doi:10.20944/preprints201704.0164.v1

Peer-reviewed version available at *Energies* **2017**, *10*, , 641; doi:10.3390/en10050641

Article

Watching the Smoke Rise Up: Thermal Efficiency, Pollutant Emissions and Global Warming Impact of Three Biomass Cookstoves in Ghana

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Abstract: In Ghana, about 73% of households rely on solid fuels for cooking. Over 13,000 annual deaths are attributed to exposure to indoor air pollution from inefficient combustion. In this study, assessment of thermal efficiency, emissions and total global warming impact of three cookstoves commonly used in Ghana was completed using IWA water boiling test (WBT) protocol. Statistical averages of three replicate tests for each cookstove were computed. Thermal efficiency results were: wood-burning cookstove 12.2 ± 5.00% (Tier 0), coalpot charcoal stove 23.3 ± 0.73% (Tier 1-2) and Gyapa charcoal cookstove 30.00 ± 4.63% (Tier 2-3). The wood-burning cookstove emitted more CO, CO_2 and $PM_{2.5}$ than coalpot charcoal stove and Gyapa charcoal cookstove. Emission factor for $PM_{2.5}$ and emission rate for the wood-burning cookstove (Tier 0) were over four times higher than the coalpot charcoal stove (Tier 3) and Gyapa charcoal cookstove (Tier 2). To complete WBT, the study results showed that using Gyapa charcoal cookstove instead of the wood-burning cookstove, global warming impact could be potentially reduced by approximately 75% and 50% using Gyapa charcoal cookstove instead of coalpot charcoal cookstove. We conclude that there is the need for awareness, policy and incentives to enable end-users switch to and adopt Gyapa charcoal cookstoves for increased efficiency, reduced emissions/global warming impact.

Keywords: cookstove; emissions; emission factor; efficiency; global warming impact; Ghana

1. Introduction

Inefficient burning of biomass fuels in poorly designed and fabricated cookstoves results in indoor air pollution that affects the health of users and contributes to global warming and climate change. In poorly ventilated dwellings, indoor smoke can be 100 times higher than acceptable levels for fine particles. Smoke from cooking fuels is estimated to account for nearly 2 million deaths in 2004, 3.5 million deaths in 2010 and 4.3 million deaths in 2012, more than 99% of which occur in developing countries [1-3]. In Ghana, about 73% of households use firewood (41.3%) or charcoal (31.5%) for cooking, with LPG (22.3%) and other sources like kerosene (0.2%), electricity (0.3%) and crop residue (0.4%) constitute the rest [4]. Further, over 13,000 annual deaths are attributed to

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exposure to household air pollution from inefficient indoor combustion [5]. Personal exposure to smoke from cookstoves is particularly high among women and young children, who spend the most time near the domestic hearth [6, 7].

Incomplete burning of solid biomass releases a toxic mix of health damaging pollutants that contribute to climate change at local, regional and global levels. According to GACC [8] black carbon, which results from incomplete combustion in biomass cookstoves, is estimated to contribute equivalent of 25- 50% of carbon dioxide warming globally. It is therefore estimated that universal adoption of advanced biomass cookstoves could have an impact equivalent to reducing carbon dioxide (CO_2) emissions by about 25–50% 9]. Well-designed cookstoves have been shown to mitigate 1.5 to 3.6 tons of carbon dioxide equivalent, thus reducing emissions of greenhouse gases [10]. There is mounting evidence that biomass burned inefficiently contributes to climate change at the local, regional and global levels, suggesting that the climate change debate needs to take household energy issues into consideration [11, 12]. According to SEI [12] the global technical potential for greenhouse gas (GHG) emission reductions from improved cookstove projects has been estimated at 1 gigatonne of carbon dioxide (1 Gt CO_2) per year, based on an estimate of 1-3 tons of CO_2e per stove.

The reliance on solid fuels for cooking and heating has drawn attention lately because of the role of black carbon in global warming. Black carbon originates from incomplete combustion of fossil fuels, particularly diesel, but also of biomass and other solid fuels at the household level. There is a growing body of evidence that black carbon alone may be the second-most-important factor affecting the rise in global temperatures after carbon dioxide (CO_2) [13,14]. Inhaling particulate matter ($PM_{2.5}$) can cause acute respiratory infections and a host of other diseases [15] and particulate matter can increase global climate change [16]. To protect the health of a family, high levels of indoor air pollution must be prevented. Similarly, carbon monoxide (CO) is one of the primary products of incomplete combustion (PICs). It has a global warming potential (GWP) of 1.9 times that of CO_2 [17]

The objectives of this study are, in summary, to: (1) analyse thermal efficiency, carbon dioxide (CO_2), fine particulate matter ($PM_{2.5}$) and carbon monoxide (CO) emissions; and (2) determine global warming impact and estimate annual global warming impact potential of three biomass cookstoves that are commonly used in Ghana for improvement in design and development. The results are intended to contribute to knowledge in regard to performance metrics of different biomass cookstoves. This will contribute to raise awareness on the need for design improvement and provide evidence-based data for policy and incentives to enable end-users switch to better designed and improved cookstoves for economic, heath and climate benefits.

