Developing Local Technical Capacity for Gasification of Biomass for Bioenergy Access in Nigeria

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Abstract- Gasification has proven to be an efficient technology to obtain clean bioenergy from biomass. A region like Sub-Sahara Africa which is still battling with energy poverty could benefit from the deployment of such technology. However, lack of local expertise has hampered successful establishment of such technology in the region despite having vast biomass resources. This work, therefore, intends to address this gap by developing and operating a pilot biomass gasification system to convert wood residues in Nigeria into synthesis gas (syngas) from which bioenergy can be generated. A preliminary study was carried out to determine wood wastes availability in the study area. Thereafter, a downdraft gasification system was developed and tested for syngas production using wood wastes as feedstock. Performance analyses of the gasifier system revealed a feedstock consumption rate was about 3.52kg/h, yielding syngas that burns with a stable blue flame for about 43 minutes. Feedstock availability assessment revealed a wood waste generation rate of about 3.778,02 tonnes per year in the study area, indicating enough feedstock availability. The average syngas yield was 2.955m^3 per kg of wood waste consumed, while the average syngas LHV was 5.24MJ/m^3. Several challenges, such as clogging of syngas filter and blocking of pipes due to tar accumulation, encountered were successfully solved, enabling the garnering of significant technical capacity in biomass gasification. This research will provide theoretical consideration and technical guidance to researchers and industries for the implementation of such technology in developing countries like Nigeria.

Keywords Bio-energy, Biomass, Gasification, Syngas, Wood waste.

1. Introduction

Gasification is one of the most efficient technologies to obtain clean energy from biomass for heat or power purposes [1]. Small-scale gasification provides a possibility for biomass to substitute fossil fuels for running internal combustion engines (ICE) for electricity generation [2]. Generally, gasification therefore, presents a fitting alternative for businesses, projects, or governments aspiring to transit to renewables for electricity or heat production [1]. Gasification is very well apt for locations with huge biomass availability, where residues from forest, agricultural, and municipal activities can be utilized as feedstock [1]. According to Basu [3], small-scale biomass gasification for bioenergy production comprises different stages, which include feedstock feeding into the reactor, reactor operation at high temperatures to produce syngas, syngas cleaning and cooling, and ICE operation as shown in Fig. 1. Nigeria has a different variety of biomass that could be harnessed to meet her rapidly increasing demand for energy. Effective harnessing of biomass for bioenergy generation can play a crucial role in improving energy access, which is vital to unlocking further economic development and improving the standard of living. In recognition of this, the Nigeria government in its Renewable Energy Master Plan (REMP) intends to increase the share of renewable electricity in the country, from 13% of electricity generation - mainly met by large hydro - in 2015, to 23% in 2025 and 36% by 2030. REMP considers bioenergy technologies as one of the major drivers to achieve this quest, with a planned installed capacity of 400 MW by 2025 [4]. Considering that biomass availability is closely linked to agricultural activities, appropriately designed bioenergy projects have the potential to boost agricultural productivity, localise energy supply, reduce greenhouse gas (GHG) emissions, reduce deforestation, generate supply chain economic activities, provide social benefits and empower poor communities. Biomass gasification is one of such bioenergy projects.

The Department for International Development (DFID), United Kingdom carried out a study on Bioenergy for Sustainable Energy Access in Africa (BSEAA-1) in 2017 [1] and another on Bioenergy for Sustainable Local Energy Services and Energy Access in Africa (BSEAA-2) in 2021 [2]. The studies investigated the opportunities and challenges for the roll-out of bioenergy technology in Sub-Sahara Africa (SSA) countries, including Nigeria. The studies revealed that although, biomass gasification technology has promising prospects for decentralized heat and electricity generation in SSA, successful implementation of such projects have been hindered by several challenges [1,2]. Chief of these challenges is lack of local technical capacity to operate and maintain gasifier systems. According to the studies, all the gasifier systems in SSA were imported technologies mainly from India and few from China and USA, with majority of the systems based on the downdraft, fixed-bed reactor technology. The imported gasifier design generally comprises a reactor, single or multiple cyclone separators, wet scrubbers (mainly water-based), a suction blower, and gas filtration system (Fig. 2). The gasifier systems convert biomass into synthesis gas (syngas), which is purified and utilized as fuel in internal combustion engines to produce electricity.

