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Development of a Small-Scale Downdraft Waste Gasification Power Generation Plant for Electrification of Households in Okada Environs

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Abstract: *The rising energy demand and the environmental challenges associated with improper waste disposal underscore the need for sustainable and renewable energy solutions. This project outlines the development of an improved 6 kW biomass gasification plant for syngas production. The syngas was deployed for power generation to provide reliable and sustainable electricity for a highly agro-rich settlement in the Okada environs which currently lacks access to the national electricity grid. The components of the gasification plant including the air supply channel, reactor, grate, the hopper etc were designed. Performance analysis was carried out using food waste pellet and wood waste as fuel to test the lower heating value and cold gas efficiencies of the produced syngas. Results showed that the lower heating values and cold gas efficiency using fuel wood were 4.3417 MJ/kg and 59.0316% respectively, while for food waste pellet were 5.5995 MJ/kg and 76.2463% respectively. A total cost of three hundred and fifty thousand naira was utilized in the fabrication of the gasification plant.*

Keywords: *Biomass, Cold Gas Efficiency, Gasification, Lower Heating Value, Tars*

1. INTRODUCTION

Energy generation and waste disposal are among the most critical challenges facing the world today [1]. The depletion of fossil fuel resources is leading to an escalating energy supply crisis, while global population growth and rising living standards are increasing energy demand and contributing to unprecedented levels of waste production. In Nigeria, where a significant portion of the land is covered by forests and agricultural zones, and a rapidly growing population generating substantial amounts of municipal solid waste, there is considerable potential for these resources to contribute to the country's energy needs [2]. This is particularly important given the persistent environmental and health challenges associated with reliance on domestic fossil fuels for energy production. Most households in the rural areas in Nigeria heavily depend on these agricultural residues for animal feed and cooking fuel, constituting 98.3% of biomass energy consumption [3; 4]. Despite widespread use, the conversion efficiency of crop residues is notably low, leading to significant mismanagement as observed by Alatzas et al., [5] The incineration of crop residues has significant adverse effects on both human health and the environment. Studies have indicated that in-situ burning of crop residues in Nigeria contributes to over one-third of total biomass burning [6] which releases particulates (PM), including PM10 and PM2.5, along with greenhouse gases (GHGs) [7; 8].. Okada town being the headquarters of Ovia North East local government area in Edo state, Nigeria is surrounded by several rural settlements which lack national electricity grid connection and are significantly agriculturists producing various crop residues such as cassava peels, corn cubs, oil palm residues, plantain residues, cocoa residues, saw dust etc. Some of these settlements include Ayeku, Alajido, Sule, Bode, Fatayi, Sunday 1 & 2 camps under Ugbuwe village, Jabaro, Toba, Sule, Kayode, Doctor, Faloyi, Adajido and Sam camps under Usen village.

Small scale Waste-to-Energy (WtE) technologies offer a vital solution to this growing imbalance. Gasification is a well-established and efficient technology that enables the conversion of agricultural residues, municipal solid wastes, and other solid fuels into synthesis gas, commonly referred to as syngas [9]. Adoption of biomass utilization for electricity generation is on the increase worldwide. This approach aligns with several United Nations Sustainable Development Goals (SDGs) [10], notably SDG 1 (No poverty), SDG 3 (Good Wealth and Well-being), SDG 7 (Affordable Clean Energy), SDG 8 (Decent Work and Economic Growth), SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable City and Communities) and SDG 13 (Climate Action).

Famoso et al. [11]; Yang et al. [12] highlighted its potential as a renewable energy source and an effective waste management solution. The choice of biomass is driven by recent advancements in conversion technologies, environmental benefits, improved energy security, increased employment, rural development, and the restoration of degraded lands, potentially enhancing biodiversity [13]. Compared to other renewable energy sources, biomass is often more economical due to lower capital investment and per-unit production costs [14]. Studies have shown that waste gasification significantly decreases methane emissions compared to traditional waste disposal methods, offering a more environmentally sustainable waste management strategy [15].