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2. Materials and Methods

2.1 Materials

Wood-burning cookstove (a), Coalpot charcoal stove (b), and Gyapa charcoal cookstove (c) were the three cookstoves evaluated in this study (Figure 1). The three cookstoves were selected because they are among the most commonly used biomass cookstoves in small towns and cities of Ghana. These cookstoves were purchased at random in local markets.

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

Figure 1 Pictures of (a) Wood-burning cookstove, (b) Coalpot charcoal cookstove and (c) Gyapa charcoal cookstove

Appropriate fuels for each cookstove were used during testing. Fuel properties were measured from representative samples and are included in **Error! Reference source not found.**. Figure 1 shows the laboratory, equipment and measuring devices that were used for the tests. Note that this testing does not account for emissions during production of charcoal.

2.2 Initial test conditions

Table 1 Fuel Properties

Property	units	Wood value	Charcoal value
Fuel species		*Acacia farnesiana*	*Azadirachta indica* (Neem)
Average dimensions of fuel (W x H x L)	cm x cm x cm	2x3x40	2x3x6
Wood moisture content (MC)	% (wet)	7.0	8.0
Gross calorific value	MJ/kg (dry)	19.2	29.4
Net calorific value	MJ/kg (dry)	17.9	28.2
Effective calorific value	MJ/kg (wet)	16.5	25.7

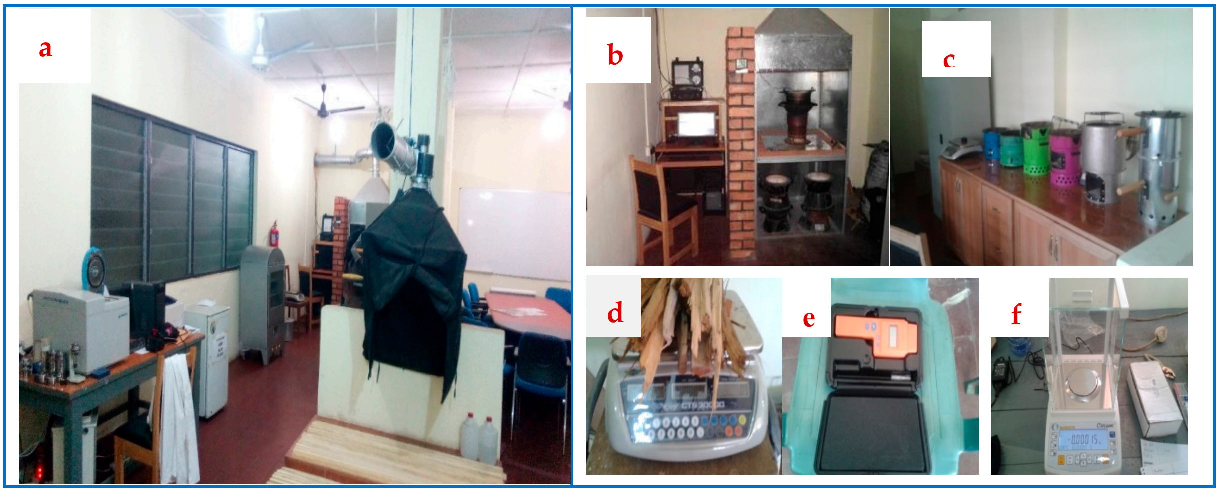

Figure 1 - (a) Testing facility including (b) test hood (LEMS), (c improved cookstove library (d) large capacity scale (CAPACITY, ACCURACY), (e) Delmhorst J-2000 moisture meter,), and (f) precision balance (CAPACITY, ACCURACY)

2.3 Methods and data analysis

The cookstoves were evaluated at the Cookstove Testing and Expertise Laboratory (C-Lab) at the Technology Consultancy Centre, KNUST, Kumasi-Ghana. The laboratory emission monitoring system (LEMS, Aprovecho Research Centre, Oregon, USA) is used to perform water boiling tests (WBTs) according to the current protocol [18]. The LEMS uses an actively ventilated, total capture hood to remove emissions. The sheet metal hood and large variable speed blower enable the LEMS to accurately measure the emissions from cookstoves (CO, CO_2, $PM_{2.5}$) over a range of sizes and firepower. The laboratory allows for careful control of the environment so that tests are more consistent and repeatable.

A continuous sample is pumped from the total emissions and analysed for CO_2, CO and $PM_{2.5}$ concentrations. Analog signals from the sensors are read by a data acquisition board, and concentration data are displayed in real time on a computer monitor. Total PM was measured gravimetrically and used to calibrate the optically measured PM according to the ISO/IWA guidelines [19]. Identical 7 Litre stainless steel cooking pots were used in the study to boil water. Fuel moisture content is determined using a moisture meter (Delmhorst J-2000) and calorific value is measured using a bomb calorimeter (Sundy SDC5015).