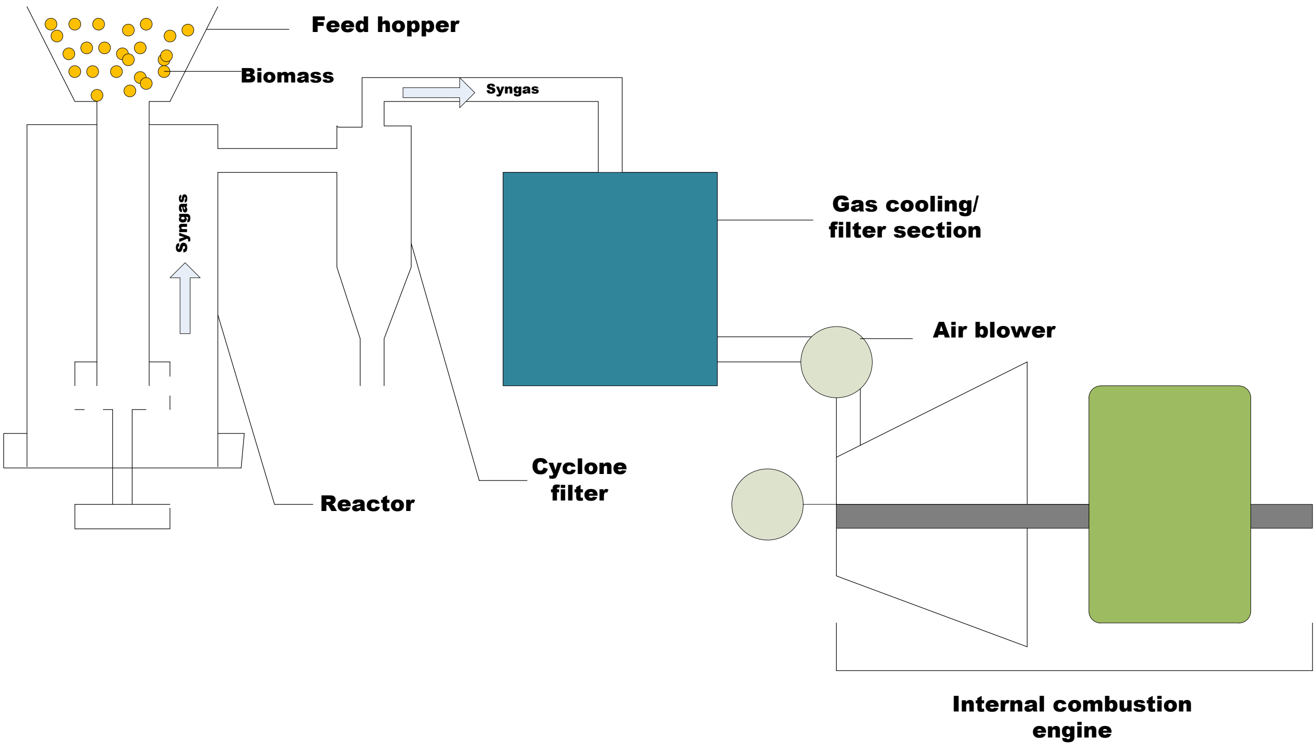

Fig. 1: Small-scale biomass gasification power plant (adapted from [3])

Generally, in the Indian design, the majority of entrained particulates in the produced syngas are removed in the cyclone separator (s). The syngas then goes through one or more wet scrubbers to cool it and remove tar and particulates in it [2]. Thereafter, the syngas is processed through a fixed-bed filter to remove final traces of tar and particulates using sawdust, charcoal, rice husk, oil, fibrous organic or metallic materials, before entering ICE for electricity generation. According to the DFID studies, these technologies were quite complex for local users in SSA to operate and maintain, hence, hindering their successful adoption [1,2]. The studies attributed this inability to mainly dearth of technical and institutional support within the region for the development, establishment and management of biomass gasification systems, arising from the absence of commercial manufacturers of gasifiers in SSA. Consequently, restricting access to spares, technical guidance and refresher trainings. In addition, foreign manufacturers are hardly ever invested in the projects beyond installation and commissioning, and they have no local representation for easy access. Also, the technology suppliers are quite unwilling to share information on their technologies' weaknesses and failures.

In view of these difficulties, which have been preventing the successful implementation of gasification technology in SSA, it is imperative to build up suitable local technical and engineering capacity for the development, operation and maintenance of biomass gasification systems in the region. Hence, the motivation for this present study, which aims to contribute to such capacity development by designing, fabricating, and testing a pilot downdraft gasifier system equipped with syngas cleaning facilities. The main objectives of the study include to (i) design and fabricate a pilot downdraft gasifier equipped with syngas cleaning facilities, (ii) carry out tests on the developed gasifier system using wood wastes as feedstock and evaluate its performance, (iii) evaluate the quality and properties of the produced syngas. The methodology deployed is presented in Section 2. The obtained outcomes are discussed in Section 3. Finally, conclusions from the study are drawn in Section 4.

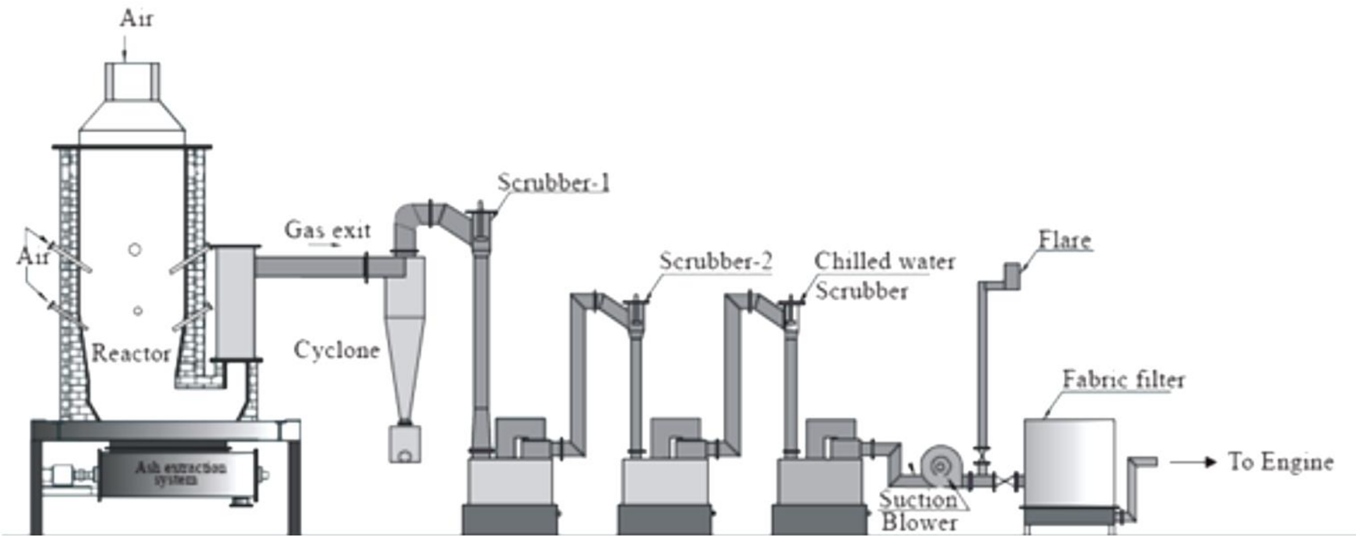

Fig. 2: Typical configuration of an Indian biomass gasifier [1,2]

