68.7 ± 7.4
Low Power CO emissions	g/(s.l)*1 × 10^{-3}	5.00 ± 0.67	1.33 ± 0.08	−73.3 ± 3.9
High Power PM emissions	g/MJ*1 × 10^{-3}	116 ± 10.7	38.1 ± 2.4	−67.2 ± 9.5
Low Power PM emissions	g/(s·l)*1 × 10^{-6}	35.0 ± 0.33	20.0 ± 0.4	−42.9 ± 1.1

Table 9. Results from the WBT tests using briquettes BSW3 as fuel.

IWA PERFORMANCE METRICS	UNITS	TCS	ICS-G	ICS-G. vs. TCS (%)
High Power Thermal efficiency	%	21.8 ± 1.2	55.1 ± 0.03	153 ± 14
Low Power Specific Fuel Consumption	kJ/(s·l)	0.57 ± 0.05	0.19 ± 0.02	−66.7 ± 4.4
High Power CO	g/MJ	16.3 ± 3,8	6.9 ± 0.4	−41.0 ± 3.4
Low Power CO	g/(s·l)*1 × 10^{-3}	4.83 ± 0.17	1.50 ± 0.17	−66.9 ± 3.7
High Power PM	g/MJ*1 × 10^{-3}	83.3 ± 6.4	13.5 ± 3.1	−83.8 ± 3.9
Low Power PM	g/(s.l)*1 × 10^{-6}	20.7 ± 2.3	1.5 ± 0.4	−92.8 ± 1.8

Table 10. Comparison of traditional stove (TCS)/charcoal vs. ICS-G/BSW3.

IWA PERFORMANCE METRICS	UNITS	TCS	ICS-G	ICS-G. vs. TCS (%)
High Power Thermal efficiency	%	22 ± 1.0	55.1 ± 0.03	150 ± 11
Low Power Specific Fuel Consumption	kJ/(s·l)	0.64 ± 0.05	0.19 ± 0.02	−70.3 ± 3.9
High Power CO	g/MJ	11.7 ± 0.07	6.9 ± 0.4	−41.0 ± 3,4
Low Power CO	g/(s·l)*1 × 10^{-3}	5.00 ± 0.67	1.50 ± 0.17	−70.0 ± 5.3
High Power PM	g/MJ*1 × 10^{-3}	116 ± 10.7	13.5 ± 3.1	−88.4 ± 3.9
Low Power PM	g/(s.l)*1 × 10^{-6}	35.0 ± 0.33	1.5 ± 0.4	−95.7 ± 1.1

Obtained improvement in emissions are in agreement with the results published in [16], where at lower air supply rates, low emissions of both PM and CO are achieved.

3.2. Results from the CCT Analysis

Tables 11 and 12 show the results of the CCT tests carried out in the preparation of the typical meal consumed in the city of Bandundu. Table 11 summarizes the comparison between the ICS-G and TCS stoves using charcoal as fuel. A fuel saving of 61% is observed as well as a 20% decrease in the time used for cooking when the improved ICS-G stove is used. This is an improvement on the 40% fuel economy reported in [15] for a natural air gasifier. Table 12 shows the test results using BSW3 as fuel. In this case, ICS-G has very similar fuel savings in relation to the TCS independent of the type of fuel, charcoal or BSW3, than in the previous case, 61%. Similarly, cooking time saving is almost the same for the two kinds of fuel: 18% compared to the traditional system. However, BSW3 main advantage comes from the fact that this fuel is obtained from agricultural residues, so no cutting down of trees, as in the use of charcoal, is needed. Besides this, there is a saving in fuel consumption mainly due to the fact that in an ICS-G, the firepower can be fully controlled; i.e., during the simmering phase of the food, the power is reduced with the corresponding fuel saving. For a TCS, it is impossible to vary the fire power during the different phases of the cooking process, given that it is based on natural ventilation. Besides this, the ICS-G includes a greater thermal insulation, especially in the lateral surface.

Table 11. CCT results (charcoal as fuel, n = 6).

	TCS	ICS-G	ICS-G. vs. TCS (%)
Fuel (g)	2063 ± 119	805 ± 80	−61.0 ± 4.5
Cooking Time (s)	15,120 ± 960	12,160 ± 612	−20.2 ± 6.5
SFC (g charcoal /kg cooked meal)	313 ± 16.5	123 ± 11.2	−60.7 ± 4.1
SEC (MJ /kg cooked meal)	9.3 ± 0.5	3.7 ± 0.3	−60.2 ± 3.9

SFC, specific fuel consumption; SEC, specific energy consumption.

Table 12. CCT results (BSW3 briquettes as fuel n = 6).

