

## Development of a top-lit-up-draft biomass gasifier as a sustainable heat source for effective drying of plantain slices in a cabinet dryer

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### Abstract

This paper explored the development of a top-lit-up-draft biomass gasifier as a sustainable heat energy alternative to the traditional sun drying and the costly, unreliable heat energy sources such as grid-electricity and petrochemical fuels commonly used for cabinet dryers, especially in developing countries like Nigeria. The gasifier utilized the principle of top-lit-updraft biomass gasification system to thermochemically converts agricultural residues into clean heat energy. The designed gasifier has reactor diameter and height of 28cm and 90cm, fuel consumption rate of 55kg/hr, gasification airflow rate of 82.1m<sup>3</sup>/hr, DC fan motor of 15W, equipped with 30Ah battery power source, and capable of supplying heat energy of 260.16MJ/h. Performance testing using input variables of fuel loading (10kg-20kg), fan speed (4000rpm-6000rpm), and fuel type (palm-kernel shell, coconut shell, coconut husk, and wood shavings) assessed the gasifier responses such as fuel gasification time, flame temperature, thermal and combustion efficiencies, and carbon monoxide (CO) emission of the flame. Results revealed maximum thermal efficiency, peak flame temperature and longest gasification time of 86.02%, 8750C, and 130min respectively, when operated with palm-kernel shell at maximum fan speed and fuel loading, which emitted average CO of 1ppm lower than the least international air pollutant threshold of 9ppm. Highest combustion efficiency of 99.9% was attained using wood shavings at maximum fan speed and fuel loading. The results highlighted the potential of the gasifier as an effective heat source for drying applications, particularly for drying plantain slices in a cabinet dryer.

**Keywords:** Biomass; Gasifier; Heat Source; Thermal Efficiency; Combustion Efficiency.

### 1. Introduction

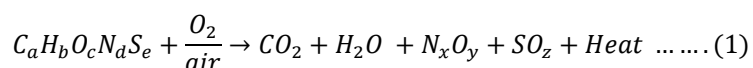
Drying of agricultural products, which involves the reduction of the products' moisture contents to safe levels, is a critical post-harvest process. It is an important process that aid the reduction of microbial effects on the products and preserve their quality over a long period of time. The effectiveness of drying methods depends on the type and availability of heat energy used [1]. Several methods of drying are adopted through ages. The age-long traditional sun drying method, which involves products being laid out on mats under sunlight, are the common methods adopted for drying especially in the developing parts of the world [2]. Despite the low cost associated with this method, it is fraught with several challenges. These challenges ranged from labor intensity, time consuming, and it is described as arduous due to the constant need to manually turn and monitor the product to ensure even drying process. Likewise, it is weather dependent, and exposes products to airborne contaminants and animal attack, therefore posing several health risks when consumed [3]. The challenges associated with traditional sun drying has been addressed with mechanically harnessed energy sources. The derived sources have been developed and applied for several drying purposes that ranged from solar dryers, which harness the solar energy, to mechanical dryers powered by petrochemicals such as

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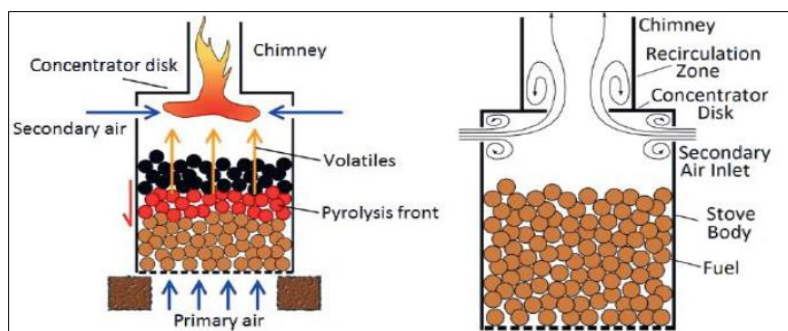
diesel, petroleum motor spirit (PMS), liquify petroleum gas (LPG), and grid electricity [4]. Solar dryer has the advantage to offer a more controlled drying environment, but can be expensive to install and maintain and is weather dependent. Similarly, mechanical dryers that relied on electricity or petrochemicals can provide consistent heat supply and faster drying time but are underlined with pressing challenges, especially in the developing country such as Nigeria. The various costs of electricity and fuel are sporadically high and fluctuate often, having significant effect of increased operational costs of the drying facilities. These costs, in turn, impacts the overall cost of food production, contributing to higher food prices beyond the reach of common man.

Considering the various economical and logistical challenges associated with traditional and mechanical drying methods discussed above, the best ideal alternative has been proposed to be the usage of biomass materials as alternative heat energy source. Biomass, which involves agricultural residues (such as shells and husks), wood chips, and other organic waste, offers a promising, renewable, cost-effective, and locally sources energy option for drying technologies [5]. It offers the opportunity of reduction in over reliance on fluctuating and costly fossil fuel and electricity, and also contribute significantly to sustainable energy practices by utilizing waste energy recovery technology effectively [6]. This system can be designed to minimize environmental impacts while sustaining a more stable and cost-effective energy source for drying. The adoption of biomass-based drying technology could benefit regions with abundant biomass resources, therefore contributing to more sustainable agricultural practices leading to development of the regions. The long-term benefit of drying energy transition to biomass-driven dryers could significantly reduce drying cost, leading to affordable food products and potentially boosting food security in developing countries like Nigeria [7].

