World Journal of Advanced Engineering Technology and Sciences
eISSN: 2582-8266
Cross Ref DOI: 10.30574/wjaets
Journal homepage: https://wjaets.com/

(RESEARCH ARTICLE)

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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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World Journal of Advanced Engineering Technology and Sciences, 2024, 13(01), 852–864

Publication history: Received on 02 September 2024; revised on 10 October 2024; accepted on 12 October 2024

Article DOI: https://doi.org/10.30574/wjaets.2024.13.1.0492

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 82.1m3/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 300^0C - 1400^0C and atmospheric or elevated pressures up to 33 bar [8]. The principal gaseous products are hydrogen (H_2) and carbon monoxide (CO), with smaller amounts of water (H_2O), methane (CH_4), higher hydrocarbons (CxHy), nitrogen (N_2), particulates, and carbon dioxide (CO_2) with general combustion reaction, according to [9], illustrated below:

$$C_aH_bO_cN_dS_e + \frac{O_2}{air} \rightarrow CO_2 + H_2O + N_xO_y + SO_z + Heat \;\ldots\ldots (1)$$

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.

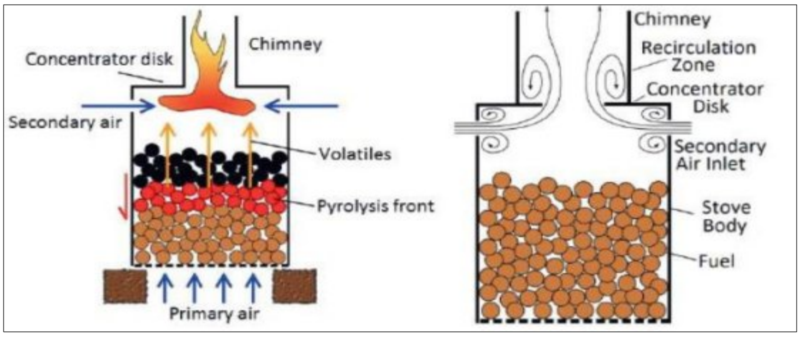

Figure 1 Illustration of the combustion process and the fluid-flow patterns in a TLUD gasifier stove [11]

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].

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^{0}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 300^0C 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_2), methane (CH_4), Figure 5. Other non-combustible gases, such as (CO_2), water vapor (H_2O) 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 700^0C [16], cracking the tar, CO_2 and H_2O to produced combustible CO, H_2 and O_2 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.

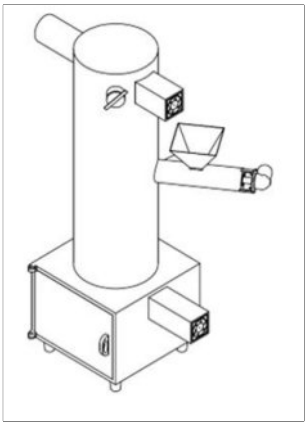

Figure 2 Isometric sketch of the TLUD biomass gasifier

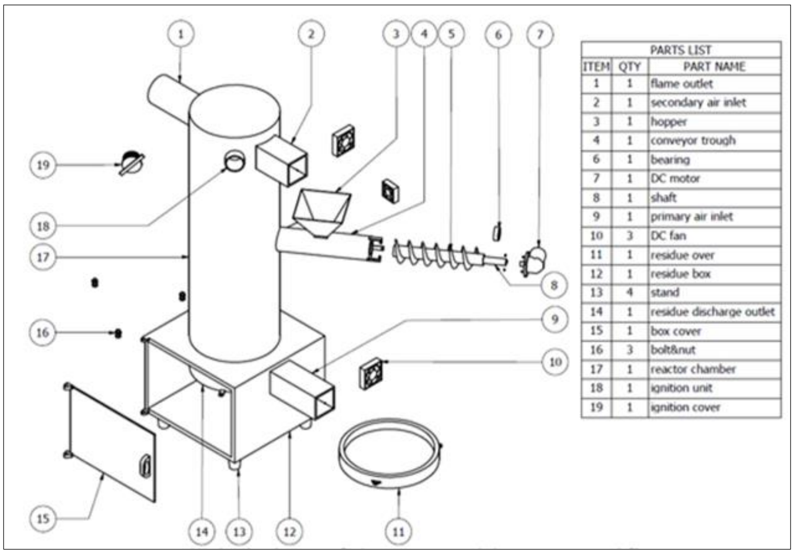

Figure 3 Exploded view of the TLUD biomass gasifier

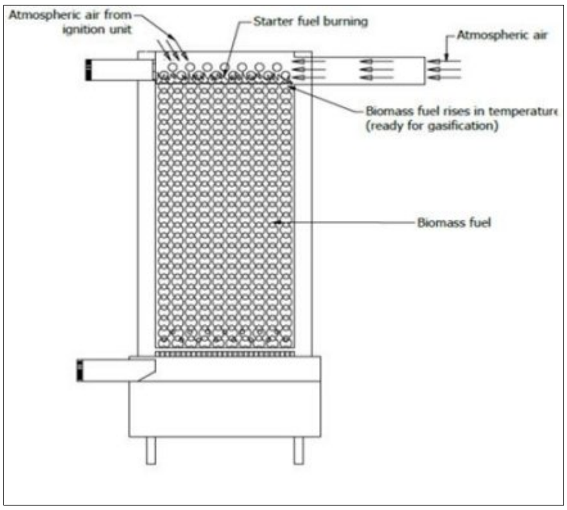

Figure 4 Fuel start up process

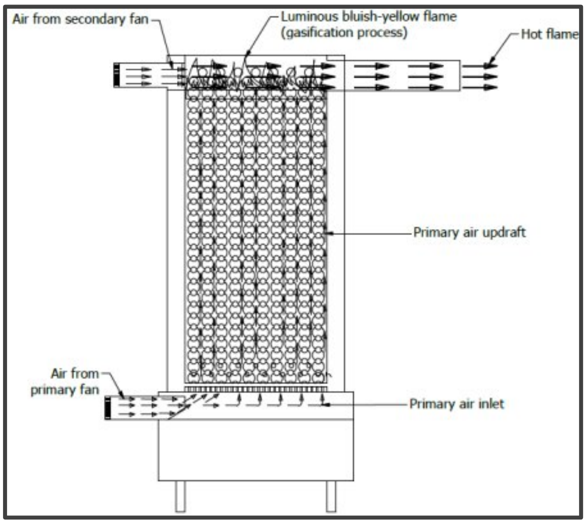

Figure 5 Initial gasification process

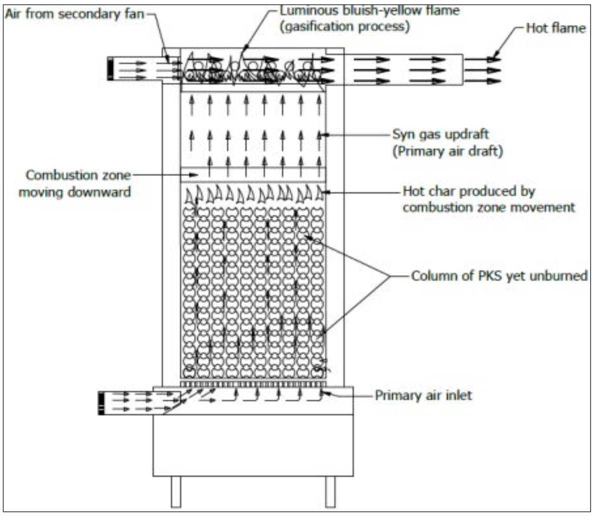

Figure 6 Principle of operation of the TLUD biomass gasifier reactor

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:

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

Where C_f is the calorific value of biomass material (kJ/kg), and $\in_s$ 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^{2}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^{2}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 (ρ_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^3 (wet) and 650 kg/m^3 (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 (ρ_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 ($\rho_a = 1.25kg/m^3$), and the recommended equivalence ratio (ε) 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.