2. Methodology

Wood waste (chips) was the feedstock used in this work. The mean sizes of the wood chips ranged between 2 – 4.5cm. The study was conducted at the Department of Mechanical Engineering, University of Benin, Benin City, in Ovia North-East Local Government Area (LGA) of Edo state, Nigeria.

In the first phase of the work, wood waste availability assessment in the study area was conducted. The second phase involved design and fabrication of the downdraft gasifier system. The third phase involved conducting experimental runs on the fabricated gasifier system to ascertain its performance for quality synthesis gas production, and evaluation of the quality and yield of the produced syngas. The composition of the produced syngas was evaluated with a gas chromatograph (Agilent 7890A) equipped with a mass spectrometer (Agilent 5970).

2.1.1. Wood Wastes Availability and Combustion Properties Assessment

According to the DFID studies, one of the criteria for the successful establishment and operation of a biomass gasification system is regular availability of biomass feedstock. Hence, an assessment of wood waste availability in Ovia North-East Local Government Area (LGA) was carried out, to ascertain if there will be enough availability of wood waste in the LGA to run the gasifier system. The wood waste availability assessment was done using 3 sawmills and 5 plank markets in the LGA. The sawmills were labelled SW1 – SW3, while the plank markets were named PM1 – PM5. The wood wastes produced daily in each sawmill and plank market were collected and weighed on a weekly basis (every Friday) using a weighing scale. The assessment was conducted over a 12-month duration, from September 2020 to August 2021. Ultimate analysis of the wood waste was conducted with a LECO CHNS 932 analyser following the ASTM D3176-15 [5] method, while the calorific value was evaluated with a LECO AC-350 bomb calorimeter following the ASTM D5865-13 [6] method.

2.2. Design of Gasifier System

A potential thermal capacity of 10kW was chosen as the output of the gasifier system for the purpose of design. This will satisfy the requirements of mechanical power of about 7kW. Fig. 3 presents the block diagram of the gasifier system.

2.3. Design of The Gasifier Reactor

The DFID studies revealed that the gasifier systems in SSA are mostly small-scale systems which operates based on the downdraft, fixed-bed reactor technology. These reactors employed either Imbert (closed-top and V-shaped throat) or open core (open-top) gasification technologies. It is difficult to add feedstock and ascertain when the feedstock is exhausted in close-top technology and tar cracking efficiency is poor in open-top technology. Hence, this study developed a modified combination of both technologies to take advantage of their merits, chiefly the ease of feedstock feeding into the reactor through the open top and the high tar decomposition efficiency at the throat in close-top technology. In addition to the open top, provision was made for air inlet through the side of the gasifier 30mm from the top. This air flows through a vertical pipe located at the vertical axis of the gasifier straight to just above the grate. This is to ensure regular and constant supply of air as well as to maintain a high temperature at the oxidation zone. A grate shaker was provided in case feedstocks are bridging and channelling at the throat.

2.3.1. Selecting Gasifier Reactor Data

The gasifier is earmarked to be fired with wood residues. Bulk density of wood was taken as 225kg/m^3 in accordance with [7], while the calorific value of the wood waste was obtained as 19.85MJ/kg. A low syngas lower heating value (LHV) of 4MJ/nm^3 was considered for this study. Gasifier efficiencies ranging from 60 to 80% have been presented in literature [8,9], hence, 60% was considered as gasifier efficiency for the study. Specific gasification rate is determined by dividing the biomass flow rate by the reactor area. The recommended specific gasification rate (SGR) ranges between 110 - 210 kg/m^2/h [10], however, 110kg/m^2/h was used in this work.

