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Techno-Economic Feasibility and Energy Performance Assessment of Small-Scale Agricultural Waste-to-Energy Pathways in Nigeria

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Abstract

Reliable electricity supply remains a major constraint on economic activity in Nigeria, while large quantities of agricultural residues and processing wastes are generated with limited productive use. This study evaluates the techno-economic feasibility and energy performance of small-scale agricultural waste-to-energy (WtE) pathways suitable for decentralized deployment in Nigeria. Three representative conversion routes are assessed using a harmonized framework: biomass gasification coupled with an internal combustion engine, direct combustion integrated with an Organic Rankine Cycle, and anaerobic digestion with biogas-to-power. A consistent functional unit of one tonne of waste processed (as received) and common system boundaries are applied to enable technology-neutral comparison of specific electricity yield, conversion efficiency, and levelized cost of electricity (LCOE). Base-case scenarios are defined using literature-supported technical and economic parameters relevant to Nigerian agricultural residues. Results indicate that gasification-ICE delivers the highest net electricity yield (574.2 kWh/t) and the lowest LCOE (0.138 USD/kWh) under electricity-only operation, while combustion–ORC produces lower electricity output (311.4 kWh/t) but achieves the highest overall energy utilization when useful heat is recovered in combined heat and power mode. Anaerobic digestion yields lower electricity per tonne (169.2 kWh/t) but demonstrates strong compatibility with wet wastes and high conversion efficiency on a biogas-energy basis. Sensitivity analysis shows that capacity factor and capital cost are the dominant drivers of economic viability, while feedstock moisture content and methane fraction strongly influence energy output. The findings highlight the importance of aligning WtE technology choice with feedstock characteristics, heat demand, and operational conditions, and provide evidence-based guidance for decentralized agricultural waste-to-energy deployment in Nigeria.

Keywords: Nigeria; Agricultural residues; Processing wastes; Waste-to-energy (WtE); Techno-economic feasibility; Energy performance; Biomass gasification; Internal combustion engine (ICE); Combustion-ORC; Organic Rankine Cycle (ORC); Anaerobic digestion; Biogas-to-power; Levelized cost of electricity (LCOE); Combined heat and power (CHP); Sensitivity analysis; Decentralized deployment

1. Introduction

Reliable and affordable electricity supply remains a critical constraint on economic productivity, industrial competitiveness, and social welfare across many developing economies, particularly in Sub-Saharan Africa. Nigeria exemplifies this challenge through persistent grid outages, limited generation capacity relative to demand, and poor

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service reliability, which have entrenched widespread reliance on petrol and diesel generators for residential, commercial, and agro-industrial energy needs [1–3]. While recent tariff reforms aim to improve cost recovery and sector sustainability, they have also intensified the need for technically reliable and economically viable decentralized energy alternatives that can reduce exposure to volatile fuel prices and mitigate the environmental impacts of fossil-fuel-based self-generation [4], [5]. At the same time, Nigeria's agricultural sector generates substantial quantities of residues and processing wastes that remain largely underutilized or improperly managed. Cassava processing, a major agro-industrial activity in the country, produces significant solid and liquid wastes that pose environmental and public health risks when discharged untreated, yet represent a valuable feedstock for bioenergy conversion [6]. Similarly, rice production generates large volumes of rice husk that are typically concentrated around milling clusters; recent Nigeria-focused characterization studies indicate that rice husk possesses fuel properties suitable for decentralized thermochemical energy conversion [7] also [25], [26] considered work-done. In oil-palm value chains, residues such as palm kernel shell (PKS) exhibit favorable heating values and combustion characteristics and have been widely discussed as promising solid biofuels for small-scale energy applications [22], [23]. These agricultural residue streams therefore present an opportunity to address two persistent challenges simultaneously: improving local energy supply reliability and reducing the environmental burden associated with unmanaged agricultural waste.