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

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

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), ΔT 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 (ρ_f) and specific heat capacity of the exhaust flame as the density of ideal gas under standard atmospheric pressure (0.303 kg/m^3) and 1.005kJ/kg/K respectively, and fan blade diameter ($\emptyset_F$) 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]:

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

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, ^{0}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^{0}C and minimum thermal efficiency of 20.58% at lowest flame temperature of 395^{0}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.

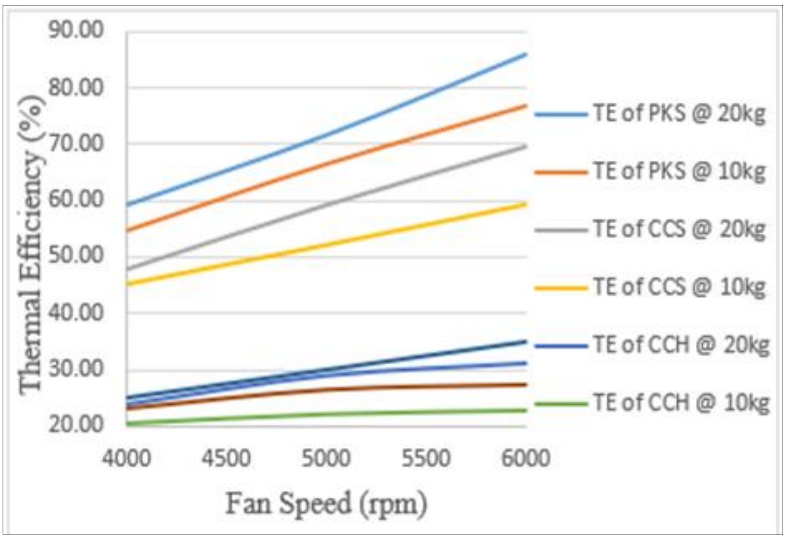

Figure 7 Themal efficiency ghaph

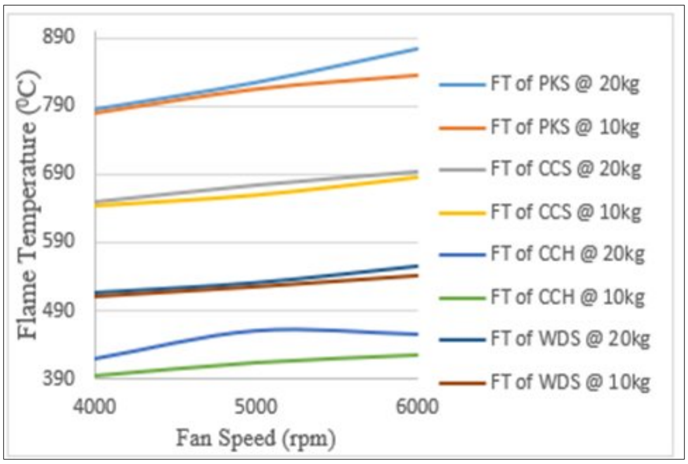

Figure 8 Gasifer exhaust flame temperahure graph

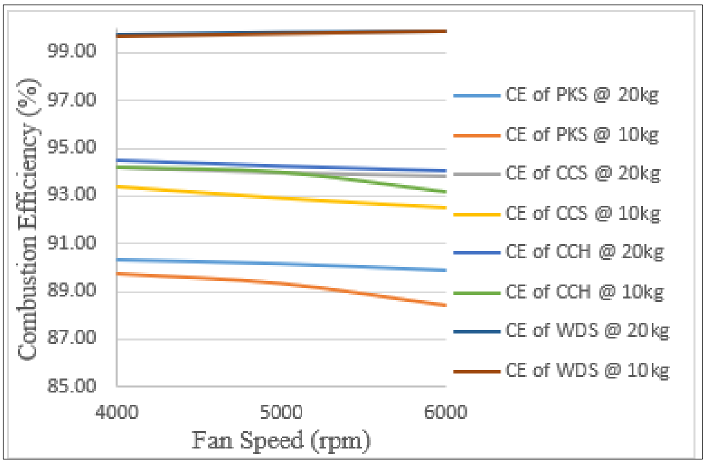

Figure 9 Combustion efficiency graph

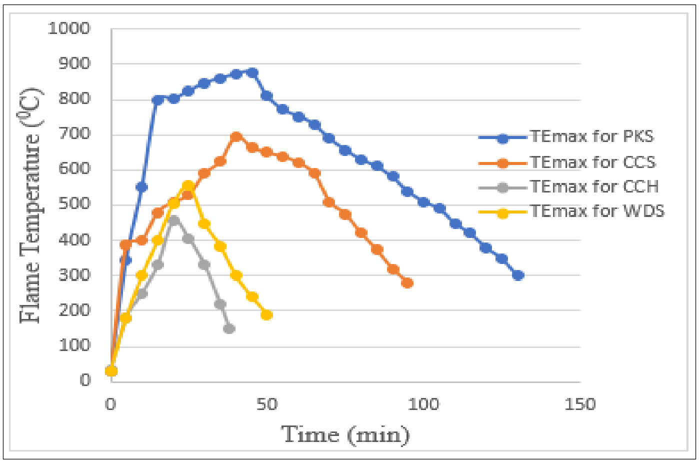

Figure 10 Flame temperature profile graph

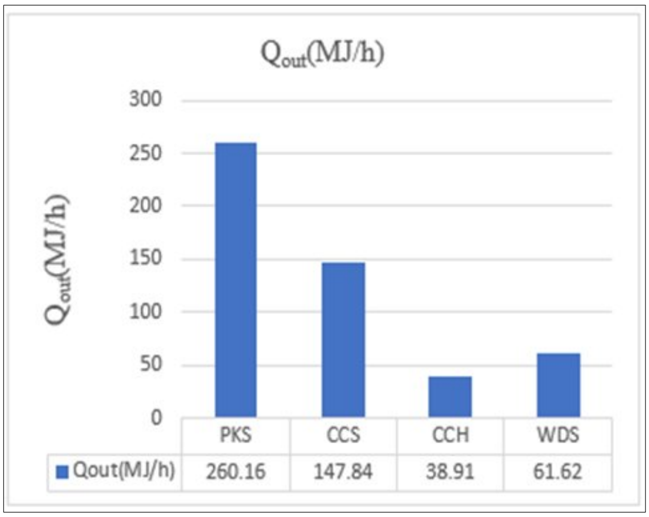

Figure 11 Heat energy output graph

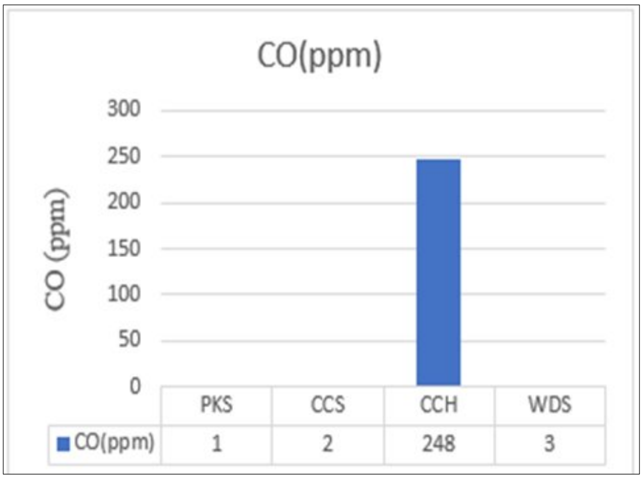

Figure 12 Flame emission quality graph

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^{0}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^{0}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.