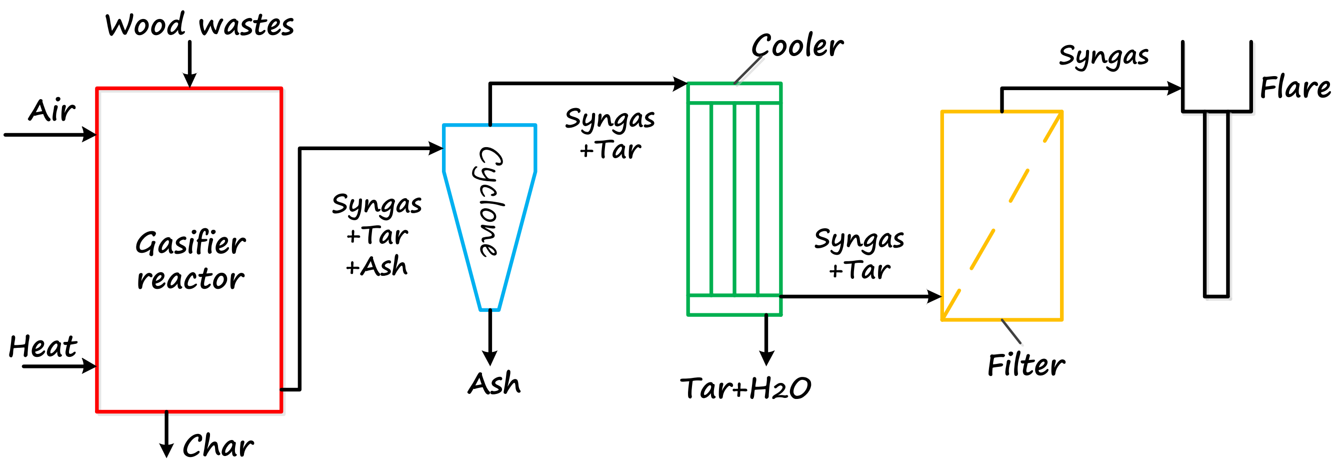

Fig. 3. Proposed biomass gasification system for syngas production

Sivakumar *et al.* [11] reported that throat angles of 45 degrees increase the aggregate conversion efficiency while throat angles of 90 degrees decrease the aggregate conversion efficiency due to decrease in temperature at larger throat angles resulting from the effect of divergence and rates of reaction. After comparing the design characteristics of several gasifier reactors, Venselaar, [10] proposed throat angles between 45 to 60 degrees. A throat angle of 60 degrees was chosen for the design.

For a thermal power output (P) of 10kW, syngas generation rate (SG) was obtained using equation (1).

$$SG = \frac{P}{LHV} \tag{1}$$

While the fuel consumption rate (FCR) was determined using equation (2)

$$FCR = \frac{P}{CV \times \eta} \tag{2}$$

Where CV is calorific value.

A gasifier throat diameter is obtained from the value of Specific Gasification Rate (SGR). Hence,

$$SGR = \frac{FCR}{Ath} \tag{3}$$

Where, A_{th} = Area of throat

and

$$Ath = \frac{\pi dth^2}{4} \tag{4}$$

Where, d_{th} is the throat diameter

For stable flow of biomass inside the reactor, the ratio of throat height to throat diameter is considered as 1.50 [10].

∴ Height of throat is given by

$$h_{th} = 1.5 \times d_{th} \tag{5}$$

According to Venselaar [10],

$$\frac{hr}{dth} = 2 \tag{6}$$

Where h_r is the height of the reduction zone.

The height of the reactor's hopper (H_h) was determined using equation (7).

$$H_h = \frac{SGR \times t}{\text{Density of biomass}} \tag{7}$$

Where t = operating time

2.3.2. *Design of Cyclone Separator*

To design the cyclone separator, syngas volumetric flowrate was used in combinations with certain assumptions. Diameter of cyclone barrel (D) was taken to be 17 cm (to provide ample room for vortex action). Dimensions of other parts of the cyclone separator was obtained using Simplex's geometrical ratios [12], which states that syngas exit pipe diameter is De = Di = 0.25D = 0.0425 m, length of vortex finder is Lv = 3De = 0.1275 m, length of cyclone barrel is Lc = 4D = 0.68 m, and ash exit pipe diameter is Dd = 0.2De = 0.0085 m. The shape of the designed cyclone separator is shown in Fig. 4.

2.3.3. *Design of Syngas Cooler*

An indirect syngas cooling system was employed in the study. The indirect syngas cooler works on the open-air free convection cooling principle, whereby the gas flows inside of the pipe, and then heat is exchanged between the syngas and ambient air due to temperature difference. The indirect cooling system was designed to cool the syngas from 800°C to 250°C putting into consideration the syngas flow rate from the developed pilot downdraft reactor. Cylindrical pipes made from copper, aluminium, and galvanized steel were considered for selection. Pipe diameter of 2.54 cm (1 inch) and thickness of 1.27 mm was used in the design of the syngas cooler. Properties of the pipe materials and ambient air temperature (T_∞) (taken as 32°C) were extracted from [13]. Equations (8) to (15) were used to determine the required length of pipe. All equations were adapted from [13].

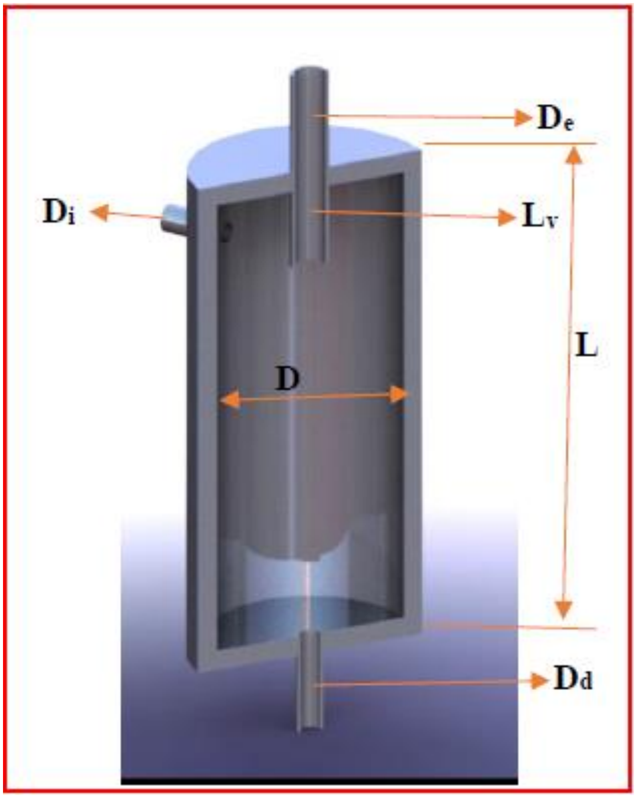

Fig. 4 Cross sectional view of cyclone separator

Heat transfer rate was obtained using

$$\dot{q} = \dot{m}g * Cpg(T1 - T2) \quad (8)$$

Where, $\dot{q}$ is the heat transfer rate, $\dot{m}_g$ is the syngas mass flow rate, C_{pg} is syngas specific heat capacity of syngas and T is syngas temperature.