The safe method of utilizing biomass, as heat source for drying purposes, is through gasification process. Biomass gasification is a thermochemical conversion of solid biomass into combustible gas mixtures, known as syngas or producer gas, in the absence of air or with less air than the stoichiometric requirement of air for complete combustion, at an elevated temperature range of 300°C - 1400°C and atmospheric or elevated pressures up to 33 bar [8]. The principal gaseous products are hydrogen (H<sub>2</sub>) and carbon monoxide (CO), with smaller amounts of water (H<sub>2</sub>O), methane (CH<sub>4</sub>), higher hydrocarbons (C<sub>x</sub>H<sub>y</sub>), nitrogen (N<sub>2</sub>), particulates, and carbon dioxide (CO<sub>2</sub>) with general combustion reaction, according to [9], illustrated below:



Biomass gasification can be achieved through several gasification principles which are updraft, cross draft, down draft, and fluidized bed gasification systems. In top-lit updraft gasification, Figure 1, fuel to be gasified is loaded and lit from the top, with the air for combustion drawn from the bottom to create an updraft of combusted gases and a descending combustion zone. This mechanism enhances pyrolysis and reduce tar production at very high temperature with controlled air flow. This design typically yields cleaner combusted gases when properly designed with its potential lying in the production of clean flame for heat generation [10]. The prospect of top-lit updraft biomass gasifier in its design simplicity and the production of clean flame for heat energy generation made it suitable for various thermal applications. It is majorly employed in the development of biomass gas stoves, however, its adaptation as sustainable heat source for drying purposes is green and promising and will enhance waste-derived renewable energy system for drying technology.



**Figure 1** Illustration of the combustion process and the fluid-flow patterns in a TLUD gasifier stove [11]

Crop drying, especially for heat-sensitive starchy vegetables like plantains, requires effective control over the heat source and demands uniform heat distribution pattern. This product is typically sliced before being loaded into

mechanical dryers, with cabinet dryers being the most commonly used due to their simplicity, ease of installation, effectiveness, and maintenance. A cabinet dryer principally consists of a drying chamber, trays to hold the products, and a heat energy source. Its effectiveness lies on the continuous supply of uniform hot air throughout the drying space in the cabinet chamber, which is crucial for optimal drying [12]. For effective removal and steady migration of moisture from the plantain slices placed on the trays of the cabinet dryer, the hot-air supplied into the chamber, through a plenum, must be from a reliable and sustainable heat source to ensure consistent and evenly distributed heat needed for drying. The quality of dried plantain slices significantly relies on the stability and consistency of the heat exposure, as these factors profoundly affect the drying kinetics of the plantain slices [13]. The top-lit-up-draft biomass gasifier surfaced as a viable solution to meet these vital requirements. It is capable of providing a clean and consistent hot flame with stable flow rate which are important for maintaining even temperature distribution necessary for efficient drying processes [14]. Furthermore, the heat produced by the gasifier can be effectively controlled to needed specification by directing it through a heat exchanger unit, with effective air control mechanisms, into the cabinet chamber based on the design specification of the drying system. The heat exchanger enables the channeling of constant velocity hot-air, through a plenum, into the drying chamber therefore ensuring a uniform heat distribution pattern in the cabinet drying system. This will not only harvest the needed heat but also aid the continuous and optimal heat supply into the cabinet chamber for sustainable drying process. Such arrangement not only enhances thermal efficiency of the dryer but also significantly improves the overall drying performance of the system, resulting into uniformly dried plantain slices of improved quality [15].

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## 2. Materials and Methods

The top-lit-up-draft (TLUD) biomass gasifier was designed and fabricated using appropriate materials in the Department of Agricultural and Environmental Engineering, Centre for Renewable Energy Technology, Federal University of Technology Akure. The design concept adopted for the gasifier put into consideration the gasification phenomenon of the selected biomass residues.

### 2.1. Materials Selected

The materials and equipment utilized for this research work include: mild steel used for the construction of the gasifier, thermocouple (0-1200°C), digital thermometer, D.C fan (15W), fan control (4800rpm and 6600rpm), backup dry cell battery (30Ah), digital weighing balance (CAMMRY model: 200g-45kg), and biomass fuel (palm kernel shell, coconut shell, coconut husk, and wood shavings).

### 2.2. Design Consideration

The design consideration of the TLUD biomass gasifier was based on its ease of operation, compatibility for drying purpose, low fuel consumption, high thermal and combustion efficiency, and low initial and running cost.

### 2.3. Description of the TLUD biomass gasifier

The gasifier, Figure 2 and 3, comprised of a reactor, outer chamber, residue chamber, D. C fans, primary and secondary air inlets, hopper, feed auger, D.C motor, ignition unit, flame outlet tube, and stand. The reactor is the unit where biomass is fed and combusted for clean energy generation. The reactor chamber houses the reactor and includes a lagging space of 100mm filled with fiberglass insulation in order to enhances thermal efficiency by reducing heat loss but also provides structural support for the integration of thermocouples, which monitor temperature throughout the experimental process. The residue discharge chamber serves as a unit to offload the biomass residues, mainly slag, char and ash, after complete gasification process. The D. C fans supplied the needed air for gasification, while the primary and secondary air inlets are channels for controlled air into the gasifier. The hopper is the unit where biomass fuel is fed into the gasifier while the feed auger and D.C motor aid the conveyance (loading) of this biomass fuel into the gasifier. The ignition unit is the point where biomass is ignited for startup and gasification processes. The flame outlet tube is the unit where gasified clean flame exit the gasifier for further usage while the stand serves as support for the gasifier.