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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JOURNAL OF AGRICULTURE,
ENVIRONMENTAL TECHNOLOGY
& COMMUNICATION
jaetcom2022@gmail.com, jaetcom@fecaakure.edu.ng

Volume 2 Issue 1, 1-15, (2025) *ISSN3043-5080*

RESPONSE SURFACE METHODOLOGY (RSM) OPTIMIZATION OF THE THERMAL RESPONSES OF A TOP-LIT-UP-DRAFT BIOMASS GASIFIER DEVELOPED AS HEAT SOURCE FOR PLANTAIN SLICE DRYING

BY

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Abstract
An optimized top-lit-up-draft (TLUD) biomass gasifier with efficient fuel consumption provides optimum and clean energy for several thermal applications, such as drying. This study optimized a developed TLUD biomass gasifier, using response surface methodology (RSM) in Design Expert v13, to establish predictive models for its thermal responses which include thermal efficiency (TE), flame temperature (FT), gasification time (GT), and CO emission using fuel loading (20kg, 15kg, and 10kg), fan speed (400rpm, 5000rpm, and 6000rpm), and biomass fuel type [palm kernel shell (PKS), coconut shell (CCS), coconut husk (CCH) and wood shaving (WDS)] as input factors. Utilizing a central composite design (CCD) approach in RSM, two factorial interaction (2FI) models were adopted for FT, GT, and TE, yielding R^2 values of 0.9991, 0.9966, and 0.9953, respectively, and showing strong predictive accuracy ($p < 0.001$). The lack of fit tests underlined model validity with F-values of 2.03, 0.91, and 0.45 ($p > 0.05$). A quadratic model was utilized for CO emissions, with R^2 of 0.9962, similarly having insignificant lack of fit ($F = 11.94$, $p > 0.05$). The analysis of variance (ANOVA) revealed that linear terms of fuel loading, fan speed, and fuel type, in conjunction with their interactions, had significant effects on all response variables. The models effectively captured the relationships between the independent variables and the responses, optimizing the gasifier performances including thermal efficiency, flame temperature control, and CO emissions reduction, making the gasifier suitable as a sustainable heat source for plantain drying.

Keywords: *Gasifier, Biomass, Performance Evaluation, RSM, Optimization.*

1.0 INTRODUCTION

Top-lit-up-draft (TLUD) biomass gasifier has emerged as a promising heat energy alternative to conventional heat sources for drying methods. Its potential leverage on the renewable biomass sources for heat energy generation to effectively dry agricultural products such as plantain slices. Traditional drying of agricultural produce, which relied on the sun, are grossly affected by the weather conditions and are embroiled with unstable non-uniform heat distribution hampering the drying kinetics and quality of products being dried (Gunathilake et al., 2018). In addition, it exposes food items to various hazardous conditions and predictors, such as animal, affecting the economic value of the drying method (Ibrahim et al., 2023). Mechanical drying methods, on the other hand, are free from these challenges but are grossly affected by their heat sources. In most developing countries, such as Nigeria, the heat energy sources of mechanical dryers ranged from grid-electricity to petrochemical fuel which are hampered by high costs, reliability issues, and are known to be unstable posing high energy cost for drying (Yao et al., 2022). In contrast, the TLUD gasifier utilizes locally sourced biomass, such as agricultural residues and wood chips, presenting a cost-effective and sustainable solution that reduces overreliance on non-renewable and costly energy sources (Bhadha et al., 2021). TLUD gasifier utilizes thermochemical conversion of biomass, at high temperatures ranging from 300°C to 1400°C in a controlled air or steam environment, to produce clean syngas, mostly carbon monoxide (CO), methane (CH_4), and hydrogen (H_2) gases, that optimizes heat utilization and minimizes environmental impact. The gasification of biomass, to generate clean heat energy for thermal application, not only supports sustainable waste-recovery practices but also contributes to reduced operational costs in drying agricultural products which in turn lower food prices (Sapariya et al., 2021).

Optimizing the TLUD gasifier for mechanical dryers, such as cabinet drying applications, offers great opportunity in ensuring consistent, uniform and optimum heat distribution in the drying space, which is essential for high-quality drying of heat-sensitive products like plantains. Cabinet dryers, favored for their effectiveness and simplicity, require reliable and consistent heat source to maintain the necessary drying kinetics and product quality of material dried in them, especially starchy vegetables such as plantain (Gunathilake et al., 2018). The TLUD gasifier is very compatible with cabinet dryer as a sustainable heat source that supplies reliable and sustainable heat energy. This is possible due to the high heat energy output and firepower of TLUD gasifier. The level of heat generated in the gasifier can be controlled by the air inlets into the gasifier for optimum performance. The clean heat generated can be effectively harnessed in the dryer through the incorporation of heat exchanger unit and plenum for sensible heat energy profile essential for even temperature distribution throughout the drying chamber in order to maintain optimal drying conditions (Gunathilake et al., 2018). Such technical configurations improve the thermal efficiency of the drying process and also ensure that plantain slices are dried uniformly, preserving their quality and extending shelf life (Famurewa et al., 2017). This method explains the TLUD gasifier's potential to revolutionize biomass-based drying technologies, making it a sustainable and economically viable option for drying applications in developing countries.

In addition, a sustainable heat energy source, using TLUD biomass gasifier, requires system optimization to determine the optimal conditions necessary to operate the gasifier for the best peak thermal performances needed to supply heat energy required for optimum drying of the plantain slices, for the best drying kinetics and improved product quality (Muritala et al., 2022). Optimization of machineries and devices involves systematic way of improving performance parameters (responses) by fine-tuning controllable input factors (dependent variables) of a machine process or production. Commonly employed methods such as Response Surface Methodology (RSM) enable the exploration of complex interactions between variables through mathematical modelling and experimental planning (Inyang et al., 2017). The merits of optimization include enhanced operational efficiency, reduced resource consumption, and improved product consistency, leading to cost savings and increased competitiveness. Similarly, it reduces the need for trial-and-error methods and offers accurate operating conditions that optimize efficiency while minimizing equipment wear and downtime. These phenomenal has been applied to optimize the performances of several machineries for improved results (Soudagar et al., 2024).

Ozkan et al. (2023) carried out studies on Response Surface Methodology (RSM) treatment optimization for wastewater from office paper recycling. The ideal circumstances for turbidity reduction were determined by the researchers by examining the interactions between microwave power, duration, and centrifuge time. A three-factor RSM technique was employed in the investigation, and statistical analysis was done to validate the model. Turbidity was significantly reduced to 6.65 NTU under the ideal conditions, which included 150 Watts of microwave power, 60 seconds of irradiation, and 15 minutes of centrifugation. With R^2 = 99.71% and a lack-of-fit value showing good agreement between the model and the experimental data, the model was found to be very accurate. The turbidity was further lowered to 1.43 NTU under ideal conditions, which nearly matched the experimental outcome of 1.47 NTU.

Khayer et al. (2019) investigated the use of response surface methods in the structural design optimization of a pedal-operated paddy thresher. Using Response Surface Methodology (RSM) in the Design Expert tool, the study concentrated on optimizing important design parameters of a pedal-operated paddy thresher (POPT), such as loop spacing, tip height, drum peripheral speed, and the number of strips on the drum, to maximize threshing capacity. The results of the analysis of variance (ANOVA) showed that the threshing capacity was strongly influenced ($P<0.05$) by the quadratic terms of loop spacing and drum peripheral speed, the interaction of drum peripheral speed and number of strips, and loop spacing and tip height (linear terms). With a coefficient of determination (R^2) of 0.95, the model demonstrated a robust correlation between the experimental and predicted values. The machine's optimized parameters were 14 strips on the drum, a loop spacing of 3.99 cm, a tip height of 5.09 cm, and a drum peripheral speed of 398.215 rpm. Under these conditions, the thresher achieved a capacity of approximately 53.01 kg/h with minimal worker discomfort.

Sada (2018) presented research on modelling performance artificial neural networks and response surface methodology. In order to forecast the tensile strength of a mild steel plate that is 6 mm thick and has been welded using gas tungsten arc welding, the study evaluates the capacities of RSM and ANN while taking into account various factors such as filler rod, weld current, weld speed, and gas flow rate. Based on a comparison using the coefficient of determination, it was discovered that the ANN model performed better in terms of prediction accuracy than the RSM model, with a R^2 value of 0.836.