The film temperature (T_f) was obtained using

$$Tf = \frac{T\infty - Ts}{2} \quad (9)$$

Where T_∞ is the free stream (air) temperature and T_s is the surface temperature of the pipe (taken to be constant along the pipe length and equal to syngas approach temperature)

The expansion coefficient (β) was computed using

$$\beta = \frac{1}{Tf} \quad (10)$$

The calculation of Rayleigh Number (R_{aD}) was done using

$$RaD = \frac{g\beta(Ts - T\infty)D^3}{\nu\alpha} \quad (11)$$

The Nusselt Number ($\bar{N}uD$) was obtained as

$$\bar{N}uD = C(RaD)^n \quad (12)$$

For $R_{aD} = 5.011\times10^5$, C = 0.480 and n = 0.250 [13].

Convection heat transfer coefficient ($\bar{h}$) was determined using

$$\bar{h} = \frac{\bar{N}uD \times Kair}{D} \quad (13)$$

The calculation of the logarithmic mean temperature difference (ΔT_{lm})

$$\Delta Tlm = \frac{(Tho - T\infty) - (Thi - T\infty)}{ln\frac{(Tho - T\infty)}{(Thi - T\infty)}} \quad (14)$$

Where, T_{ho} and T_{hi} are the syngas temperatures at outlet and inlet of the cooling pipe respectively.

Required pipe length (L) was computed using

$$L = \frac{\dot{q}}{\bar{h} \cdot \pi \cdot D \cdot \Delta Tlm} \quad (15)$$

2.3.4. Dry Biomass-Based Filter

Dry biomass-based filters are deemed as an economical and environmentally-friendly option for removal of tars from syngas [14,15]. This type of filter (biomass in a container) was used in the Indian technologies available in SSA [2]. Hence, a similar filter was adopted in the study.

2.4. Fabrication of The Wood Wastes Gasifier System

Fabrication of various components of the gasification system (gasifier reactor and syngas cleaning unit) took cognizance of the design considerations. Accordingly, proper functionality of all the component parts was taken into consideration in order to ensure that they operate optimally. After the fabrication, it was tested to evaluate its performance.

2.5. Operation and Testing of The Gasification System

The constructed gasification system was operated and tested using wood wastes (chips) as feedstock and atmospheric air as gasifying medium. Before starting the gasifier system, all its parts (flanges, joints and fittings) were properly tightened and checked for leakages and it was positioned in an open space. The air suction blower remained switched off and the lid of the gasifier reactor was opened. 200g of charcoal (initially purchased, but subsequent runs used biochar generated from previous runs) was placed into the combustion zone above the grate and some of them were wetted with combustible liquids. The charcoal was ignited using an ignition source. The blower was thereafter turned on to supply sufficient air to sustain combustion which generally takes about 3 to 4 minutes. The reactor was then loaded with wood waste from its open top. The time after loading wood waste was considered the start time for gasification runs. Syngas ignition at the burner signified the production of syngas. Wood waste consumption rate was observed. To put off the gasifier system, the suction blower was turned off and all air inlet ports were closed.

2.5.1. Performance Evaluation of The Gasifier System

Performance of the wood waste-fired downdraft gasification system was assessed in terms of biomass consumption rate, syngas yield, composition and LHV, and gasification efficiency (CGE). The biomass consumption rate, i.e., the quantity of biomass consumed per hour, was determined using:

$$\dot{m}b = \frac{mb}{t} \quad (16)$$

Where $\dot{m}_b$ is biomass consumption rate, m_b is mass of biomass fed in and t is the time taken to consume the fed biomass.

The CGE of the system was ascertained using equation (17) [3].

$$\text{CGE} = \frac{\dot{m}g \times \text{LHV}g}{\dot{m}b \times \text{CVww}} \times 100\% \quad (17)$$

Where CVww is calorific value of the wood waste, LHV_g syngas lower heating value and $\dot{m}_g$ is mass of syngas in kg.

2.5.2. Syngas Characterization

Produced syngas was collected after the filter with sample bags and weighed. The syngas composition was determined with a gas chromatograph (Agilent 7890A) equipped with a mass spectrometer (Agilent 5970). The syngas LHV (MJ/m^3) was calculated using equation (18) [3].

$$\text{LHVg} = (X\text{CO} \times \text{LHVCO}) + (XH2 \times \text{LHV}H2) + (X\text{CO2} \times \text{LHVCO2}) \quad (18)$$

Where, X individual gas molar fraction and LHV_g syngas lower heating value

3. Results and Discussions

3.1. Wood Waste Availability and Combustion Properties Assessment

Results of the field survey on wood waste availability revealed that in Ovia North-East Local Government Area about 3,778,017.336kg of wood waste is generated per annum. From the design calculations, wood waste consumption rate is about 3.023kg/h. It is expected that the gasifier system will be in operation for about 5480 hours per year, this would require a total of 17,654.32kg of wood wastes, which implies that there will be enough wood wastes to run the gasifier system for years without interruption. This satisfies the feedstock availability requirement for successful implementation of a small-scale biomass gasification project as stated by [1,2]. Obtained combustion properties of mixed wood wastes used for the study are given in Table 1.