The protocol used for the test was the Water Boiling Test (WBT). This is a standardized test in which 5 litres of water is boiled for each phase -high power with the cookstove at room temperature (high power cold start), at steady operating temperature (high power, hot start), and at a simmer for 45 minutes (low power, 3°- 6°C below full-boiling temperature). WBT is composed of three phases: *cold-start, hot-start, and simmer.* McCarty in GACC [18] temperature and time model depicted in Figure 3 is used for providing a clear and vivid understanding of the three phases involved in the process.

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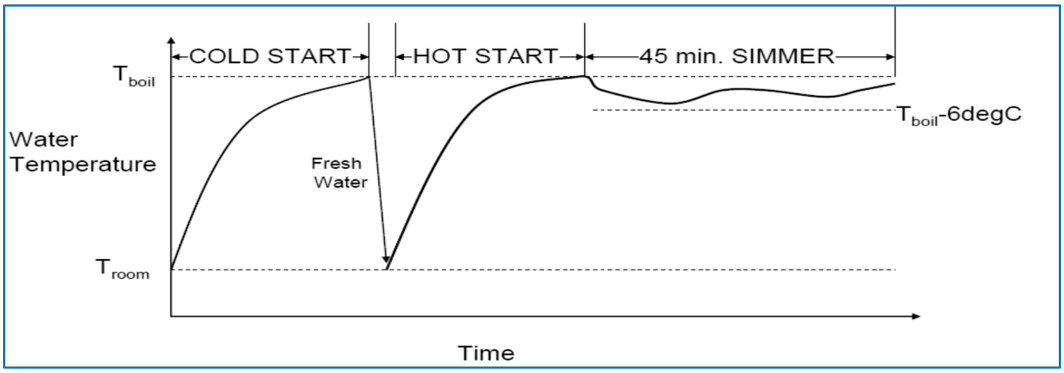

Source: *Nordica MacCarty in GACC [14]*

Figure 3 Temperature-time graph during the three phases of water boiling test

The fuel consumed and emissions produced for each of the three stages are measured and analyzed as a time-weighted average to determine the WBT key indicators [18, 20]. Three (3) replicate WBTs were conducted for each cookstove to calculate average performance metrics. Data were analyzed in conjunction with WBT 4.2.3 data calculation spreadsheet. IWA performance metrics are connected with Tier ratings (Tier 0-4) to allow for easier comparability and communication of results. Statistical significance and standard error for all tests were determined using the Student's t-test with 95% confidence interval. This is appropriate when measurements are assumed to be normally distributed but the sample size is small (n < 30) [21, 22].

3. Results and Discussion

3.1 Fuel and energy consumption, time to boil, and thermal efficiency

3.1.1 Fuel and energy consumption

Fuel used and energy consumption rate values were computed by averaging the cold start and hot start values and then adding the low power values [23]. The results in Table 2 indicate that the Gyapa charcoal cookstove (Gyapa type) used 1036 ± 212 (824 – 1248) g of fuel, the coalpot cookstove used 1178.1 ± 230 (948 – 1408) g of fuel, while the wood-burning cookstove used 2872.3 ± 390 (2482.3 – 2972.3) g of fuel. The fuel used correlated with the energy consumed per minute. The results indicated that Gyapa charcoal cookstove consumed less energy per minute 669 ± 75 (594 – 744) kJ/min to boil the water compared to coalpot charcoal stove 844 ± 152 (692 – 996) kJ/min and wood-burning cookstove 1237 ± 269 (968 – 1509) kJ/min.

3.1.2 Time to boil

The time required to bring 5 litres of water to a boil was computed by averaging the cold start and hot start values Time to boil is an important practical metric because users often value time savings and convenience [23].. Among the stoves tests, the Gyapa charcoal cookstove was the fastest to boil 5 litres of water. A typical temperature time profile during the WBT is presented in Figure 3.

3.1.3 Thermal efficiency

Thermal efficiency is a metric representing the fraction of heat produced by the burning fuel that is transferred into the pot. The remaining energy is lost to the environment. The cookstove

 doi:10.20944/preprints201704.0164.v1

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performance test results in Table 2 indicate that the average high power thermal efficiency of the Gyapa charcoal cookstove (30%) was 6.7% and 17.8% percentage points higher than coalpot charcoal cookstove and wood-burning cookstove, respectively.

According to Energica Ghana, the efficiency of wood-burning stoves available on the Ghanaian market is 8-15% [24]. Coalpot charcoal cookstove thermal efficiency determined from this work is consistent with Boafo-Mensah et al. who determined thermal efficiency at high power cold start of 22.7% and hot start of 24.0% for coalpot charcoal cookstove [25]. Aidkins et al. reported thermal efficiencies of up to 36% for charcoal cookstoves [26]. For the Gyapa charcoal cookstove, Kshirsagar and Kalamkar reported that some researchers tested many African charcoal stoves including Gyapa charcoal cookstove to calculate average efficiency of 34% [27]. This result is consistent with our study, which measured thermal efficiency of Gyapa charcoal cooktove at high-power hot start of 27.3 ± 5.7%.