	TCS	ICS-G	ICS-G/TCS [%]
Fuel (g)	3327 ± 210	1270 ± 95	−61.8 ± 3.7
Cooking Time (s)	15,960 ± 432	13,080 ± 654	−18.0 ± 4.7
SFC (g charcoal /kg cooked meal)	506 ± 27	194 ± 13.0	−61.7 ± 3.3
SEC (MJ /kg cooked meal)	9.3 ± 0.5	3.5 ± 0.2	−62.4 ± 2.9

3.3. Environmental Analysis

By using data from the results in Tables 11 and 12, we can deduce that the fuel savings by the use of the ICS-G stove instead of the TCS is 1.21 kg when using charcoal, and 2.06 kg when using BSW3 briquettes. CO_2 emission reductions have been calculated according to the AMS-II methodology. Table 13 indicates the annual reduction in wood consumption and CO_2 emissions for a household and for the entire city of Bandundu, where around 90% depend on biomass for cooking food. We are considering that 1 kg of charcoal is equivalent to 5 kg of firewood.

Table 13. Bsavings and ER-CO_2 for ICS-G.

Fuel	Bsaving (t/Year) Household	Bsaving (t/Year) Bandundu City	ER-CO_2 (t/Year) Household	ER-CO_2 (t/Year) Bandundu City
Charcoal	2.288	1248.194	1.97	1,073,384
BWS3	3.766	2,054,480	3.24	1,766,751

3.4. Socioeconomic Analysis

The use of ICS-G with BSW3 fuel will provide significant economic benefits to the households in developing countries. The price of one kilogram of charcoal is estimated at 0.6 $/kg in Bandundu and the price of BSW3 could be around 0.2 US$/kg. In accordance with the fuel consumptions deduced in the CCT tests, the daily fuel purchases under current conditions (TCS stove using charcoal) reaches 1.23 US$/family/day. This would be reduced to 0.48 US$/family/day when using the ICS-G stove with charcoal and up to 0.25 US$/family/day if the fuel for this stove would be BSW3. Therefore, monthly savings of US$ 22.6 will be obtained by the introduction of ICS-G stoves using charcoal and US$ 29.4 when the fuel used is BSW3. Taking into account that the purchase price of this ICS-G stove is in the order of US$ 50, the return periods are 2.2 and 1.7 months, respectively. Therefore, the savings for the first year are US$ 222 and US$ 303.5 for the both cases of ICS-G under consideration.

4. Conclusions

The causes of deforestation and greenhouse gas emissions and pollutants in developing countries, such as those in sub-Saharan Africa, are diverse, but they include in a high percentage from the use in cooking activities of traditional fuels with low energy efficiency stoves. A possible solution to reduce deforestation and the rate of polluting and greenhouse gases emissions would require the improvement of the stoves and the fuels used for those cooking activities. In this work, an improved stove based on gasification and a new fuel obtained from agricultural wastes have been designed and built to address these goals. Results using standard protocols, such as BWT and CCT, indicates fuel savings up to 61% and cooking time reduction of 18% by the introduction of these improvements in stove and fuel. Environmental impact remediation is obtained by wood savings of 2.05 Mt/year, from the substitution of this wood by agricultural wastes, and 1.9 Mt CO_2/year emissions in the case of the Bandundu City in the DRC. Economic improvement can also be obtained with these new elements, reaching, for a standard family with six members, annual savings up to US$ 303 by the introduction of ICS-G stoves with BSW3 fuel, and a return period for the investment in the new stove of less than 2 months.

Author Contributions: Conceptualization, O.M.I. and E.H.P.; methodology, O.M.I.; software, E.H.P.; validation, O.M.I., E.H.P. and D.A.S.; formal analysis, D.A.S., M.C.M.G. and P.B.-M.; investigation, O.M.I. and E.H.P.; resources, O.M.I. and E.H.P.; data, D.A.S., O.M.I. and M.C.M.G.; writing (original draft preparation), O.M.I.; writing (review and editing), E.H.P. and M.C.M.G.; visualization, P.B.-M. and D.A.S.; supervision, P.B.-M., D.A.S. and M.C.M.G.; project administration, M.C.M.G., P.B.-M. and E.H.P.; results interpretation, all authors. All authors have read and approved the final manuscript.

Funding: This research received no external funding. P.B.M. was funded by the Generalitat Valenciana under the grant ACIF/2018/106.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

BC	Black carbon
BSW	solid fuel briquettes
CCT	cooking controlled test
ER-CO_2	Carbon dioxide emission reduction
FCR	Fuel consumption rate
HP	High power WBT phase
ICS-G	improved gasification stove
LP	low power WBT phase
PM	particle matter
PEMS	portable emissions measurement system
DRC	Democratic Republic of Congo
SA	Stequiometric air
SFC	specific fuel consumption
SEC	specific energy consumption
SGR	specific gasification rate
TCS	traditional stove
WBT	water boiling test

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