3.2. Gasifier System Design and Performance

3.2.1. Gasifier Reactor Dimensions

After several technical considerations, a thermal capacity of 10kW was chosen as the designed capacity for the downdraft gasifier system. This was used as the basis of the design. This capacity will require $9.0m^3$ of syngas per hour, and from design calculations, the quantity of wood wastes to produce $9.0m^3$ of syngas is 3.023kg/h. Using these data, the dimensions of the gasifier reactor were obtained as follows; the height of the reactor's reduction zone is 0.56m, the height of the reactor is 1.3304m, the throat (oxidation zone) height is 0.2805m, and throat diameter is 0.187m.

3.2.2. Syngas Cooler Design

An indirect syngas cooling system was employed in the study. This was to avoid the problem associated with the direct syngas cooling system such as difficulty in disposing tar-contaminated water and deployment in locations where there are water shortages. These challenges led to decommissioning of several biomass gasification facilities across countries in Sub-Sahara Africa [1,2]. For the design of the syngas cooling system, three pipes of different materials (aluminium, copper and galvanized) were considered. The merits and demerits of the pipe materials were compared. Galvanized pipes were found to be cheaper than aluminium and copper pipes. Although, all three pipe materials are conductors of heat, copper pipe has a higher thermal conductivity value than the other pipes, making it the best heat conductor of the three pipes.

Table 1: Combustion properties of mixed wood wastes (dry basis)

Ultimate analysis (%wt on dry basis)	
Constituents	**Percentage by weight**
Carbon	57.54
Hydrogen	5.21
Oxygen	37.10
Nitrogen	0.11
Sulphur	0.04
Other properties	
Moisture Content	7.52%
Calorific value	19.85MJ/kg

However, galvanized pipes have the additional advantages of being safer to handle and have higher thermal resistance than aluminium and copper pipes. These were crucial specifications for this design, hence, for the study, galvanized pipe was selected for use. From design calculations, it was observed that the length of pipe required to cool the syngas from 800°C to 250°C was 3.475m (~11.4ft). To give allowance for material loss during fabrication, a 12ft length of galvanized pipe was acquired and configured as shown in Fig 5. 2-inch galvanized pipe was used to hold the 1-inch pipe cuts in place vertically, while 2.5inch pipe was used at the inlet to the syngas cooler.

Fig. 5: Fabricated syngas cooler

3.2.3. Dry Biomass-Based Filter

A syngas retention time of 5 seconds in the filter was considered in the design of the biomass-based filter, and its height (hf1+hf2+hf3) was designed to be approximately 100 cm. Table 2 gives the dimensions of the filter, while Fig. 6 shows the schematic of the filter, with the various partitions. Section two (hf2) of the filter contained wood shavings.

Table 2: Dimensions of filter

Sections/Part	**Dimension (cm)**
h_f1	5
h_f2	90
h_f3	5
d_f	17

Wood shavings sieved through 2 mm wire mesh were used as filtration medium in the filter.

3.3. Operation and Testing of The Developed Gasifier System and Challenges Encountered

Fig. 7 shows the constructed gasification system with all the required components assembled together, while Fig. 8 shows the flow diagram for the syngas inside the gasifier system. The gasifier system was tested using wood chips, and its performance was assessed. Based on these, few modifications were made to the design. During some initial experimental runs, the produced syngas combustion at the flare tube was not sustaining. Initially, it burns with a yellow swirly flame with white smoke embedded in it, and this was adduced mainly to high moisture in the produced syngas. There were times when no gas was observed at the flare tube, this was obviously due to cogging in the biomass filter or blockage of pipes due to tar accumulation. Blockage of pipes due to tar accumulation was also cited as one of the reasons for decommissioning of several biomass gasification facilities across countries in Sub-Sahara Africa (SSA) according to the DFID reports [1,2].

After several technical considerations, it was decided that two drums, each having a height of 0.89 m and a diameter of 0.58 m, be introduced into the system. Sawdust and cotton wool were initially used as filtration media in the filter. Sawdust was loaded into section two (hf2) (Fig. 6), while cotton wool was packed in section one (hf1) above it. The use of these materials' combination led to situations where no syngas was available at outlet of the filter. This was observed frequently, and investigation revealed that the filter was clogged due to tar accumulation on the cotton wool blocking any passage of syngas after a few gasification runs. So, the cotton was replaced with sawdust and utilized as the only filtration medium in sections 2 and 1. Clogging was also frequently experienced but not as often as in the sawdust + cotton combination. After several technical considerations, it was decided that wood shavings be used in section 2, while stage one is left empty. After much effort, concentrated caustic soda solution was found to be effective for dissolving the accumulated tars inside pipes.