The Gyapa charcoal cookstoves in Ghana have some design features that help them to reach higher efficiency. Typically they consist of a ceramic liner in a metal cladding (See Figure 1c). The ceramic liner encloses the fire and provides better insulation compared to traditional (wood-burning cookstove and coalpot) all metal charcoal cookstoves. Such design featrures lead to higher efficiency, a hotter flame, and improved combustion. However, there are opportunities to optimize some design characteristics, such as the shape of the stove, the gap between the pot and the burning charcoal, and the size of the grate holes [27]. Optimizing such features can bring about improvement in the air circulation to recycle heat and create the draft needed for more efficient combustion [27].

Table 2 Performance test results

Performance Metrics	Wood-burning Cookstove		Coalpot charcoal stove		Gyapa charcoal cookstove	
	Mean	SD	Mean	SD	Mean	SD
High power thermal efficiency (%)	12.20	2.03	23.30	0.29	30.00	1.85
Low power specific fuel consumption rate (MJ/min/L)	0.13	0.07	0.106	0.01	0.107	0.01
Time to boil 5 litres of water (min)	31.70	3.53	25.50	2.80	23.10	3.37
Fuel to cook 5 litres of water (g)	2872.3	390	1178.1	230	1036	212
Energy consumption rate (kJ/min)	1237	269	844	152	669	75S
Firepower (Watt)	8589.7	3377.13	6066	934.07	4802.7	909.88
No of replicates	3		3		3	

SD = Standard Deviation; Mean = arithmetic mean (average value)

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3.2 *Emission performance results*

3.2.1 General emissions

From the results in Table 3, the wood-burning cookstove emitted more total CO, CO2 and $PM_{2.5}$ than the coalpot charcoal stove and Gyapa charcoal cookstove. In general charcoal cookstoves emit less $PM_{2.5}$ but can have considerable CO emissions compared to wood cookstoves [23]. The fuel type (wood or charcoal) and combustion conditions (e.g. mixing, temperature, residence time) influence the emissions performance. Charcoal is made by carbonizing wood, during which volatiles compounds are burnt off, which results in relatively little smoke emissions compared to unprocessed firewood during cooking. Although the Gyapa charcoal cookstove showed better thermal performance, its indoor emission $PM_{2.5}$ were slightly higher than those of the coalpot charcoal stove. A reason for this is that in the Gyapa charcoal cookstove the fire is enclosed in a ceramic liner which has a large mass that is used to insulate and reduce heat loss. The ceramic liner walls absorb heat and cool the fire as they heat up causing higher emissions of products of incomplete combustion (PIC), including $PM_{2.5}$ [28].

Table 3 Emissions Performance Results

	Wood-burning Cookstove	Coalpot charcoal cookstove	Gyapa charcoal cookstove
CO to Cook 5 Litres of Water (g)	330.3	137.4	108.6
$PM_{2.5}$ to Cook 5 Litres of Water (mg)	22210.4	556.5	5258.9
CO_2 to Cook 5Litres of Water (g)	10811.0	3901.7	2082
Indoor Emissions, CO (g/min)	2.95	1.64	2.32
Indoor Emissions, $PM_{2.5}$ (mg/min)	169.8	5.3	9.95
Total Global Warming Impact (g CO2e)	11438.54	4162.65	2489.56

3.2.2 CO_2 and CO emissions

Figure 4 shows an example of CO_2 and CO concentration trends during a cookstove test of this study. The trends of CO_2 and CO when water was brought to a boil and simmered for 45 minutes seemed to be related. As the wood-burning cookstove heats up, both CO and CO_2 increase during the cold start high power phase. However, CO_2 remains fairly constant while CO increases during the hot start high power phase. Overall the results show a positive relationship, although in the case of the wood-burning cookstove and coalpot charcoal stove, CO_2 and CO levels were higher than the Gyapa charcoal cookstove. For most of these cookstoves the temperature is not sufficiently high to ignite the CO-air mixture in the exhaust gases. CO is created by incomplete combustion of the fuel. It is a poisonous, odorless gas which should be minimized to meet the ambitious health targets for household fuel combustion (≤0.42 g/min - Tier 4) [19].