Recent researches have focused extensively on the economic and environmental performance of residual biomass gasification for decentralized electricity production. Desclaux and Pereira [16] emphasized the critical role of business models in ensuring project viability. Kirkels and Verbong [17] conducted a comprehensive review of small-scale biomass gasification systems, analyzing both technical and economic aspects. García et al. [18] developed and tested a mobile power generation system utilizing densified carbonized wood pellets. Hanchate et al. [19] evaluated small-scale downdraft gasifiers using agricultural residues. The results revealed high thermal efficiency and low tar production, establishing the suitability of these systems for rural power generation. Sikarwar et al. [20] explored the integration of small-scale gasification with internal combustion engines for combined heat and power (CHP) applications. Kumar et al. [21] investigated the feasibility of mixed biomass pellets in small-scale gasification systems. Their findings showed that blending biomass types significantly improved syngas quality and gasification performance, offering a practical strategy for optimizing feedstock utilization. Meyer et al. [22]; Onochie et al., [23] conducted a life cycle analysis of small-scale gasification plants to evaluate their environmental impacts. The application of small-scale gasification systems in remote communities was in Ojolo ets examined by Ramos et al. [24]. Their findings indicated that these systems can provide reliable power, promote local economic development, and alleviate energy poverty. Zhang et al. [25] analyzed the co-gasification of biomass and plastic waste in small-scale systems. Their results revealed that co-gasification enhances syngas yield and calorific value, while also addressing integrated waste management challenges effectively. Li et al. [26] proposed advanced control strategies for small-scale gasification plants. Their simulations demonstrated significant improvements in efficiency and operational stability, paving the way for smarter and more adaptable gasification technologies. This project will therefore focus on the development of a small scale gasification plant in Okada environs using locally available materials.

2. DESIGN ANALYSIS, CONSIDERATIONS AND PROCEDURES

This section outlines the key design parameters, assumptions, and step-by-step procedures adopted in developing the biomass gasification system.

2.1 Detailed Design of the Gasification Plant

The detailed design of the gasifier components are:

1. Fuel Consumption Rate (FCR)

This laboratory scale gasifier is designed to deliver a power of 6 kW_{th}. The fuel consumption rate (FCR) is given by Equation (1) [27].

$$FCR = \frac{P_{Mech}}{LHV_{biomass} \times \eta} \tag{1}$$

Where P_{Mech} is Mechanical Power (kW) considered as 6kW based on the design specification of the plant, $LHV_{biomass}$is the lower heating value of biomass (16.262MJ MJ/kg based on Table 2 for food waste) and η is the overall efficiency, the product of gasifyer efficiency (70% presented in Ojolo et. al., [27] and mechanical shaft efficiency of 25% [28].The $P_{Mech}$is 6kWbased on the design specification of the plant.

2. Throat Diameter (d_{th})

The throat diameter is determined using Equation (2) [29];

$$d_{th} = \sqrt{\frac{4 \times FCR}{SGR \times \pi}} \tag{2}$$

Where SGR = Specific gasification rate (SGR =200 kg/m^2h (Range from 100 to 250kg/m^2h [27]).

3. Height of the Reactor

The height of the gasifier reactor refers to the distance between the top of the gasifier and the grate. This determines how long the gasifier would be operated in one loading of fuel pellets. The higher the height, the more pellets the gasifier can hold and the longer the time (Ti = 90min –design specification) it will take to consume all the loaded pellets. The height can be determined using Equation (3)

$$h_g = \frac{SGR \times Ti}{\rho_{biomass}} \tag{3}$$

Where $\rho_{biomass}$ is the density of the biomass (590kg/m^3 for food waste pellet) as adopted from Table 2.

4. Determination of Volume of the Hopper

The purpose of a hopper is to store the biomass for continuous feeding into the gasification zone. It is mounted above the reactor of the gasifier. The fuel storage hopper is made up of 2mm thick mild steel material. The diameter of the hopper is chosen to be 250mm while the height is obtained from Equation (3). Cylindrical shaped hopper was chosen to prevent the problem of biomass being stuck. The top is covered by a circular shaped cover that is attached by means of a string for easy removal for feeding of feedstock to the gasifier. Figure 1 shows the design of the hopper.

The hopper is cylindrical in shape. The volume is given by Equation (4).

$$Vol_h = \frac{\pi d_h^2 h_g}{4} \quad (4)$$

Where d_h is the diameter of the hopper (0.35m) and h_g is the height of the hopper obtained from Equation (3).

5. Reaction Zone

This is the main component of the gasifier. The main reactions of gasification like oxidation, and reduction take place in this zone. It is in the shape of vertical convergent and divergent nozzle (from top to bottom direction) and made by 4mm thick mild steel. Upper diameter of divergent section is 200mm and the lower diameter is of 250mm with 80mm height. Figure 2 shows the design of the reaction zone.