### 2.4. Principle of Operation

The biomass gasifier utilized the principle of top-lit-updraft biomass gasification process to thermo-chemically convert biomass materials into producer gas (primarily carbon monoxide) which, in the presence of controlled oxygen, produced clean flame suitable for thermal applications, such as drying. The gasification process occurred in the gasifier reactor with the aid of air supplied, through the primary and secondary air inlets, from the D.C fans. After loading the reactor to desired level ( $F_L$ ), preferably  $100\% \leq F_L \leq 50\%$ , the biomass material is lit from the ignition unit with the help of starter fuel (0.01ml of kerosene per batch with dried wood pines) and the starter fuel are allowed to burn evenly which took maximum of eighty seconds before the fan is put on for gasification to commenced. The combustion process

of the starter fuel, which is supported by natural surrounding air coming through the ignition unit and the flame outlet pipe, Figure 4, initiated the combustion of the biomass material rising the temperature of the biomass to above 300°C enough for drying, pyrolysis and combustion processes [16]. The biomass material, during gasification process initiated at the top level of the reactor, get converted into char which mixed with the oxygen in the air from the secondary air inlet and up draft from the primary air, in the air volume ratio of 2:1, to react with the carbon in the char at high temperature to produced combustible carbon monoxide (CO), hydrogen (H<sub>2</sub>), methane (CH<sub>4</sub>), Figure 5. Other non-combustible gases, such as (CO<sub>2</sub>), water vapor (H<sub>2</sub>O) and tar, are also produced, in limited quantities for dried and clean biomass, which are eliminated from the reactor by elevated combustion of the biomass to very high temperature above 700°C [16], cracking the tar, CO<sub>2</sub> and H<sub>2</sub>O to produced combustible CO, H<sub>2</sub> and O<sub>2</sub> needed for gasification. The burning layer of the biomass, combustion zone, moves down the reactor as the gasification progresses. As the combustion zone moves down, burned biomass are left in the reactor in the form of char or carbon which mixed with the air supplied by the primary air and produced combustible gases. These gases are up-drafted to the secondary combustion zone for further combustion, Figure 6. Literarily, the primary air gasifies the biomass while the secondary air combusts the biomass syn gases produced and eject it through the flame outlet pipe. The intensity of the heat energy generated and the rate of biomass combustion can be controlled by the speed of the primary and secondary fans with direct relationship. In case of the need for continuous energy generation, the gasifier can be recharged by feeding biomass continuously into the it through its hopper. After complete gasification of the biomass in the reactor, characterized with the absence of flame in the reactor, the residues (majorly char, slag and ash) are allowed to cool and discharged through the residue chamber off the gasifier.