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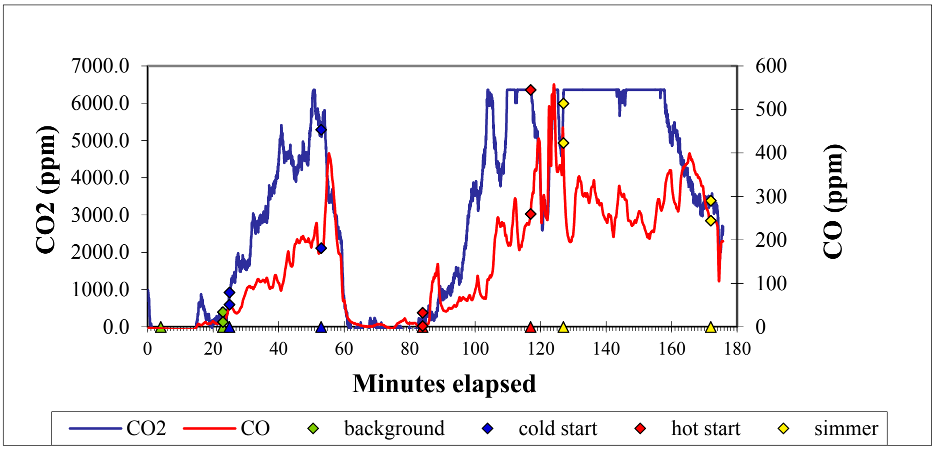

Figure 4 Example of CO_2 and CO Emission Trends During Test

3.2.3 Particulate matter ($PM_{2.5}$)

The emission test results (Table 3 above) showed that the indoor particulate matter ($PM_{2.5}$) emissions of 169.8 mg/min (Tier 0) for the wood-burning cookstove was higher than the indoor $PM_{2.5}$ emissions of 5.3 mg/min (Tier 3) for the coalpot charcoal stove and indoor emissions $PM_{2.5}$ of 9.95 mg/min (Tier 2) for the Gyapa charcoal cookstove. The data indicated that the indoor $PM_{2.5}$ emissions for the Gyapa charcoal cookstove was a little higher than the $PM_{2.5}$ emission for the coalpot charcoal stove. A reason for that had already been given above (under general emissions).

3.2.5 Emission factors

Emissions indicators that are also included in this study are emission factors (EF). EF is a metric that quantifies the magnitude of emissions normalized by fuel or energy consumed [29]. Mass EF indicates the emission of a pollutant per unit of dry fuel that is consumed (g pollutant/kg fuel), while energy EF indicated pollutant emissions per unit fuel energy during combustion on a net calorific basis (mg/MJ or kg/TJ) of emission [30, 31]. EFs for $PM_{2.5}$, CO_2 and CO are presented in Table 4. EFs for CO_2 are presented in kg/TJ to enable comparison to 2006 IPCC Guidelines [31]. Similar to total emissions, EFs for $PM_{2.5}$, CO_2 and CO for the wood-burning cookstove were higher than the EFs for coalpot charcoal stove and Gyapa charcoal cookstoves. From the data the CO_2 EFs for charcoal burned in coalpot stove (117,440 kg/TJ) and Gyapa charcoal cookstove (71,660 kg/KJ) falls within the Lower and upper values presented in the 2006 IPCC Guidelines values for charcoal (95,000-132,000 kg/TJ) [31]. The CO_2 EFs for the wood-burning cookstove (119,550 kg/TJ) also falls within the 2006 IPCC Guidelines value of (95,000-132,000 kg/TJ) for wood/wood waste fuel combustion [31]. According to Gómez et al [31] and Naussbaume et al [32] emissions of each greenhouse gas from stationary sources are calculated by multiplying fuel consumption by the corresponding emission factor (EF).

$PM_{2.5}$ emission factor for charcoal fuel burned in the coalpot charcoal cookstove of 0.47 g /kg is consistent with $PM_{2.5}$ emission factor for charcoal (0.20±0.1 g/kg) reported by Amaral et al [33]. $PM_{2.5}$ emission factor for woodfuel burned in the wood-burning cookstove (7.74g/kg) compares favorably with $PM_{2.5}$ EF for burning of biomass with aircraft sampling of tropical forest (4.50±2.54 g/kg) and crop residue (6.19±2.36 g/kg) reported in Amaral et al [33]. Overall, the EFs in mg/kJ for

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the wood-burning cookstove were 2-4 times higher than the EFs for Gyapa charcoal cookstove. The implication is that burning woodfuel in the wood-burning cookstove emitted more pollutants into the atmosphere than burning of charcoal in the Gyapa charcoal cookstove. The significance is that such knowledge is helpful for developing mechanisms to help achieve the goal of reducing pollutant emissions in locally fabricated cookstoves.

Table 4 Emission Factors

	Wood-burning cookstove	Coalpot charcoal stove	Gyapa charcoal cookstove
$PM_{2.5}$ emissions factor (mg/kJ)	0.43	0.02	0.18
CO_2 emission factor (kg/TJ)	119,550	117,440	71,660
CO emissions factor (mg/kJ)	6.43	4.14	3.74
$PM_{2.5}$ emissions factor (g/kg)	7.74	0.47	5.06
CO_2 emission factor (g/kg))	3766.90	3306.44	2009.6
CO emissions factor (g/kg))	115.09	116.44	104.42

3.3 *Pot temperature and relative humidity*

In Figure 5 the relative humidity (RH) of the environment of the laboratory was 31- 54%. On average the cold start temperature was 26±1°C, hot start was 97°C and simmering 95°C. The study results showed little variation in temperature as well as RH of the laboratory environment.The results of the RH and temperature indicated that the laboratory environment was within a suitable range. However the influence of temperature over RH can be part of further research to be explored in the future. In general when temperature is high and RH is low, evaporation of water is rapid. But when temperature is low and RH is high, evaporation of water is slow. RH below 20% is considered extremely low. Indoor RH should be kept above 30-40% to reduce the likelihood of the occupant's nasal passages drying out [34]. Humans can be comfortable within a wide range of humidities depending on the temperature—from 30-70%, but ideally 50-60% [35].