Figure 1: The hopper

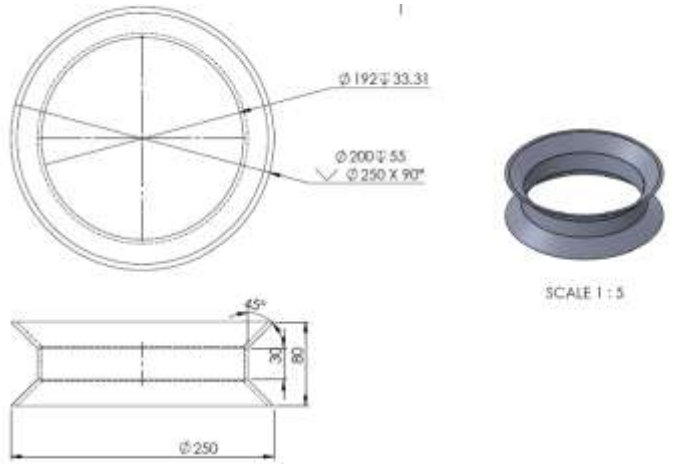

Figure 2: The reaction zone

6. Casing of Gasification Zone

Syngas from gasification zone contains tar and in order to reduce the amount of tar in the syngas gas, it was passed through a hot region. Due to various chemical reactions in gasification zone, the body of gasification zone becomes hot thus it would be more beneficial to pass syngas from the outer surface of gasification zone to reduce tar concentration. Thus a gasification zone casing is fabricated as a cylindrical shape round the gasification zone so as to pass the producer gas through the gap between gasification zone and its casing as shown in Figure 3. The outer diameter of the ring is 300mm and the height of the ring is 130mm.

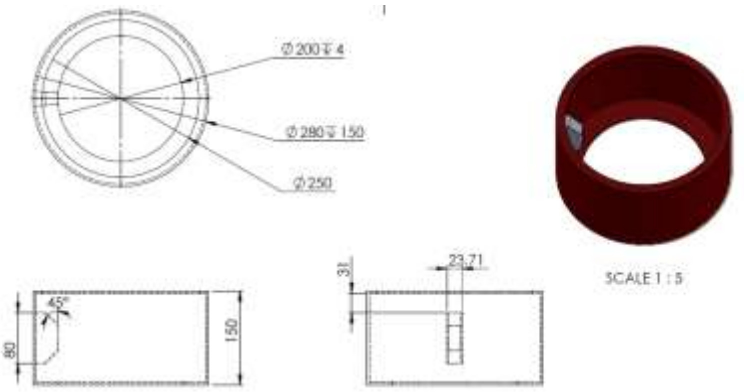

Figure 3: The reaction zone casing

7. The Grate

The grate is positioned below the reaction zone in the gasifier to hold the feedstock during gasification. It is circular in shape of diameter 250 mm. It contains circular openings of 10 mm diameter.

8. Ash Pond

The ash pond is positioned under the grate to collect the ash after gasification. It is cylindrical in shape with a diameter and height of 200mm and 300mm respectively. Figure 4 shows the design of ash pond

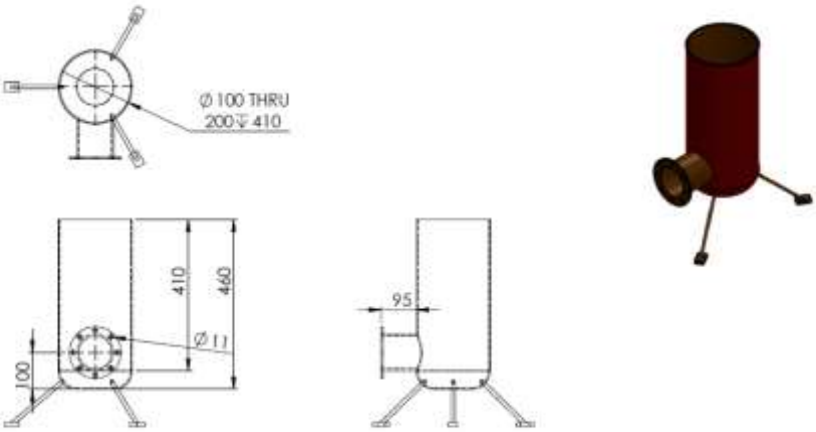

Figure 4: The ash pond

9. Air inlet pipe

The air inlet pipe is located at the top of the gasifier and shaped downwards towards the feedstock in the gasifier. The pipe is made of mild steel of diameter 40mm and thickness 2mm. The outer end is slightly covered by an adjustable screw. This mechanism is to the help regulate the amount of air going into the gasifier. Figure 5 shows the design of the air inlet pipe