Okouzi et al. (2021) investigated batch process optimization using response surface methodology (RSM) in a rectangular passive greenhouse dryer. The research refined the batch process within the solar dryer and created a numerical model for the digital prototyping of a rectangular passive greenhouse dryer. For a factorial experiment, multiple regression was used as the data analysis strategy. ANSYS 14.0 software was used to create an empirical model that predicted the response variable and tested hypotheses. In order to determine the dryer parameters that maximize the mean temperature, Response Surface Methodology (RSM) optimization was also carried out using this program. The central composite design (CCD) factorial trials showed that the only variable that substantially affected the dryer's mean temperature was the size of the inlet vent. The usefulness of RSM for analysing dryer variables was confirmed by the model's coefficient of determination ($R^2 = 0.99973$), which showed that the model could explain 99.973% of the variability in the dryer's mean temperature. Through parametric analysis, the ideal design factors were found to be an inlet vent width of 0.45 m and an inlet vent height of 0.27 m, which optimized the drying air temperature to 320.48 K (47.30°C). The batch process in the passive dryer was successfully optimized and prototyped with the help of this numerical approach.

Thus, the objective of this study is to optimize the thermal responses of a TLUD biomass gasifier designed as heat source to supply optimum heat energy needed for drying plantain slices in a cabinet dryer, with respect to its operational parameters, using response surface methodology (RSM) and central composite design (CCD) techniques.

2.0 MATERIALS AND METHODS

The TLUD biomass gasifier, developed in the Department of Agricultural and Environmental Engineering, Centre for Renewable Energy Technology, Federal University of Technology Akure., was evaluated using input factors (dependent variables) which include fuel loading (FLD: 10kg and 20kg), fan speed (FSP: 4000rpm, 5000rpm, and 6000rpm), and fuel type [palm-kernel shell (PKS), coconut shell (CCS), coconut husk (CCH), and wood shavings(WDS)] to determine the thermal responses of the stove which includes thermal efficiency (TE, %), combustion efficiency (CE, %), flame temperature (FT, ^{0}C), gasification time (GT, min), heat energy output (HE, MJ/h), and flame emission quality (CO, ppm). The gasifier test results were subjected to response surface methodology (RSM) using central composite design (CCD) techniques of Design Expert v13 software. This was done in order to determine the optimal conditions necessary to operate the gasifier for effective and sustainable energy supply into the cabinet drying system for effective plantain slice drying.

2.1 Brief Description of the TLUD Biomass gasifier

The gasifier, Figure 1 and 2, 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 where controlled air are introduced 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.

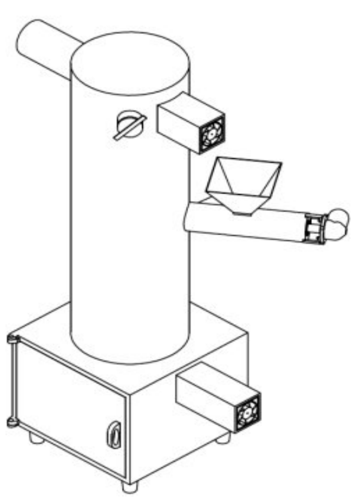
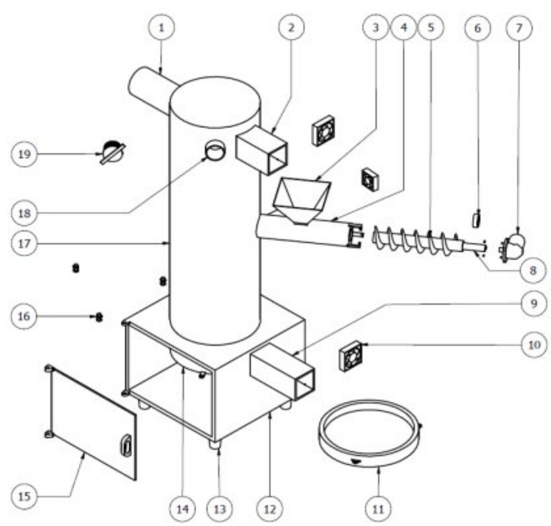


Figure 1: Isometric sketch of the TLUD biomass gasifier



PARTS LIST		
ITEM	QTY	PART NAME
1	1	flame outlet
2	1	secondary air inlet
3	1	hopper
4	1	conveyor trough
6	1	bearing
7	1	DC motor
8	1	shaft
9	1	primary air inlet
10	3	DC fan
11	1	residue over
12	1	residue box
13	4	stand
14	1	residue discharge outlet
15	1	box cover
16	3	bolt&nut
17	1	reactor chamber
18	1	ignition unit
19	1	ignition cover

Figure 2: Exploded view of the TLUD biomass gasifier

2.2 Central Composite Design

A Central Composite Design (CCD) was implemented with three independent variables: fuel loading height (X_1), fan speed (X_2), and fuel type (X_3), with three levels each for X_1 and X_2 respectively (numerical factors) and four levels for X_3 (categoric factor), using the Stat-Ease Design Expert v13 software. In this study, Response Surface Methodology (RSM) was applied using a Central Composite Design (CCD) to fit a second-order polynomial equation, following the methodologies outlined by (Khayer et al., 2019). The CCD of RSM was employed to derive an optimal solution among the three independent variables and four dependent variables, as per (Singh et al., 2008). The range of fuel loading spacing (X_1) was set to 10kg, 20kg, and 30kg; fan speed (X_2) 4000 rpm, 5000rpm, and 6600rpm; and fuel type (X_3) PKS, CCS, CCH, and WDS, as shown in Table 1. The boundary values of the independent variables were derived from a survey of existing biomass and a review of relevant literature. Based on these limiting values, two coded levels (-1, 0, and +1) were selected and used for the numerical factor variables. The independent variables were then coded for statistical analysis, following the approach detailed by (Khayer et al., 2019).

$$x_i = \frac{X_i - X_m}{\Delta X_D}; \quad i = 1,2,3 \tag{1}$$

Where X_i is the uncoded value of the i^{th} test variable, x_i is the coded value of the i^{th} variable, X_m is the uncoded value of the i^{th} test variable at the center point, and ΔX_D is the step change value.

To optimize the machine parameters, a second-order polynomial equation (Equation (2)) was formulated to model the gasifier thermal responses, based on the coded values of the independent variables (Okouzi et al., 2021).

$$Y = \beta_0 + \sum_{i=1}^{n} \beta_i X_i + \sum_{i=1}^{n} \beta_{ii} {X_i}^2 + \sum_{i}\sum_{j} \beta_{ij} X_i X_j + \varepsilon \tag{2}$$

The goodness of fit of the developed non-linear equations was assessed using the F-value for the lack of fit (LoF). The independent variables were set at two distinct levels according to the CCD experimental design, with a total of 36 experiments conducted, as detailed in Table 2.