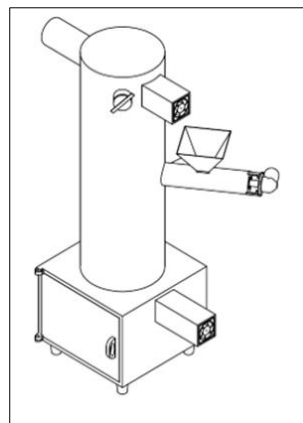


Figure 2 Isometric sketch of the TLUD biomass gasifier

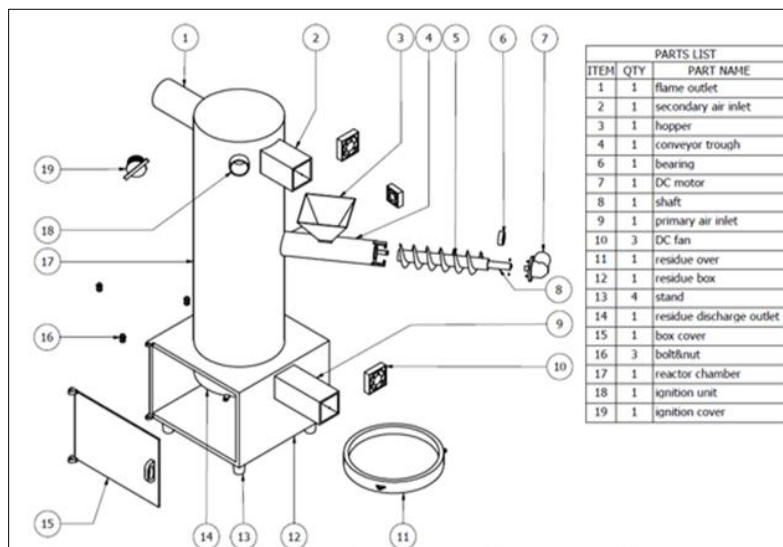
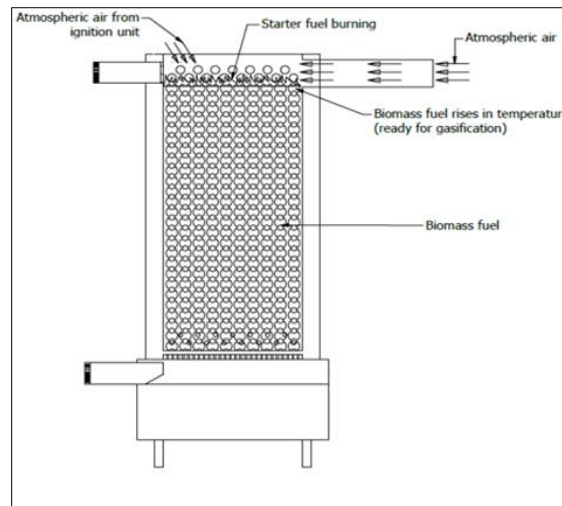
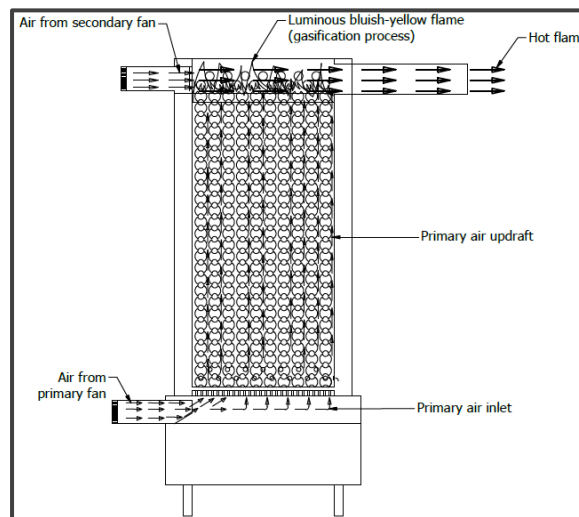


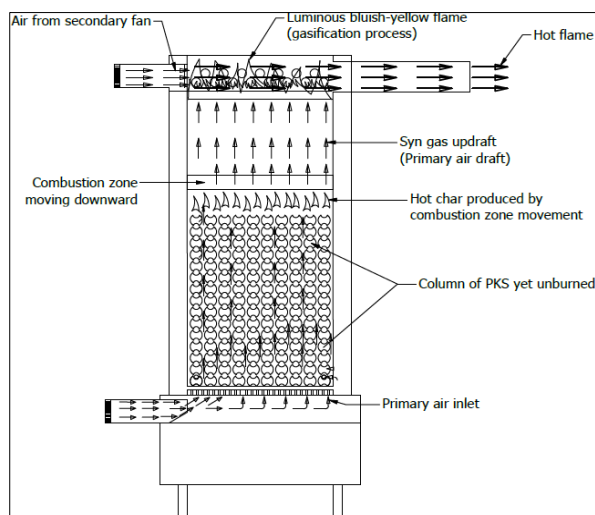
Figure 3 Exploded view of the TLUD biomass gasifier



**Figure 4** Fuel start up process



**Figure 5** Initial gasification process



**Figure 6** Principle of operation of the TLUD biomass gasifier reactor

## 2.5. Energy required from the gasifier

The gasifier was specifically designed for thermal application in drying of plantain slices in a cabinet dryer, however, provision was made for its usage in general drying for cottage and industrial purposes. The gasifier was designed to provide energy of 260MJ/h, which is sufficient for several thermal applications, especially for post-harvest drying processes.

## 2.6. Energy Input

The amount of biomass fuel needed to be fed into the gasifier to supply the required energy (FCR), fuel consumption rate, according to [17], is given as:

$$FCR = \frac{Q_r}{C_f \times \epsilon_s} \dots \dots (2)$$

Where  $C_f$  is the calorific value of biomass material (kJ/kg), and  $\epsilon_s$  is the theoretical gasifier efficiency. The maximum of the calorific values of selected biomass (PKS, CCS, CCH and WDS) will be selected. The calorific values of CCS and CCH, according to [18] are 17400kJ/kg and 10010kJ/kg respectively, while according to [19], calorific value of WDS is 13206.05kJ/kg, and according to [20], the calorific value of PKS is 23604.71kJ/kg. PKS has the maximum calorific value, as such, 23604.71kJ/kg will be selected. Assuming gasifier efficiency of 20%, hence:

$$FCR = 55kg/hr$$

## 2.7. Diameter of the Reactor

The diameter of the reactor refers to the cross-sectional diameter of the cylinder (reactor) where biomass fuel is being combusted. It dictates the intensity of heat energy that will be generated by the gasifier [21]. The reactor diameter is a function of the fuel consumption rate and the specific gasification rate (SGR) of the fuel ranging from 110 – 250kg/m<sup>2</sup>hr [17] which can be determined, thus [22]:

$$D_s = \frac{4 \times FCR}{SGR \times \pi} \dots \dots (3)$$

Selecting maximum SGR's value, 250kg/m<sup>2</sup>hr, thus:

$$D_s = 28cm$$

The reactor diameter was selected as 28cm.