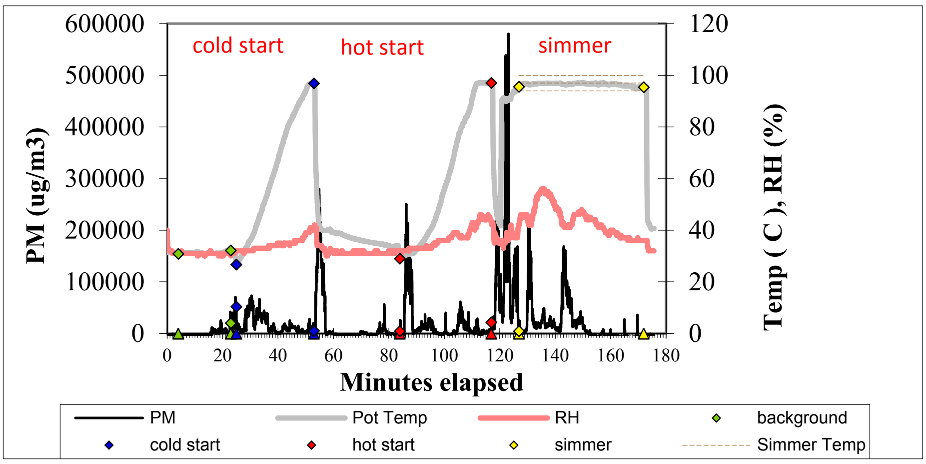

Figure 5 Typical PM, Temperature and Relative Humidity During Test

3.4 *Standard guideline for the indicators (Tier Designation)*

The IWA Tier designation provides standard guidelines for the performance indicators. Advancing from Tier 0 toward Tier 4 signifies improvement. Thermal efficiency and emission factors and rates are key measures that many cookstove programmes are adopting. In general, the lower the emissions, the higher the efficiency of cookstoves [36]. The Tiers of Performance provide a map towards incremental improvement from traditional open fire cookstoves (Tier 0) to aspirational goals for meeting ambitious health and/or environmental targets (Tier 4) [19]. According to GACC [37] cookstoves that meet Tier 2 for efficiency or higher will be counted as efficient; cookstoves that meet Tier 3 for indoor emissions or higher will be counted as clean, as it relates to potential health impacts; and **cook**stoves that meet Tier 3 for overall emissions or higher will be counted as clean, as it relates to potential for environmental impacts.

The Tier designations for thermal efficiency and emissions from the study are presented in Table 5. With efficiency of 30.00 ± 4.63% (25 - 35%) (Tier 2-3) the Gyapa charcoal cookstove is counted as efficient. With indoor emission $PM_{2.5}$ of 5.3 mg/min (Tier 3) the coalpot charcoal stove is counted as clean. However, care should be taken to interpret the indoor $PM_{2.5}$ emission of 9.95 mg/min (Tier 2) for the Gyapa charcoal cookstove. Two reasons can be considered for careful interpretation. First, the Gyapa charcoal cookstove indoor $PM_{2.5}$ emission value of 9.95 mg/min is closer to (≤8 mg/min = Tier 3) than (≤17 mg/min = Tier2). Secondly ceramic lined cookstoves have the tendency to cool the fire initially and cause the fire to smoke a bit. However, there is an opportunity for design improvements which could help the Gyapa reach clean cookstove status. Woodstoves are noted for emitting $PM_{2.5}$ and hence indoor emission $PM_{2.5}$ of 169.8 mg/min (Tier 0) for the wood-burning cookstove is counted as unclean.

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Table 5.Thermal efficiency, Indoor Emission and Tier Designation

Thermal efficiency - Tier designations						Remarks
Wood-burning cookstove (Tier 0)		Coalpot charcoal cookstove (Tier 1-2)		Gyapa charcoal cookstove (Tier 2-3)		With Tier 2-3 the Gyapa charcoal cookstove is counted as **efficient**
Indoor Emissions ($PM_{2.5}$) - Tier designations						
Wood-burning cookstove (Tier 0)		Coalpot charcoal cookstove (Tier 3)		Gyapa charcoal cookstove (Tier 2)		With Tier 3 the coalpot charcoal cookstove is counted as **clean**.
	IWA Tier Designation (Standard Guideline)					
	units	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4
High power thermal efficiency	%	<15	≥15	≥25	≥35	≥45
Low power specific consumption	MJ/min/L	>0.05	≤0.05	≤0.039	≤0.028	≤0.017
Indoor emissions CO	g/min	>0.97	≤0.97	≤0.62	≤0.49	≤0.42
Indoor emissions PM	mg/min	>40	≤40	≤17	≤8	≤2