Table 1: Experimental design for conducting the study

S/N	Variable	Unit	Level 1(-1)	Level 2(0)	Level 3(1)	Level 4
1	Fuel loading height	kg	10	20	30	
2	Fan speed	rpm	4000	5000	6000	
3	Fuel type		PKS	CCS	CCH	WDS

Table 2: Design of experiment using CCD

Std	Run	X_1	X_2	X_3	Y_1	Y_2	Y_3	Y_4
		FLD (kg)	FSP (rpm)	Fuel	FT (^{0}C)	GT (min)	TE (%)	CO (ppm)
13	1	15	6000	PKS	854	93	80.0219	1
2	2	15	6000	CCH	437	29	30.2266	243
7	3	20	4000	PKS	785	150	59.1495	2
11	4	10	6000	WDS	542	20	27.2801	2
5	5	15	4000	CCH	412	31	20.2273	303
17	6	10	5000	PKS	815	65	66.6147	1
19	7	20	4000	CCH	420	48	23.9779	250
28	8	15	6000	WDS	547	32	29.3813	2
10	9	10	4000	PKS	780	70	54.842	1
18	10	10	4000	CCH	395	22	20.5815	278
35	11	20	4000	CCS	650	105	47.8343	2
16	12	20	4000	WDS	515	58	24.9882	1
8	13	15	4000	PKS	782	116	60.7483	1
36	14	10	4000	CCS	645	50	45.1908	1
25	15	10	4000	WDS	510	27	23.0265	5
32	16	20	5000	CCH	460	42	28.8951	223
3	17	15	6000	CCS	689	62	60.0263	5
4	18	20	6000	PKS	875	130	86.0242	0
9	19	15	5000	CCH	435	25	21.6086	273
31	20	20	5000	WDS	530	54	29.975	1
21	21	10	5000	CCH	414	18	22.1361	260
15	22	20	5000	CCS	675	100	59.2307	3
29	23	15	4000	WDS	513	40	22.8835	5
27	24	20	6000	CCH	455	38	31.0096	195
12	25	20	5000	PKS	825	138	71.6114	2
26	26	15	4000	CCS	647	75	45.3371	6
33	27	10	5000	WDS	525	24	26.3796	2
14	28	10	6000	CCS	685	41	59.1825	6
1	29	15	5000	PKS	821	100	68.843	1
34	30	20	6000	WDS	555	50	34.9609	1
24	31	20	6000	CCS	695	95	69.6071	8
23	32	10	6000	PKS	835	61	76.9224	1
30	33	15	5000	WDS	527	42	30.8998	2
6	34	10	5000	CCS	660	45	52.0737	4
22	35	10	6000	CCH	425	15	22.7653	240
20	36	15	5000	CCS	669	70	54.7701	4

3. Result and Discussion

The study was conducted to evaluate and optimize the thermal performances of the TLUD biomass gasifier using varying fuel types in combination with different fuel loadings and fan speeds. The model's statistical significance was evaluated using regression analysis and ANOVA. The models summary, as shown on Table 3, selected two factorial interaction model (2FI model) with an R^2 values of 0.9991, 0.9966, and 0.9953; an adjusted R^2 of 0.9987, 0.9948, and 0.9928; and a predicted R^2 values 0.9975, 0.9920, and 0.9902 for FT, GT and TE respectively, demonstrating a good degree of accuracy ($p<0.001$), as detailed in Table 3. The lack of fit test for the FT, GT and TE responses yielded an F-values of 2.03, 0.91 and 0.45, which were statistically insignificant ($p>0.05$), confirming that the two factorial interaction model was appropriate for accurately predicting the FT, GT and TE responses (Table 4). Quadratic model predicted the flame CO emission response, Table 3, with an R^2, adjusted R^2, and predicted R^2 values of 0.9962, 0.9996, 0.9980 respectively, demonstrating a good degree of accuracy ($p<0.0001$). The lack of fit test for the CO emission response yielded an F-values of 11.94, Table 4, which was statistically insignificant ($p>0.05$), confirming that the quadratic model was appropriate for accurately predicting the flame's CO emission response of the gasifier. ANOVA analysis of FT response revealed that the linear terms of fuel loading (A), fan speed (B), fuel type (C) and the 2FI terms of fuel loading and fan speed (AB), fuel loading and fuel type (AC), and fan speed and fuel loading (BC) had a significant impact on the FT response. The model coefficient of determination (R^2) of 0.9991 indicates a strong correlation between the predicted and experimental values, suggesting that 99.91% of the variation in flame temperature of the gasifier are explained by the independent variables. The relationship between the flame temperature and the variables A, B, and C was effectively captured by the second-order polynomial equation, as presented in Equation 3 with an R^2 of 0.9991. In the same vein, the ANOVA analysis of GT response revealed that the linear terms of fuel loading (A), fan speed (B), fuel type (C) and the 2FI terms of fuel loading and fuel type (AC), and fan speed and fuel loading (BC) had a significant impact on the GT response. The model coefficient of determination (R^2) of 0.9966 indicates a strong correlation between the predicted and experimental values, suggesting that 99.66% of the variation in flame temperature of the gasifier are explained by the independent variables. The relationship between the flame temperature and the variables A, B, and C was effectively captured by the second-order polynomial equation, as presented in Equation 3 with an R^2 of 0.9962. Similarly, the ANOVA analysis of gasifier thermal efficiency (TE) response revealed that the linear terms of fuel loading (A), fan speed (B), fuel type (C) and the 2FI terms of fuel loading and fan speed (AB), and fan speed and fuel loading (BC) had a significant impact on the TE response. The model coefficient of determination (R^2) of 0.9953 indicates a strong correlation between the predicted and experimental values, suggesting that 99.91% of the variation in thermal efficiency of the gasifier are explained by the independent variables. The relationship between the thermal efficiency and the variables A, B, and C was effectively captured by the second-order polynomial equation, as presented in Equation 5 with an R^2 of 0.9950. Lastly, the ANOVA analysis of gasifier flame's CO emission response revealed that the linear terms of fuel loading (A), fan speed (B), fuel type (C), the 2FI terms of fuel loading and fuel type (AC), fan speed and fuel loading (BC), and the quadratic terms of fuel loading (A^2), and fuel loading and fuel type (A^2C), had a significant impact on the CO response. The model coefficient of determination (R^2) of 0.9962 indicates a strong correlation between the predicted and experimental values, suggesting that 99.62% of the variation in CO emission of the gasifier are explained by the independent variables. The relationship between the flame's CO emission and the variables A, B, and C was effectively captured by the second-order polynomial equation, as presented in Equation 6 with an R^2 of 0.9996

Table 3: Model summary statistics

Response	Source	Std. Dev.	R²	Adjusted R²	Predicted R²	PRESS	
FT (^{0}C)	Linear	10.19	0.9961	0.9954	0.9943	4584.12	
	2FI	5.54	0.9991	0.9987	0.9975	2003.26	Suggested
	Quadratic	5.56	0.9992	0.9986	0.9973	2180.30	
	Cubic	4.48	0.9997	0.9991	0.9952	3830.92	Aliased
GT (min)	Linear	9.39	0.9422	0.9326	0.9142	3921.59	
	2FI	2.62	0.9966	0.9948	0.9920	366.85	Suggested
	Quadratic	2.56	0.9970	0.9950	0.9917	377.77	
	Cubic	2.62	0.9985	0.9947	0.9765	1075.56	Aliased
TE (%)	Linear	3.61	0.9727	0.9681	0.9590	585.40	
	2FI	1.71	0.9953	0.9928	0.9901	141.75	Suggested
	Quadratic	1.73	0.9956	0.9926	0.9887	160.77	
	Cubic	2.06	0.9970	0.9896	0.9548	645.55	Aliased
CO (ppm)	Linear	14.92	0.9844	0.9818	0.9772	9731.03	
	2FI	9.78	0.9949	0.9922	0.9879	5158.83	
	Quadratic	8.80	0.9962	0.9937	0.9893	4570.85	Suggested
	Cubic	2.12	0.9999	0.9996	0.9980	864.71	Aliased

Table 4: ANOVA for response surface quadratic model

Response	Source	Sum of Squares	df	Mean Square	F-value	p-value	
FT (^{0}C)	Model	7.968E+05	12	66400.96	2161.01	< 0.0001	significant
	A-FLD	1820.04	1	1820.04	59.23	< 0.0001	
	B-FSP	12150.00	1	12150.00	395.42	< 0.0001	
	C-FUEL	7.804E+05	3	2.601E+05	8466.40	< 0.0001	
	AB	175.56	1	175.56	5.71	0.0254	
	AC	622.46	3	207.49	6.75	0.0020	
	BC	1609.00	3	536.33	17.45	< 0.0001	
	Residual	706.72	23	30.73			
	Lack of Fit				2.03	0.4120	Insignificant
	Cor Total	7.975E+05	35				
GT (min)	Model	45559.19	11	4141.74	572.74	< 0.0001	significant
	A-FLD	12604.17	1	12604.17	1742.96	< 0.0001	
	B-FSP	661.50	1	661.50	91.48	< 0.0001	
	C-FUEL	29824.53	3	9941.51	1374.75	< 0.0001	
	AC	2360.83	3	786.94	108.82	< 0.0001	
	BC	108.17	3	36.06	4.99	0.0079	
	Residual	173.56	24	7.23			
	Lack of Fit				0.9091	0.5638	Insignificant
	Cor Total	45732.75	35				
TE (%)	Model	14199.95	9	1577.77	570.84	< 0.0001	significant
	A-FLD	205.74	1	205.74	74.44	< 0.0001	
	B-FSP	1048.36	1	1048.36	379.30	< 0.0001	