## 2.8. Height of the Reactor

The height of the reactor ( $H_r$ ) refers to the distance from the base to the top of the reactor. It is an essential geometry of the gasifier that must be determined as it dictate how long the gasifier would be operated in a single loading of fuel. It is a function of some variables of the gasifier which are the time to operate the gasifier ( $T_s$ ), the bulk density of the fuel ( $\rho_k$ ) and specific gasification rate (SGR). According to [22], the gasifier height can be computed using the formula:

$$H_r = \frac{SGR \times T_s}{\rho_k} \dots (4)$$

Selecting the maximum density of the selected biomass (PKS, CCS, CCH and WDS), according to [23], the bulk density of PKS is 740 kg/m<sup>3</sup> (wet) and 650 kg/m<sup>3</sup> (dry). Selecting the dry base bulk density and a desired operating time of 2.35 hour;

$$H_r = 90.38cm$$

For easy of construction, the gasifier height was selected as 90cm.

## 2.9. Time taken for Fuel Consumption

The time taken for fuel consumption is the total time taken to consume the fuel in the reactor from startup, when the fuel is lit, till complete fuel gasification, when the fuel no longer produced flame in the reactor. It is a function of the bulk

density of the fuel ( $\rho_k$ ), the volume of the reactor ( $V_R$ ) and the fuel combustion rate (FCR) of the biomass material, given, according to [17], as:

$$T_s = \frac{\rho_k \times \pi \times H_r \times D_s}{4 \times FCR} \dots \dots (5)$$

$$T_s = 2.34\text{h}$$

## 2.10. Stoichiometric Air requirement for Biomass Combustion

The stoichiometric air requirement for the selected biomass Combustion, which is the amount of air needed to completely burn the biomass and convert it to ash, is very essential to determine the amount of air needed to be supplied by the D.C fan for the biomass gasification in the gasifier. It can be determined, according to [24], by the expression below.

$$m_a = \frac{100}{23} (2.67C + 8H_2 + S - O_2) \dots \dots (6)$$

Where  $m_a$  is the mass of air needed (stoichiometric air),  $C, H_2, S$  and  $O_2$  are the carbon, hydrogen, sulphur and oxygen contents of the selected biomass respectively. According to [22], selecting the PKS chemical compositions at dry basis,  $C = 49.79\%, H_2 = 5.58\%, S = 0.08\%$ , and  $O_2 = 34.66\%$ .

$$m_a = \frac{100}{23} [2.67(0.4979) + 8(0.0558) + (0.0008) - (0.3466)]$$

$m_a = 6.22$  kg of air/ kg of fuel.

According to [22] selecting the CCS chemical compositions at dry basis,  $C = 49.79\%, H_2 = 5.58\%, S = 0.08\%$ , and  $O_2 = 34.66\%$ .

$$m_a = \frac{100}{23} [2.67(0.503) + 8(0.062) + (0.0005) - (0.4345)]$$

$m_a = 5.87$  kg of air/ kg of fuel.

Similarly, selecting the CCH chemical compositions at dry basis,  $C = 46.1\%, H_2 = 5.8\%, S = 0.02\%$ , and  $O_2 = 48.08\%$ .

$$m_a = \frac{100}{23} [2.67(0.461) + 8(0.058) + (0.0002) - (0.4808)]$$

$m_a = 5.28$  kg of air/ kg of fuel.

Likewise, selecting the WDS chemical compositions at dry basis,  $C = 48.5\%, H_2 = 6\%, S = 0.1\%$ , and  $O_2 = 45.4\%$ .

$$m_a = \frac{100}{23} [2.67(0.485) + 8(0.06) + (0.001) - (0.454)]$$

$m_a = 5.75$  kg of air/ kg of fuel.

The maximum mass of air needed for complete combustion of the biomass selected will be used for the design. Hence, maximum of 6.22kg of air must be supplied by the gasifier fan to gasify 1kg of the selected biomass.

## 2.11. Gasification Airflow Rate

Gasification air flow rate is the amount of air needed to gasify the selected biomass. This is very essential in determining the size of the fan needed by the gasifier for the gasification of biomass in the reactor. It depends on some factors of the gasifier which are the fuel consumption rate (FCR), the maximum stoichiometry air of biomass ( $m_a$ ), density of air ( $\rho_a = 1.25\text{kg}/\text{m}^3$ ), and the recommended equivalence ratio ( $\epsilon$ ) for gasifying biomass, 0.3 – 0.5 [22]. Considering lower heat value (LHV) of the biomass gasification, which is the best for top-lit-up-draft gasifier, according to [22], equivalence

ratio of 0.3 was selected. According [21], the biomass gasification air flow rate ( $A_q$ ) can be obtained with the expression below.

$$A_q = \frac{\varepsilon \times FCR \times m_a}{\rho_a} \dots \dots (7)$$

$$A_q = 82.1m^3/h$$

### 2.12. Thermal efficiency

The effectiveness of the gasifier in converting the energy available in the biomass fuel to usable heat energy quantifies its thermal efficiency. The thermal efficiency of the gasifier determines its maximum energy conversion ratio from waste to useful energy. According to [25], it can determine using the expression:

$$TE = \left( \frac{f_m \times LHV}{\dot{m}_F \times C_{pf} \times \Delta T \times t} \right) \times 100 \dots \dots (9)$$