Note: From Tier 0 to Tier 4 signifies improvement

3.5 Specific emissions

Table 6 shows the specific emission values (average) obtained during the high power (cold and hot start) and low power (simmer) phases of the study. For 1 litre of water boiled during the high power and low power phases the wood-burning cookstove emitted more CO, CO_2, $PM_{2.5}$ in g/litre than the CO, CO_2, $PM_{2.5}$ in g/litre from the coalpot charcoal stove and Gyapa charcoal cookstove. The coalpot charcoal stove emitted about 1/3 of CO_2 in g/litre of water boiled compared to the wood-burning cookstove. In regard to CO_2 emitted in g/litre, the Gyapa charcoal cookstove emitted about 1/2 of CO_2 in g/litre of water boiled compared to the coalpot charcoal stove and about 1/5 of CO_2 in g/litre of water boiled compared to the wood-burning cookstove From the study results, it is noteworthy to indicate that the trend of the study data on specific emissions in g/litre of water boiled is consistent with the study results obtained by MacCarthy et al [38], though the absolute values deviated by a small margin. Drawing on the study of MacCarty et al [38] the equivalent masses of emissions per 1 litre of water boiled are presented before factoring by the total global warming impact (TGWI). This helps in organizing the results in a more consistent fashion.

Table 6. Specific emissions or mass of emissions produced to boil 1 litre and then simmer for 45 minutes

Specific Emissions (g/litre)			
COLD START	Wood-burning cookstove	Coalpot charcoal stove	Gyapa charcoal cookstove
CO g/liter	21.63	16.43	14.40
CO2 g/liter	672.87	258.47	139.67
PM2.5 mg/liter	2562.97	32.13	64.40
HOT START			

CO g/liter	16.53	16.37	16.13
CO2 g/liter	560.97	287.10	139.50
PM2.5 mg/liter	2324.43	39.10	40.94
SIMMER			
CO g/liter	72.17	17.80	14.03
CO2 g/liter	1980.67	502.73	309.50
PM2.5 mg/liter	5059.37	68.53	72.03

3.6 Total global warming impact

Total global warming impact (TGWI) values calculated from the WBT results are presented in Figure 6. These study results indicate that the traditional wood-burning cookstove (TGWI = 11438.54 gCO2e) contributed 4-5 times more to global warming, while the coalpot charcoal cookstove (TGWI = 4162.65 gCO2e) contributed 1.5 times more to global warming than the Gyapa charcoal cookstove (TGWI = 2489.56 gCO2e). The study findings imply that some attention in the form of capacity building in stove design and making should be given to traditional stove makers so as to reduce their relatively high adverse environmental and global warming impacts. It is imperative that Ghana and other developing countries take climate response as a new opportunity and a development orientation to drive low-carbon industries and create new markets and jobs as indicated by Du [39]. Currently developed countries are pushing low-carbon energy development in order to lay the foundation for a new approach to development [39]. Efforts to promote in-country continuous research and improvement in cookstove design and manufacture is an opportunity for developing countries to help address global warming and to also advance industry and job creation.