	C-FUEL	12627.50	3	4209.17	1522.89	< 0.0001	
	AB	33.47	1	33.47	12.11	0.0018	
	BC	284.88	3	94.96	34.36	< 0.0001	
	Residual	71.86	26	2.76			
	Lack of Fit				0.4494	0.8972	Insignificant
	Cor Total	14271.81	35				
CO (ppm)	Model	4.268E+05	15	28453.59	3545.62	< 0.0001	significant
	A-FLD	532.04	1	532.04	66.30	< 0.0001	
	B-FSP	950.04	1	950.04	118.39	< 0.0001	
	C-FUEL	4.188E+05	3	1.396E+05	17395.78	< 0.0001	
	AC	1491.46	3	497.15	61.95	< 0.0001	
	BC	2974.79	3	991.60	123.56	< 0.0001	
	A²	572.35	1	572.35	71.32	< 0.0001	
	A²C	1479.71	3	493.24	61.46	< 0.0001	
	Residual	160.50	20	8.03			
	Lack of Fit				11.94	0.6272	Insignificant
	Cor Total	4.270E+05	35				
	Cor Total	8.468E+05	15				

$$FT = 611.22 + 8.71A + 22.50B + 207.89C_1 + 57.11C_2 - 183.11C_3 + 3.31AB + 0.4583AC_1 - 3.71AC_2 + 8.13AC_3 + 13.67BC_1 - 1.33BC_2 - 7.50BC_3 \quad (3)$$

$$GT = 60.58 + 22.92A - 5.25B + 41.97C_1 + 10.86C_2 - 30.81C_3 + 14.08AC_1 + 4.42AC_2 - 10.75AC_3 - 3.42BC_1 - 0.08BC_2 + 2.08BC_3 \quad (4)$$

$$TE = 44.15 + 2.93A + 6.61B + 25.27C_1 + 10.66C_2 - 19.54C_3 + 1.45AB + 4.76BC_1 + 1.80BC_2 - 3.41BC_3 \quad (5)$$

$$CO = 70.5 - 4.71A - 6.29B - 69.5C_1 - 65.5C_2 + 202.5C_3 + 4.88AC_1 + 5.04AC_2 - 13.63AC_3 + 5.96BC_1 + 7.96BC_2 - 19.21BC_3 - 8.46A^2 + 8.63A^2C_1 + 7.46A^2C_2 - 23.54A^2C_3 \quad (6)$$

$Where\ C_1 = PKS, C_2 = CCS, C_3 = CCH, and\ C_4 = WDS$

3.1 Variation of Thermal Responses with Independent Variables

Considering the relationship presented above between the thermal responses and independent variables, it can clearly be seen that all thermal responses were directly related to every independent variable. Figure 3 to 6 presented the various relationship between the input variables and the thermal responses of the gasifier. It can be deduced that these relationships are linear and depict the interactions between the fuel loading and the fan speed as it affects each thermal response considering the fuel type. Figure 3 to 5 explained that the average flame temperature, and the gasifier's thermal efficiency increases as the fan speed and fuel loading increases across all fuel types with PKS having the highest values followed by CCS, WDS, and CCH having the least values. Likewise, at an average, the gasification time of the gasifier increases as the fuel loading increases with decrease in fan speed, Figure 4, with PKS having the highest gasification time and CCH having the lowest. Figure 6 explained that averagely, the change in fan speed and fuel loading do not really change the magnitude of the CO emitted by the gasifier, considering each fuel type. However, the CO emitted by the gasifier's flame when operated with PKS, CCS, and WDS were below the international standard of CO emission threshold considered safe for human and its environment (Table 5). However, the CO emitted by the gasifier's flame, when CCH was combusted as fuel, was very much higher above the permissible threshold (Table 5). This disqualified CCH as viable fuel to be combusted in the gasifier, but PKS resulted the best and cleanest fuel when gasified, followed by CCS, and WDS as a viable alternative.

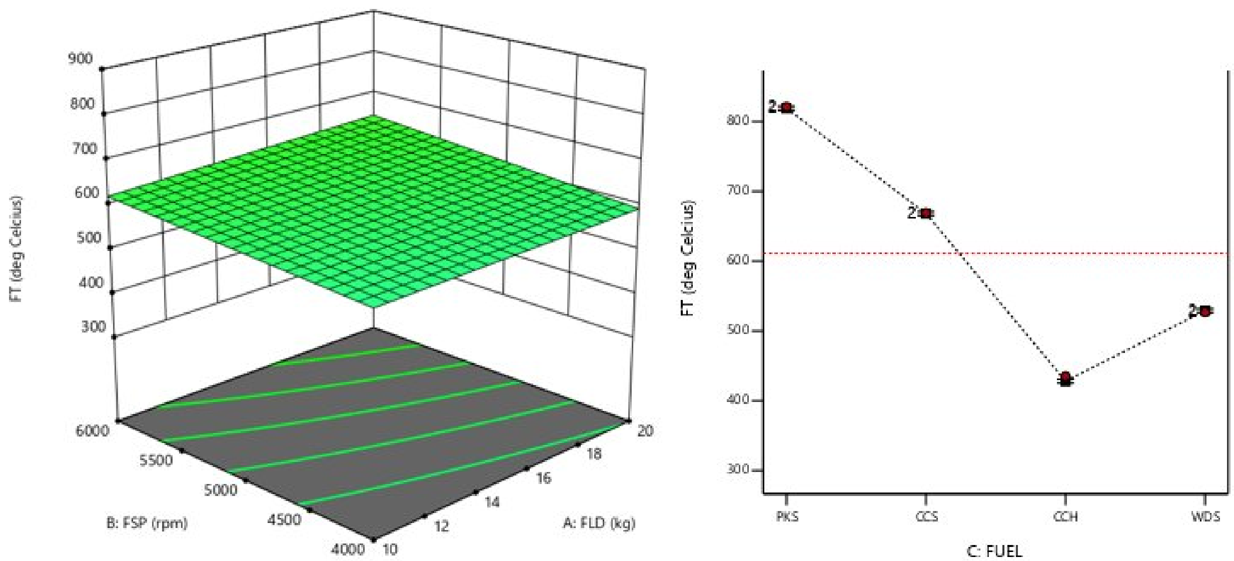


Figure 3: Effect of fan speed and fuel loading on the average gasifier's flame temperature at fuel input