Where  $f_m$  is the mass of biomass loaded into the gasifier (kg),  $LHV$  is the lower heating value of the biomass (MJ/kg),  $\dot{m}_F$  is the mass flow rate of the exhaust flame (kg/s),  $C_{pf}$  is the specific heat capacity of the exhaust flame (kJ/kg.K),  $\Delta T$  is the temperature increase of the exhaust flame from ambient to exit temperature (K), and  $t$  is the time duration of gasification (s). According to [26], the LHV of PKS is 24457.9592kJ/kg, according to [18], the LHV of CCS and CCH are 17400kJ/kg and 10010kJ/kg respectively, and the LHV of WDS is 14412kJ/kg [27]. Knowing the diameter of the gasifier exhaust pipe, 11cm (for pipe cross-sectional area,  $A_e$ ), and taking the density ( $\rho_f$ ) and specific heat capacity of the exhaust flame as the density of ideal gas under standard atmospheric pressure (0.303 kg/m<sup>3</sup>) and 1.005kJ/kg/K respectively, and fan blade diameter ( $\phi_F$ ) of 7cm (for fan speed in rpm,  $N_F$ ), the thermal efficiency of the gasifier can be simplified as:

$$TE = \left( \frac{947513.61 \times f_m \times LHV}{N_F \times \Delta T \times t} \right) \times 100 \dots \dots (10)$$

### Combustion efficiency

The combustion efficiency ( $CT$ ) of the gasifier measures the amount of biomass fuel gasified with respect to the fuel loaded, given by the expression below [28]:

$$CE = \frac{f_{mg}}{f_m} \times 100 \dots \dots (11)$$

Where  $f_m$  is the initial mass of biomass loaded into the gasifier (kg), and  $f_{mg}$  is the amount of biomass gasified in the gasifier till complete gasification (kg).

## 3. Result and Discussion

The gasifier was tested by subjecting it to input parameters (independent variables) of fuel loading into the gasifier ( $20kg \leq f_L \leq 10kg$ ); fan operational speed ( $4000rpm \leq v_f \leq 6000rpm$ ); and the fuel type used (PKS, CCS, CCH and WDS) to check their effects on the responses (dependent variables) of the gasifier which includes the fuel gasification time ( $t_g$ , min); exhaust flame temperature ( $T_g$ , °C); thermal efficiency ( $TE$ , %); combustion efficiency ( $CE$ , %); and the emission quality of the exhaust flame, which was measured by the amount of carbon monoxide (CO, ppm) emitted to the surrounding air during gasification process using air quality detector device. The gasifier was tested following the standard described by Kole [29].

### 3.1. Performance Test Result of the Stove

Based on the data obtained during the experimental testing of the gasifier, the performance test results of the gasifier were discussed with Figure 7 to Figure 11. The test results showed that increase in the fan speed of the primary and secondary fans (at same rate and ratio) with increase in fuel loading increases the flame temperature and thermal efficiency of the gasifier, Figure 7 and Figure 8, following the result obtained during the testing of PKS gas stove developed by Olaleye [30] as preliminary design adopted for the development of the gasifier. This was accounted for by



the increase in the fire power of the gasifier as the fan speed increases. It also explained that at higher speed, more oxygen was supplied for gasification, leading to higher updraft of the syngas and more intense combustion at the secondary combustion zone which emanated more hydrogen than methane and carbon monoxide, leading to higher flame temperature, given yellowish-blue flame and higher useful output heat energy resulting into higher thermal efficiency of the gasifier. The gasifier recorded maximum thermal efficiency of 86.02% at highest flame temperature of 875°C and minimum thermal efficiency of 20.58% at lowest flame temperature of 395°C when operated at configuration of PKS fuel at 6000rpm fan speed for 20kg fuel loading, and configuration of CCH fuel at 4000rpm fan speed for 10kg fuel loading respectively. On the other hand, increase in the fan speed of the gasifier's primary and secondary air inlets at the same rate and ratio with decrease in the fuel loading, Figure 9, considerably decreases the combustion efficiency of the gasifier. This explained that more biomass residues (biochar or slag or both) were recorded as the fuel loading increases and the fan speed increases. The gasifier recorded maximum combustion efficiency of 99.9% and minimum combustion efficiency of 88.4% when operated at configuration of WDS fuel at 6000rpm fan speed for 20kg and 10kg fuel loadings, and configuration of PKS fuel at 6000rpm fan speed for 10kg fuel loading respectively. These correlations explained that optimizing air supply dynamics and fuel input into the gasifier is crucial for maximizing the process of gasification energy conversion efficacy of the gasifier for sustainable energy supply into the cabinet dryer for plantain slice drying.

The flame temperature profile of the gasifier with respect to the gasification time, at the maximum thermal efficiencies obtained by the gasifier for the individual biomass fuel used, were studied, as shown on Figure 10. It can be deduced that each of the fuel attained their maximum flame temperature at gasification time of 45min, 40min, 20min, and 25min for PKS, CCS, CCH, and WDS respectively with gasification time of 130min, 95min, 38min, and 50min respectively. The PKS fuel performed best, at equal loading with other fuels, to supply clean heat energy to the dryer for longer drying time, followed by CCS as the closest alternative, then WDS and lastly CCH which performed least with minimal heat energy rate and intensity. The average heat energy output of the gasifier, Figure 11, were 260.16MJ/h, 147.84MJ/h, 38.91MJ/h, and 61.62MJ/h when operated with PKS, CCS, CCH, and WDS respectively. This conformed with the energy design of the gasifier, and also explained the potentials of the gasifier to supply heat energy sufficient for most thermal applications with multiple options depending on the fuel and thermal energy needed. The flame emission quality was also considered by measuring the amount of CO emitted to the surrounding during the test experiment. The CO emission was detected using air quality detector, and the results obtained were presented with Figure 12. It can be observed that the average emission of CO by the gasifier when operated with PKS, CCS, and WDS, were very minimal, but very high when operated with CCH. The result obtained, according to international air pollutants standards and their acceptable environmental and health thresholds, Table 1, can be concluded that the gasifier is best operated with PKS, followed by CCS and lastly WDS, but never with CCH to avoid health and environmental hazards posed by CCH when used with the gasifier.