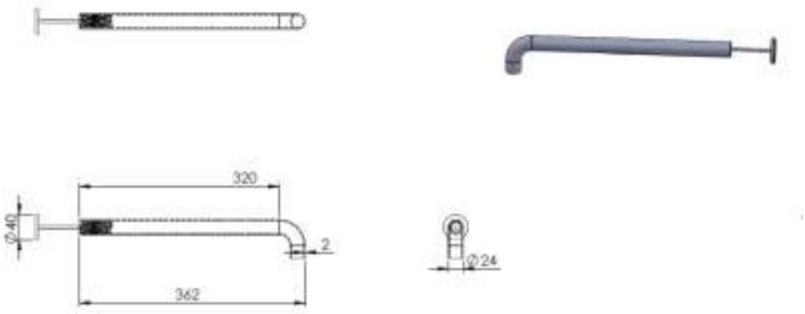

Figure 5: Air inlet pipe

10. Expansion Drum

The expansion drum consists of a conventional drum having an inlet and outlet valve. The drum is designed in a way that the gas enters at the top of it, expands as it enters and also leaves at the top of the drum as seen in Figure 6. As the syngas expands due to the available space in the drum, moisture content tends to form and settles at the bottom of the drum. Tars are also observed to drop off the syngas in the expansion drum. The top of the drum is designed in a way that it can be unscrewed to open for easy maintenance. A gasket is fitted at the top to avoid leakage of the syngas.

11. Purification Filter Unit

The purification filter consists of three compartments. Each of the compartments consist of three units. Each unit have in it 500g of Silica gel to absorb moisture content, 500g of Iron fillings to absorb the hydrogen sulphide (H_2S) in the syngas impregnated on separate iron sponges and wood shavings to absorb tars. The purification filter carries inlet valve and outlet valve. The inlet valve receives syngas from the expansion drum while the outlet valve takes the syngas to the burner and to storage unit. Figure 6 shows the syngas purification filter. The silica gel used as the purifying reagent is an amorphous and porous form of silicon oxide (SiO_2). It has an average pore size of 2.4nanometer and possesses strong affinity for water molecule. It is strongly used as a desiccant. The iron filing was collected from the Engineering Workshop, Igbinedion University, Okada. It was used as the purifying reagent in this unit also to remove hydrogen sulphide. The wood shavings were purchased from a local sawmill at Okada. A total of 2.5 kg of wood shavings was used to maintain the uniform packed bed density of the filter. The gasification experimental plant set up is shown in Figure 6.

2.2 Experimental Procedure for Testing the Gasifier

The biomass gasification plant was tested using fuel wood and food waste pellet. Food waste samples were collected from food vendors comprising of rice, yam peel, potato peel, garri and orange peels. The percentage mass composition of the collected food waste was as follows: rice (29%), yam peel (16%), potato peel (14%), orange peel (22%), and garri (19%) based on their availability. To ensure uniformity, the selected food waste samples were mixed using a food waste mixer. The uniformity of the mixture was assessed following the procedures outlined in Adingwupu et al, [30] achieving a degree of mixing of 96.8% after ten minutes of mixing. The mixed food waste was then subjected to a pelletization process using a screw-type briquetting machine, without the addition of binders, as the starchy nature of the food waste provided sufficient binding properties [31]. The resulting pellets presented in Figure 7 has a diameter of 30 mm and an average height of 100 mm. Wood pellets samples also used for the performance analysis of the gasification plant is presented in Figure 8.