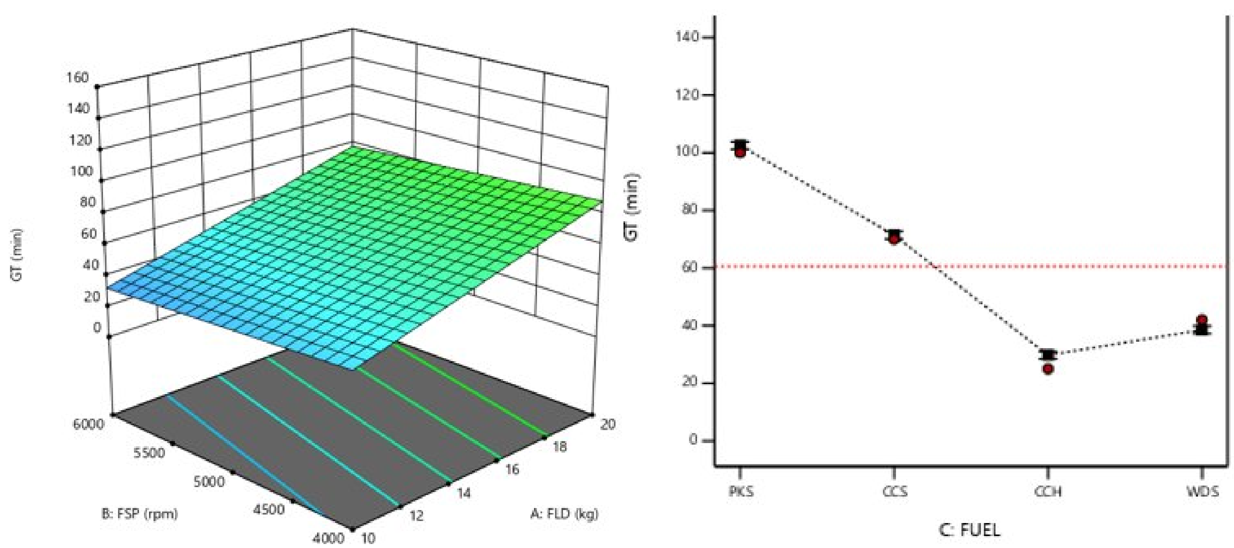


Figure 4: Effect of fan speed and fuel loading on the average gasifier's gasification time at fuel input

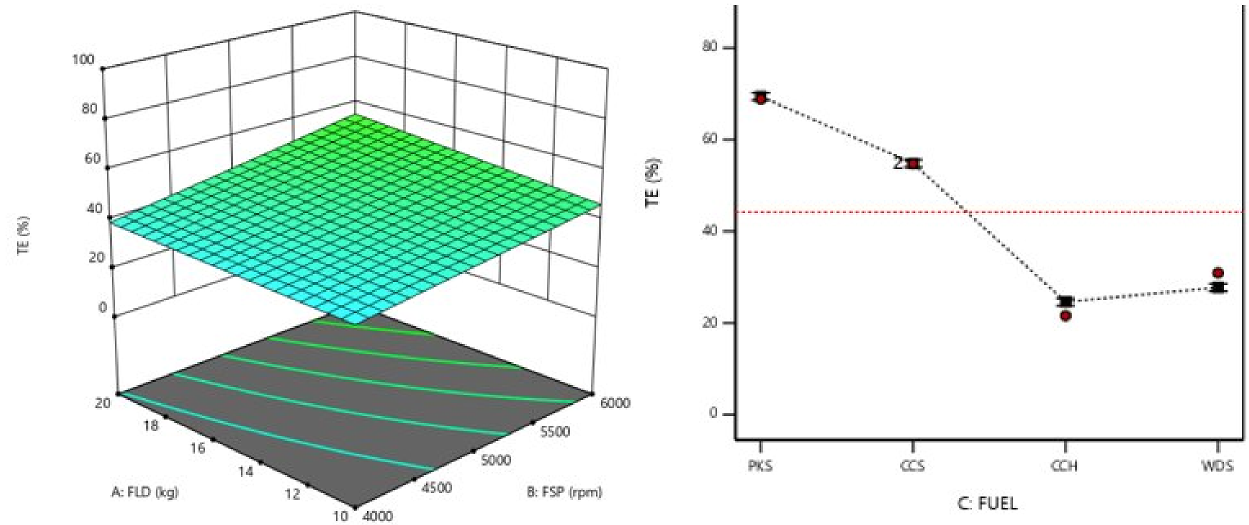


Figure 5: Effect of fan speed and fuel loading on the average gasifier's thermal efficiency at fuel input

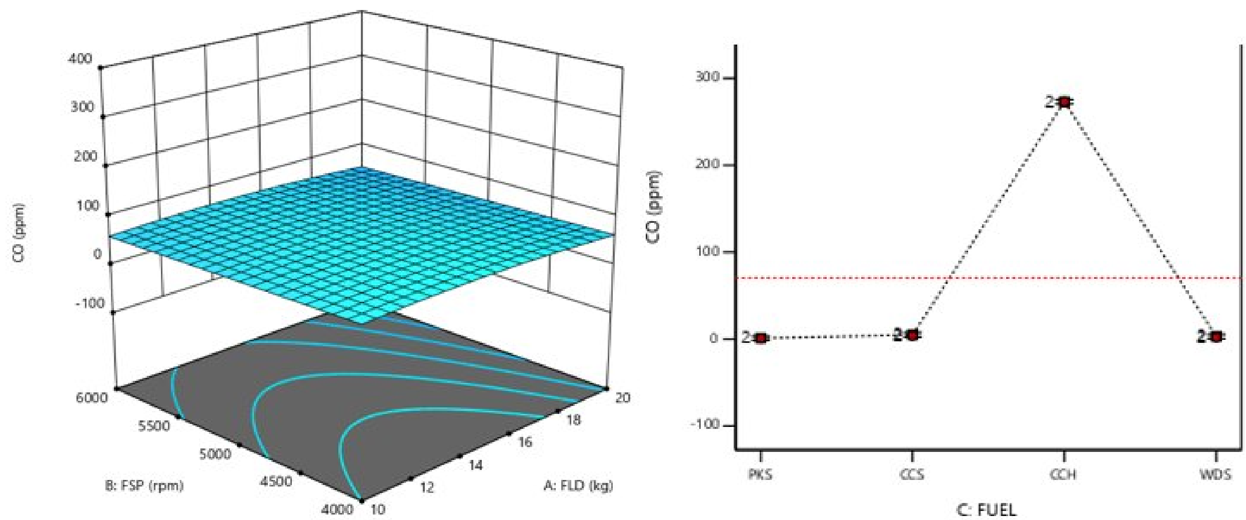


Figure 6: Effect of fan speed and fuel loading on the average gasifier's flame CO emission at fuel input

Table 5: 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: (WHO, 2021; USEPA, 2021)

3.2 Desirability Function Approach for Optimal Response

The desirability function approach is a method used to simultaneously determine the optimal settings of input variables that achieve the best performance levels for one or more responses (Khayer et al., 2019). The general procedure involves converting each response (y_i) into an individual desirability function (d_i) within the range $(-1 \leq d_i < 1)$. Based on the Design Expert analysis for optimization, the tool generated 25 potential solutions for optimizing the gasifier thermal responses, each with an associated desirability score. Among these results, the best optimal outputs, having desirability value of 0.924 was selected, as illustrated in Figure 7.