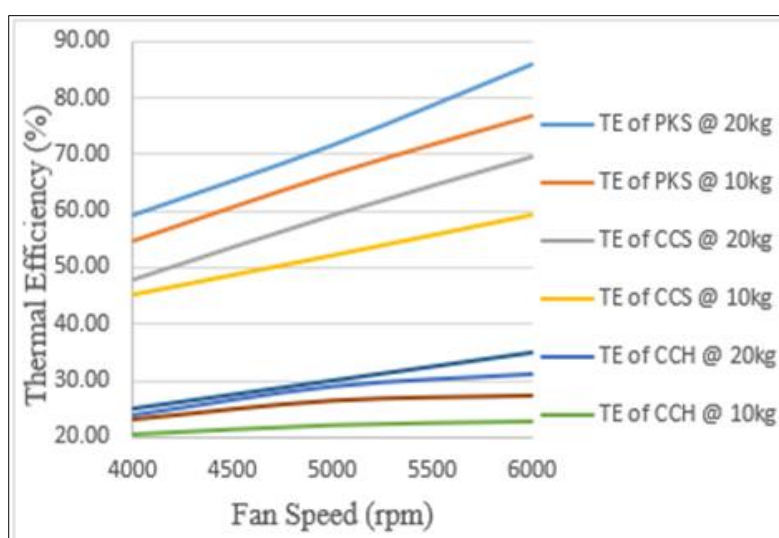
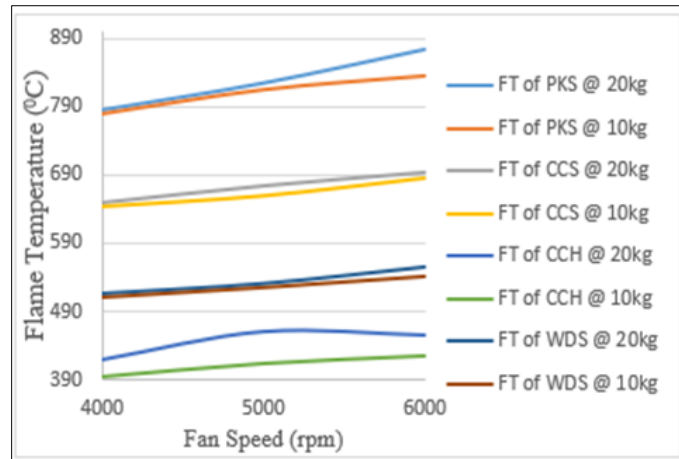
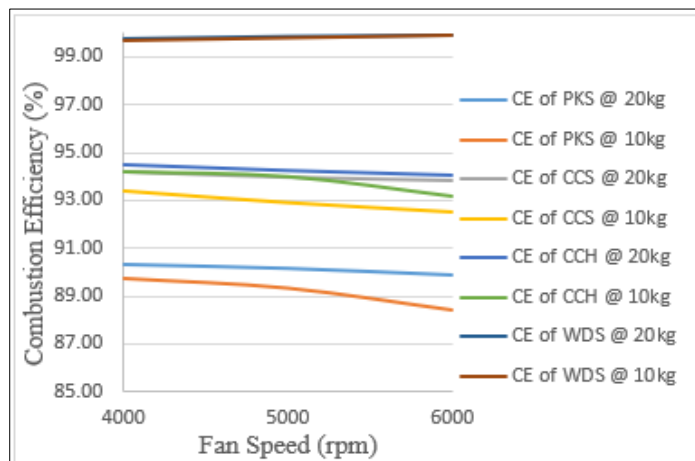