Figure 6: The gasification set-up
[1-Cyclone, 2-Cooler, 3-Induced fan, 4-Expansion drum, 5-Gas cylinder, 6-Burner, 7-Reactor, 8-Filter unit, 9-Ash pond]

Figure 7: Food waste pellets

Figure 8: The wood waste

The results of the dried fuel proximate, ultimate and heating value analysis carried out using ASTM E 871-82 standard test procedures outlined in [32] are presented in Table 2 and 3.
The procedures for testing of the gasifier are as follows:

i. The gasification plant was placed in an open space ensuring all the parts are well tightened

ii. The hopper top was opened and loaded with the fuel wood in the first instant and also the food waste pellet at the second instant
iii. The fuel was ignited by wetting some of them with fire lighter (kerosene) and ignited with a torch and the induced fan was switched on at this point to supply sufficient air/oxygen to initiate the combustion.
iv. The top cover was then closed and the air regulator was adjusted to give the right air fule ratio desired
v. After 15 minutes, the syngas was withdrawn at the exit of the gasifier after passing through the cyclone separator to remove the particulate matter, cooling system, expansion drum and the filtration unit.
vi. The purified syngas was ignited in the combustion region to test the syngas and then syngas samples were taken using a gas syringe for analysis.
vii. The flame test results using the expansion drum and filtration unit are shown in Figure 9
viii. The experiment was stopped by first switching off the fan, then closing completely the air supply lid
ix. The plant was left in the open space to completely cool down.

During the testing of the gasifier the following measurements were taken:
i. The biomass was measured to be 5kg before introduction into the hopper
ii. Air mass flow rate was adjusted to 0.002668kg/s to give an equivalence ratio of 0.3

2.3 Performance Evaluation of the Gasification Plant

The Cold Gas Efficiency and Lower Heating Value (LHV) of the syngas produced were evaluated using Equations (5) and (6) respectively [33].

$$LHV_{syngas} = \sum(LHV_i \times mm_i) \tag{5}$$

$$CGE = \frac{LHV_{syngas} \times Y_{syngas}}{m_{biomass} \times LHV_{biomass}} \times 100 \tag{6}$$

Where: mm_i is the mass fraction of specie i, LHV_{syngas} and $LHV_{biomass}$ are the lower heating value of the syngas and biomass respectively, m_{syngas} and m_{biomas} are the mass flow rate of the syngas and biomass in kg/s.

2.4 Bill of Engineering Measurement and Evaluation (BEME)

Table 1 shows the Bill of Engineering Measurement and Evaluation (BEME) for the fabrication of the gasification plant. The total cost of fabrication is three hundred and fifty thousand naira (₦350,000) as at December, 2024.

Table 1: Bill of engineering measurement and evaluation (BEME)

S/N	DESCRIPTION	QTY	AMOUNT (₦)
1	Waste cylinder	3	45,000
2	DC Induced fan	1	15,000
3	1,500mm * 1,500mm by 2mm High Carbon Steel Plate	1	10,500
4	Expansion Drum	1	18,000
5	1'' gas pipe Length 5400mm	2 Lengths	18,000
6	Air flow meter	1	10,000
7	Gasket for the filter	1	2,000
8	1'' square pipe	1/2 Lengths	5,000
9	1/2'' thick pipe	1Length	12,500
10	Paints	2 Cups	12,000
11	Gasket gum	1	1,500
12	Welding Electrodes	20PKS	100,000
13	M12mm Bolt & Nut	30	9,000
14	Clips	20	4,000
15	Hose	1	2,000
16	Grinding Stone	5	5,000
17	Cutting stones	8	12,000
18	Transportation		40,000
19	Miscellaneous		28,500
	Total		**350,000**

The proximate, ultimate and heating values analysis of the fuel wood and food waste pellets used for the performance analysis are presented in Table 2 and 3 as adopted from Waheed et. al., [33].

Table 2: Proximate and lower heating value test results

Parameter	**Fuel Wood (%)**	**Food Waste Pellet (%)**
Moisture Content	19.306	10.122
Volatile Matter	68.056	75.000
Ash	3.468	2.540
Fixed Carbon	9.170	12.338
LHV (MJ/kg)	14.64MJ/kg	16.262MJ/kg
$\rho_{biomass}$.	684kg/m^3	590kg/m^3

Table 3: Ultimate test results

Parameter	**Fuel Wood (%)**	**Food Waste Pellet (%)**
Carbon	46.8	47.5
Nitrogen	2.8	2.52
Sulphur	0.0957	0.0955
Hydrogen	6.9966	7.0983
Oxygen	39.8391	40.2517

3. RESULTS AND DISCUSION

3.1 Result of the Detailed Design of the Gasifier

The detailed design of the gasification unit is presented in Table 4.