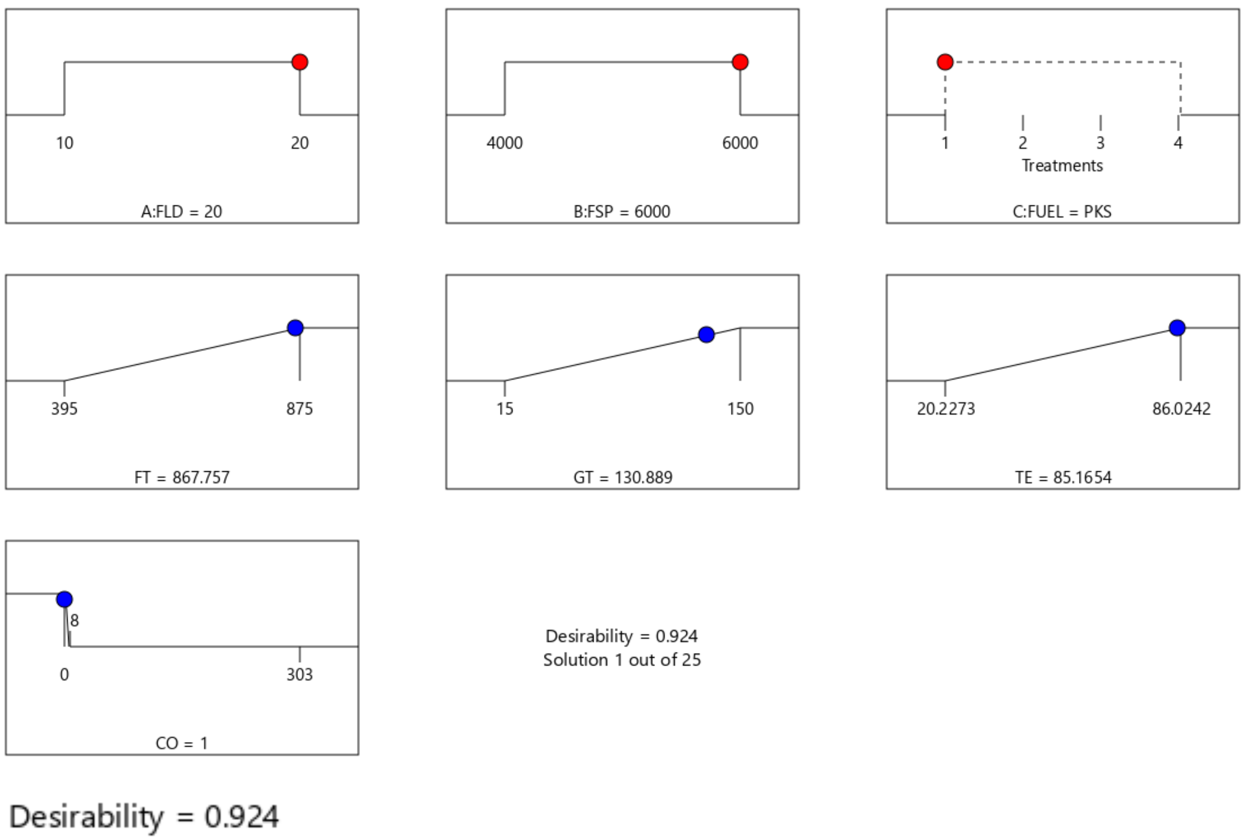
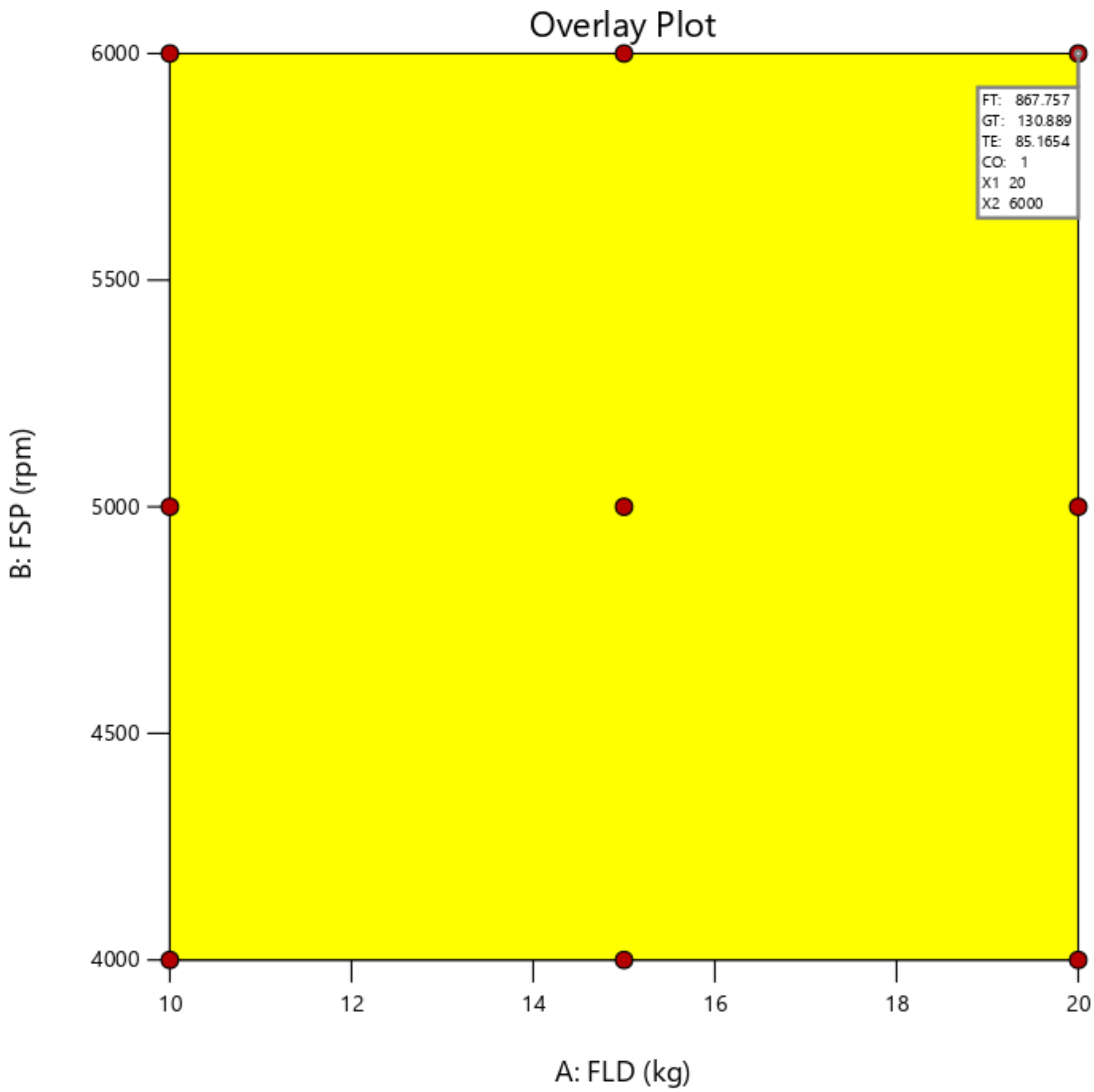


Figure 7: Desirability ramp for optimization, solution 1

3.3 Optimization of design parameter

Considering the input performance parameters (factors), the optimized conditions, Figure 7, are fuel loading of 20kg, fan speed of 6000 rpm, and fuel type of PKS to achieve maximum FT of 867.76^{0}C, GT of 130.89min, TE of 85.17% at lowest permissible CO emission of 1. These values gave very clean gas emission, with conformity to international standard, making the gasifier very safe for use at the optimal conditions. The optimal thermal responses achieved presented the gasifier to deliver optimum clean heat energy needed for uniform and sustainable heat supply to the cabinet dryer for drying plantain slices. The optimal performances of the gasifier were found to be better but in line with the result reported by Barpatragohain et al., 2021; Kole et al., 2022; and Rathore et al., 2022 who recorded thermal efficiencies & CO emissions of 33% & 20ppm, 29% & 262ppm, and 34.45% & 8.8ppm respectively for designed biomass gas stove, which adopted the same working principle of top-lit-up-draft biomass gasification.



Figur 8: Overlay plot for optimizing thermal responses for PKS fuel.

4. Conclusion

This study presented the use of response surface methodology (RSM) to optimize the most critical design parameters of a TLUD biomass gasifier. The research examined the effects of fuel loadings, fan speeds, and fuel types on the thermal responses of the TLUD biomass gasifier. The findings revealed that the optimal values for these significant factors were fuel loading of 20kg, fan speed of 6000 rpm, and fuel type of PKS to achieve maximum thermal efficiency (TE) of 85.17%, flame temperature (FT) of 867.76^{0}C, gas temperature (GT) of 130.89min, and lowest permissible CO emission of 1ppm. The study developed two factorial interaction (2FI) models for FT, GT, and TE with R^2 values of 0.9991, 0.9966, and 0.9953, respectively, and a quadratic model for CO emissions with an R^2 of 0.9962. The ANOVA analysis described that the linear terms of fuel loading, fan speed, and fuel type, in conjunction with their interactions, significantly impacted these responses. The models presented high accuracy in predicting the biomass gasifier performance, with insignificant lack of fit tests, confirming the models' robustness for optimizing the gasifier thermal responses and emissions under varying operational conditions. The obtained results presented the TLUD biomass gasifier with optimized thermal responses suitable as sustainable heat source for plantain slice drying.

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