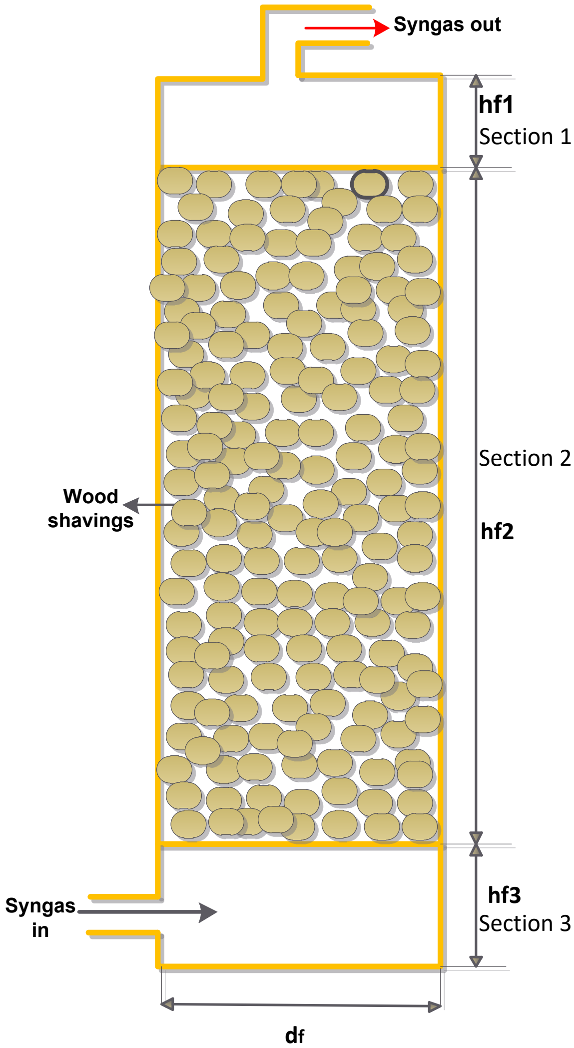

Fig. 6. Schematic of filter

These modifications and efforts led to regular production of syngas, that burned with a stable blue flame at the flare tube, like that obtained during the burning of liquified petroleum gas. It was observed that 3.52kg/h of wood waste yielded syngas which burnt for about 43 minutes. About a litre of watery liquid was collected from the drums for a full hopper load operation of the gasifier. Clogging wasn't observed anymore in the filter during gasification runs, but it was decided that the wood shavings be replaced and the pipes rinsed with concentrated caustic soda solution after 30 gasification runs at full hopper capacity.

The start-up time for the gasifier was about 3 to 4 minutes and it takes 17 minutes to operate steadily. The presence of brownish smoke indicates the availability or production of syngas. This appears few minutes after start-up but it took 17 minutes of gasifier operation for combustible gases (syngas) to be produced steadily. The wood chips flowed freely and there were no bridging problems observed at the throat during operation. Several gasification runs were carried out over the course of the study, and over the entire testing, the maximum combustion zone temperature attained was 1068°C (measured using a high temperature K-Type thermocouple ceramic kiln probe). Similar values were reported by Chawdhury and Mahkamov, [16] (1150°C), Sheth and Babu, [17] (1050°C), Erlich and Fransson, [18] (1200°C), and Simone et al. (2012) (1086°C). The temperature of the post-filter syngas varied from 155.5°C to 183.8°C (measured with digital K-Type thermocouple (TM-902C)). Chawdhury and Mahkamov, [16] reported a range of 180 - 220°C for post filter gas temperature. To stop the gasifier, the blower was switched-off and then the air inlet was closed to completely cut off air supply.

3.3.1. Biomass Consumption Rate and Syngas Characterization

Several gasification runs were carried over the course of the study, however, data collected from five runs were used to assess the performance of the gasifier system. Average results from the performance evaluation are presented in Table 3.

Table 3. Average results from performance evaluation of the wood chips downdraft gasifier system

Biomass consumption rate (kg/h)	3.52	±	0.35
Syngas yield in (m^3/h)	10.40	±	0.22
Syngas yield in (kg/h)	10.51	±	0.21
Production ratio ($m^3_{syngas}/kg_{biomass}$)	2.95	±	0.11
($kg_{syngas}/kg_{biomass}$)	2.99	±	0.13
Estimated power from wood chips (kW)	69.872	±	2.0
Estimated power from syngas (kW)	54.496	±	1.5
Gasification efficiency (%)	77.99	±	1.06

Performance analysis revealed that the gasifier consumes around 3.52kg/h of wood waste to produce syngas which burns with a stable flame for about 43 minutes. This result compares favourably with those of Chawdhury and Mahkamov, [16] who achieved a stable flame for 91 minutes from 5.9kg/h wood pellets and 41 minutes from 3.6kg/h wood chunks.

Produced syngas was characterized using a gas chromatograph. The average molar syngas composition, and obtained syngas LHV are shown in Table 4. Table 4 also presents results from previous studies that used wood as biomass and downdraft gasifiers as gasification systems.

Table 4: Average syngas and gasifier properties from this study and from literature.

Parameter	Unit	Average	SD*	Results from literature [16, 17, 18, 20 - 24]
CO	% vol.	25.2	0.67	15 – 32
H_2	%vol.	17.6	0.25	12 – 21
CO_2	%vol.	9.6	1.01	5 – 15
CH_4	%vol.	2.5	0.79	1 – 5
N_2	%vol	44.5	0.48	38 – 57
LHV	MJ/Nm^3	5.34	0.16	4 – 7
CGE	(%)	77.99	1.06	33.72 – 80.91

***SD = standard deviation**

Evaluating both sets of results, it is can be seen that the quality of produced syngas in the study compares favourably with that of syngas reported in literature. It can be observed that combustible gases (CO, H2, CH4) levels, syngas LHV and CGE are within the value range reported in literature. From table 4, CO has the highest average molar volume, followed by H2. This may be related to the breakdown of more tars, which contain more hydrocarbons, at the combustion zone due to the high temperatures in the zone. Given the syngas LHV and its stable blue flame on combustion, it can be adduced that the produced syngas from the study is within acceptable tolerances for syngas used as a fuel in internal combustion engines [25, 26]. Therefore, it can be surmised that the syngas produced from the developed wood-fired downdraft gasifier system is of good quality, and has the potential to be used to fuel internal combustion engines for electricity generation.

3.3.2. Products and Residues from Wood Chips Gasification Run

Fig. 9 shows the produced syngas ignited at the burner. Residues from the gasification runs include biochar, tar, water, and tar-laden wood shavings from the biomass-based filter. These are shown in Figs 10a, b, c and d.