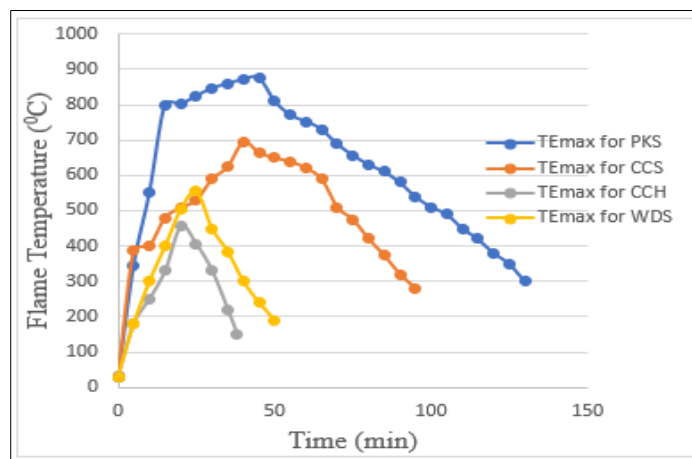
Figure 7 Thermal efficiency graph



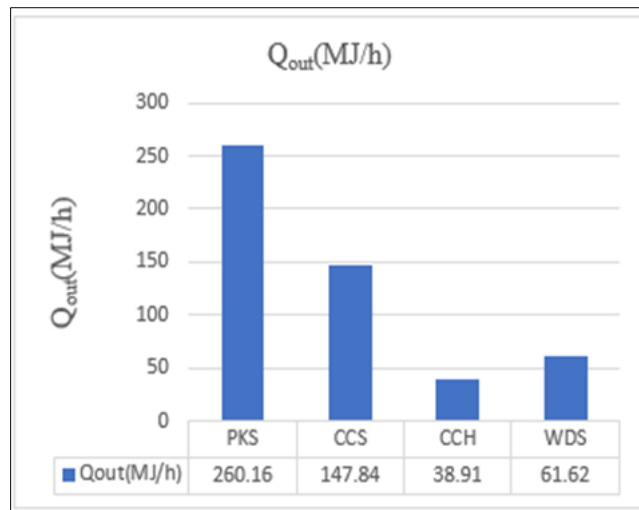
**Figure 8** Gasifier exhaust flame temperature graph



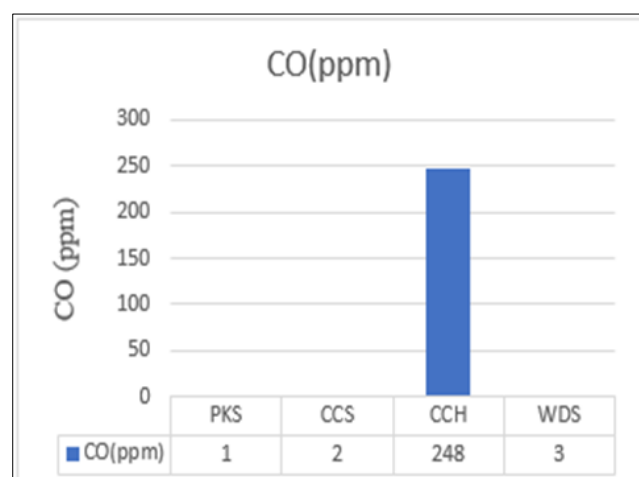
**Figure 9** Combustion efficiency graph



**Figure 10** Flame temperature profile graph



**Figure 11** Heat energy output graph



**Figure 12** Flame emission quality graph

**Table 1** International air pollutants standards and their acceptable environmental and health thresholds

Pollutant	Standard	Organization	Threshold	Units
CO	8-hour mean	WHO	9	ppm
CO	1-hour mean	WHO	26	ppm
CO	8-hour standard	USEPA	10	ppm
CO	1-hour standard	USEPA	35	ppm

Source: [31, 32]

#### 4. Conclusion

The top-lit-up-draft biomass gasifier was developed and tested in the Department of Agricultural and Environmental Engineering, Centre for Renewable Energy Technology, Federal University of Technology Akure. The gasifier was designed with a reactor height and diameter of 90cm and 11cm respectively which can accommodate maximum of 20kg of the biomass fuel per operational batch. The performance testing of the gasifier revealed its maximum thermal efficiency of 86.02% and maximum flame temperature of 875°C when operated with PKS fuel at fan speed of 6000rpm for 20kg fuel loading. The minimum thermal efficiency of 20.58% and lowest flame temperature of 395°C was recorded by the gasifier when operated with CCS at fan speed of 4000rpm for 10kg fuel loading. The thermal efficiency and the

flame temperature of the gasifier increases as the fan speed of the primary and secondary air inlets increases at increasing fuel loading. The maximum and the minimum combustion efficiencies recorded by the gasifier were 99.9% and 88.4% respectively, which increases as fan speed and fuel loading decreases. The gasification time recorded by the gasifier with respect to the fuel type used were 130min, 95min, 38min, and 50min for PKS, CCS, CCH, and WDS respectively. The gasifier is capable of supplying average maximum heat energy of 260.16MJ/hr when operated with PKS, and average minimum heat energy of 38.91MJ/hr when operated with CCH, which are sufficient for most thermal applications. The CO emission of the gasifier when operated with PKS, CCS and WDS fuel were below the air pollutant threshold but above the threshold for CCH. This disqualified CCH as a permissible fuel to be operated with the gasifier for the purpose of health and environmental safety of the user. The overall performance test of the gasifier presented PKS as the best fuel to be used for higher thermal and flame emission quality, followed by CCS as the closest alternative and WDS as a viable alternative. The performance result of the gasifier presented it as a sustainable heat source for drying plantain slices in as cabinet dryer.

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## Compliance with ethical standards

### *Disclosure of conflict of interest*

We the author of this article, Engr. Olaleye S. A, Prof. Olalusi AP, Prof. Jaiyeoba KF and Dr. Isa J, hereby declare that we have no conflicts of interest or competing interests regarding the publication of this manuscript. No institution, product, or entity mentioned in this study has influenced its outcome or findings. Furthermore, the authors declare that there are no products competing with those mentioned in the manuscript that could be perceived as a conflict of interest.

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