Table 4: Design Parameters of the Gasification Unit

Parameter	**Calculated Value**
Fuel Consumption Rate	8.54kg/h
Throat diameter	0.26m
Height of hopper	0.44m
Volume of the Hopper	0.04234 m^3

3.2 Results of the syngas compositions

The syngas samples were analysed using Gas Chromatograph Thermoquest Trace 2000GC equipment. The results of the syngas composition obtained using fuel wood and food waste pellets are presented in Table 5. As can be seen, the food waste pellet presented a higher percentage of the combustible gasses hydrogen, carbon monoxide and methane.

Table 5: Syngas composition results

Fuel	**CO (%)**	**N_2 (%)**	**CO_2 (%)**	**H_2 (%)**	**CH_4 (%)**	**H_2O (%)**
Wood Waste	38.20	37.88	10.70	7.57	3.21	2.5
Food Waste Pellet	38.41	42.53	3.84	11.15	3.08	2.5

3.3 Performance Analysis of the Gasification Plant

The results of the lower heating values and cold gas efficiencies obtained using fuel wood and food waste pellets are presented in Table 6. As can be seen, the food waste pellet had a higher cold gas efficiency of 76.2463%.

Table 6: Performance analysis results of the gasifier

Fuel	**LHV (MJ/kg)**	**CGE (%)**
Wood Waste	4.3417	59.0316
Food Waste Pellet	5.5995	76.2463

3.4 Flame Test

In order to improve the quality of syngas produced, an expansion drum was fitted to the gasification system. Result of the various test conducted using food waste pellet without expansion drum and filtration unit (No treatment), without expansion drum but with filtration unit coupled to the gasifier (Treatment 1) and lastly with both the filtration unit and expansion drum (Treatment 2) are presented in Table 7 and their corresponding gas flame observations are shown in Figures 9a-c.

Table 7: Syngas composition and tar content for the various treatments using food waste pellet

		No treatment	Treatment 1	Treatment 2
Syngas composition	**CO (%)**	28.2	32.12	38.41
	N_2 (%)	46.81	46.83	42.53
	CO_2 (%)	7.89	5.01	3.84
	H_2 (%)	5.92	8.82	11.15
	CH_4 (%)	0.98	2.09	3.08
	H_2O (%)	10.2	5.13	2.5
Tar Content (g/Nm^3)		5.8	1.08	0.74

Figure 9a: Flaring of Syngas in a Burner without Expansion Drum and Filtration Unit

Figure 9b: Flaring of Syngas in a Burner without Expansion Drum but with Filtration Unit

Figure 9c: Flaring of Syngas in a Burner with Expansion Drum and Filtration Unit

The performance of two types of syngas cleaning systems using wood shavings as the filter medium and an expansion drum were evaluated. It can be observed that wood shavings reduced the tar content from 5.8g/Nm^3 to 1.08g/Nm^3. Further reduction in the tar content was observed when expansion drum was fitted to the system. This brought down the tar to 0.74g/Nm^3.

3.5 Performance of the Generator Using Load Test

A 2.5KVA gasoline generator was powered by the syntheses gas produced from the gasification plant. The generator operated for over two hours on no load and then for a further three more hours on load with a standing fan (90watts) and a cutting machine with rating 2kW. The system functioned satisfactorily.

4. CONCLUSION

The development and successful implementation of a 6 kW biomass gasification power generation plant in the Okada environs demonstrates the practical viability and socioeconomic relevance of small-scale Waste-to-Energy (WtE) technologies in rural Nigeria. This project not only addressed the pressing issues of energy poverty and improper waste disposal but also highlighted the potential of food waste pellets as an efficient feedstock for syngas production Comparative performance results revealed higher lower heating value (5.5995 MJ/kg) and cold gas efficiency (76.25%) using food waste pellets then residues of wood waste. The system's ability to power a 2.5 kVA generator makes it an appropriate solution for decentralized electrification in remote off-grid settlements. Downstream gas purification components (the expansion drum and filtration unit) also effectively improved syngas quality (reduced tar content), thus increasing the efficiency and environmental friendliness of the system. With a relatively low fabrication cost of ₦350,000, this project exemplifies a cost-effective, scalable model for community-level energy solutions. Going forward, replicating and scaling such systems, coupled with local training and policy support, could catalyze sustainable rural electrification and cleaner waste management across Nigeria.

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