Fig. 7: Component parts of the wood wastes downdraft gasifier system

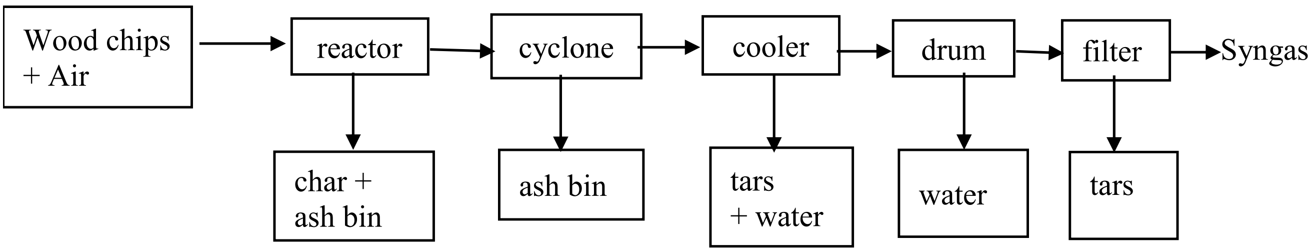

Fig. 8: Flow diagram for syngas in the designed downdraft gasifier system

4. Conclusion and Recommendations for Future Work

Biomass gasification is a viable technology that could alleviate the energy poverty in Sub-Sahara Africa. However, dearth of local technical know-how has prevented the successful implementation of such technology in the region. Therefore, in this study, a pilot downdraft biomass gasifier system was design, constructed, and successfully tested for syngas production using wood wastes as feedstock. A detailed feedstock assessment was conducted to ascertain the availability of wood wastes in the study area, a crucial criterion for successful implementation of biomass gasification technology. The gasifier reactor design was a modified combination of both Imbert and open core downdraft gasifier designs, to achieve ease of biomass feeding into the gasifier via the open top and the tar destruction at the throat. The annual availability of wood wastes in the study area was found to be about 3.778,02 tonnes per year, indicating ample availability of feedstock in the study area to run the downdraft gasifier system. Performance evaluation of the gasifier system revealed that the produced syngas is of quality applicable as a fuel in internal combustion engines. Finally, challenges encountered and successfully addressed during the operation of the gasifier system were highlighted; this is expected to be a technical guide to researchers in Nigeria and Sub-Sahara Africa when developing biomass gasification systems. As part of future research, the sustainability impact assessment of running a household generator with the produced syngas to produce electricity would be evaluated. This could act as a potential means of generating low-cost, reliable and sustainable off-grid electricity in Nigeria and Sub-Sahara Africa, to ease the present electricity crisis, especially in the rural areas. It could also provide sustainable approach to effectively manage the huge quantity of wood wastes in the region.

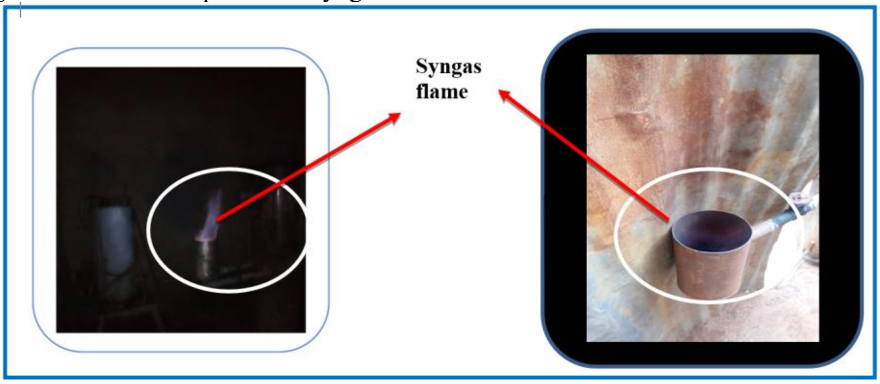

Fig. 9: Syngas flame at the burner

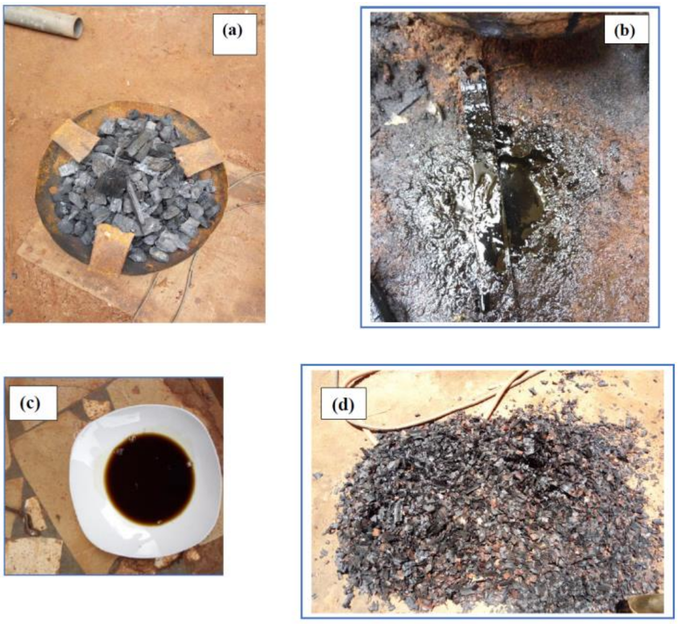

Fig. 10: (a) Char, (b) Tar, (c) Water and (d) Used wood shavings from the filter

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Conflicting Interests

The authors have no conflicting interests to declare.

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