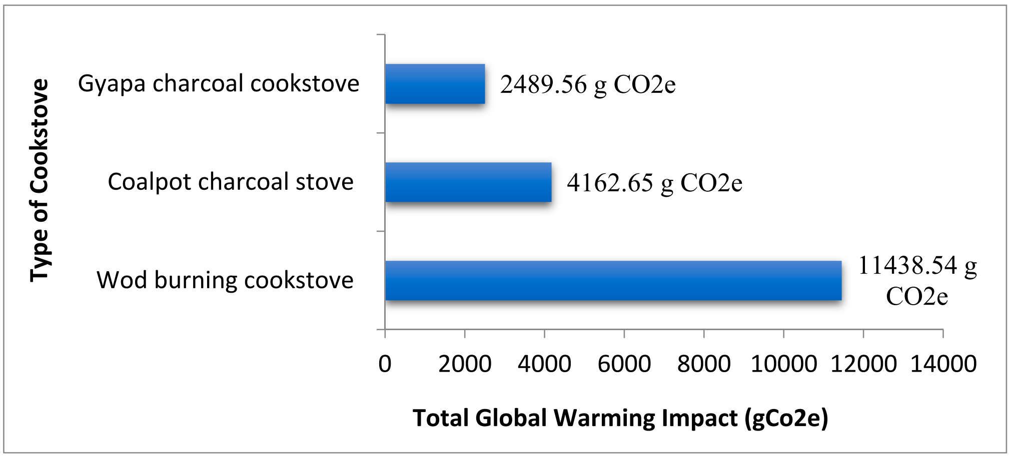

Figure 6 Type of cookstoves and total global warming impact

3.7 *Potential annual savings in tonnes CO_2equivalent*

According to MacCarty et al [36], though the laboratory study should not be used to specifically predict real-world performance, it is interesting to project the potential savings in tonnes of CO_2 equivalent per stove per year. Given the total global warming impact (TGWI) values obtained in the test, estimates can be made of how much emissions each stove is likely to contribute in one year. Table 7 provides a summary of the TGWI values and the annual TGWI projections for emissions in tonnes CO2e of the three biomass cookstoves. On the basis of the WBT, annual global warming impact potential for emissions are estimated at 4 tonnes CO_2e for the wood-burning cookstove, 2 tonnes CO_2e for coalpot charcoal stove and 1 tonne CO_2e for Gyapa charcoal cookstove. For Gyapa charcoal cookstoves the global technical potential for GHG emissions is estimated at 1-3 tonnes per year [12]. This study is therefore consistent with SEI [12].

The results of the study showed that by using Gyapa charcoal cookstove instead of the wood-burning cookstove, overall global warming impact can be potentially reduced by approximately 75%, and about 50% potential reduction using Gyapa charcoal cookstove instead of coalpot charcoal stove. In a similar laboratory study, three types of improved combustion stoves that use charcoal were shown to potentially reduce warming by 40-50% and even 50-95% for improved stoves with rocket-type combustion or fan assistance [38]. Since the three biomass cookstoves that were used in the study are predominantly used in Ghana and other African countries, such in-country data are relevant to Ghana and may be useful to other sub-Saharan Africa regions of similar conditions where there may be the need for time series estimates and quantification of reduction in pollutant emissions for cookstove carbon financing. Carbon finance has a major role to play in the development of a global market for clean cookstoves and fuels as it can change the funding dynamic for cookstove projects from traditionally donor-focused to one that attracts investment from the private sector [40].

Table 7 Total global warming impact and annual projections in tons of CO2e

Stove Type	TGWI to complete 1 WBT (approx. 1 meal) (gCO2e)	TGWI to complete 7 WBT (approx. 7 meals/week) (gCO2e)	TGWI to complete 52 weeks @ 7 WBT/week (approx 364 meals/week) (gCO2e)	Annual TGWI projection (tonnes CO2e)
Wood-burning cookstove	11438.54	80069.78	4163629	4
Coalpot charcoal stove	4162.65	29138.55	1515205	2
Gyapa charcoal cookstove	2489.56	17426.92	906199.8	1
Potential savings of Gyapa cookstove over wood-burning and coalpot charcoal stove				
Potential saving over wood-burning cookstove				3 (75%)
Potential saving over coalpot charcoal stove				1 (50%)

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4. Conclusions

This study sought to examine three widely used biomass cookstoves in Ghana with emphasis on the following predominant issues: thermal performance, emissions performance and global warming impact. From the study results, the wood-burning cookstove emitted more CO, CO_2 and $PM_{2.5}$ than the coalpot charcoal stove and Gyapa charcoal cookstove. The results showed that burning charcoal makes relatively less CO and $PM_{2.5}$ compared to the burning of wood. Although the Gyapa charcoal cookstove showed better thermal performance, better CO and CO_2, its indoor $PM_{2.5}$ emissions, particularly at the cold start was a little more than that of the coalpot charcoal stove. To complete the water boiling test, the values of the total global warming impact and annual global warming impact potential showed that by using Gyapa charcoal cookstove instead of the wood-burning cookstove, overall global warming impact could be potentially reduced by about 75%. And about 50% using Gyapa charcoal cookstove instead of coalpot charcoal stove. It is important to note that water boiling test is an approximation of the cooking process that is conducted in controlled conditions. Therefore in order to confirm desired impacts cookstoves should be measured under real conditions of use. We conclude that there is the need to create incentives for end-users to switch from poor performing cookstoves to improved ones such as Gyapa charcoal cookstove for increased thermal efficiency, low emissions and reduced global warming impact.

Acknowledgments: Special thanks go to Building Stronger Universities (BSU II) project of the Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana for providing financial support for the conduct of the research. Laboratory equipment used for testing and measurements was financed by UNDP Ghana and supported by USAID/MIT D-Lab International Development Innovation Network (IDIN) programme. The authors are also grateful to the staff of the Cookstove Testing and Expertise laboratory (C-Lab) of Technology Consultancy Centre, KNUST for experimental set up, testing and data collection which made it possible for us to analyze and interpret the data for writing of the paper.

Author Contributions: G.Y.O, E.M, G.A and O.B developed the idea of the paper. G.Y.O, E.M, G.A and O.B gathered initial information and carried out surveys. G.Y.O and E.M worked on content and structure. G.Y.O reviewed literature. G.Y.O, E.M, O.B worked on the initial draft of the paper. G.Y.O and D.S reviewed second draft and fine-tuned content of paper for submission.

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

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