Waste-to-energy (WtE) technologies offer practical pathways for converting agricultural residues into electricity and useful heat while supporting circular-economy objectives [14], [15]. For agricultural waste streams, WtE options are commonly categorized into thermochemical processes-such as combustion and gasification-and biochemical processes, most notably anaerobic digestion (AD) [9], [14], [17]. Thermochemical routes are generally more suitable for dry, lignocellulosic residues, whereas biochemical conversion is better suited to wet organic wastes with high moisture content [17], [18]. Consequently, technology selection depends strongly on feedstock characteristics, desired energy products (electricity-only versus combined heat and power), and the operational capacity available to sustain performance over time [14-17].

Small-scale WtE systems are particularly attractive for decentralized deployment in agro-processing clusters and rural or peri-urban settings where residues are generated close to energy demand. Biomass gasification coupled with internal combustion engines has been widely examined for decentralized electricity generation because of its modularity and relatively high electrical efficiency at small scale under appropriate fuel and operating conditions [9]. However, long-term reliability remains a key barrier, primarily due to producer-gas quality constraints-especially tar formation and particulate contamination-which can damage engines and increase downtime if gas cleaning is inadequate [10]. Tar mitigation and removal therefore remain central design and operational challenges for small-scale gasification systems, with documented implications for system availability, operating costs, and economic performance [11-13]. Direct combustion of agricultural residues represents a more mature and operationally robust option, particularly for fuels with variable composition. However, small-scale electricity generation based on combustion alone typically suffers from low electrical efficiency and high specific capital costs unless useful heat is productively recovered in combined heat and power (CHP) configurations [14]. The integration of Organic Rankine Cycle (ORC) systems has expanded the feasibility of small-scale biomass power by enabling electricity generation from lower-temperature heat sources, though performance and cost remain strongly dependent on heat-source temperature, scale, and capacity factor [15], [16]. Where stable local heat demand exists such as crop drying, parboiling, or agro-industrial process heat-CHP integration can substantially improve overall energy utilization and economic viability [14–16], [27]. For wet agricultural wastes such as cassava residues and manure-rich organics, anaerobic digestion is often the most compatible WtE pathway, as it leverages high moisture content as a process requirement rather than a limitation [6], [17], [18]. AD produces biogas that can be used for electricity generation while also providing co-benefits such as odor reduction, pathogen control, and the production of digestate that may be valorized as a soil amendment depending on quality and market conditions [17], [18]. Co-digestion has been widely reported as a strategy for improving methane yield and process stability by balancing substrate characteristics and carbon-to-nitrogen ratios an important consideration in agricultural contexts where waste composition varies seasonally and by processing practice [19]. Despite the growing global literature on biomass conversion and biogas systems, comprehensive comparative assessments focused specifically on small-scale agricultural WtE pathways remain limited, particularly in developing-country contexts where feedstock logistics, operational reliability, and capacity factor can dominate techno-economic outcomes [14–19]. In Nigeria, this evidence gap is especially consequential given the expanding decentralized energy ecosystem and the presence of enabling regulation for mini-grid deployment, which creates pathways for localized generation where feedstock supply and electricity or heat demand can be co-located [20], [21].

Accordingly, this study evaluates the techno-economic feasibility and energy performance of small-scale agricultural waste-to-energy pathways in Nigeria using a harmonized assessment framework. Three representative conversion routes-biomass gasification coupled with an internal combustion engine, direct combustion integrated with an Organic Rankine Cycle, and anaerobic digestion with biogas-to-power-are analyzed using consistent system boundaries, energy performance indicators, and techno-economic metrics, including levelized cost of electricity. The study further identifies the most influential parameters affecting viability through sensitivity analysis, with the objective of providing evidence-based guidance for decentralized WtE technology selection and deployment in Nigerian agricultural and agro-industrial settings.

2. Methodology

2.1. Study Design and Comparative Framework

This study conducts a Nigeria-focused comparative assessment of small-scale agricultural waste-to-energy pathways using an integrated energy performance and techno-economic analysis (TEA) framework. Three conversion routes were selected because they represent widely implemented or widely studied options for agricultural residues at decentralized scales and allow comparison across thermochemical and biochemical conversion families: biomass gasification coupled with an internal combustion engine (ICE), direct combustion integrated with an Organic Rankine Cycle (ORC), and anaerobic digestion (AD) with biogas-to-power [9], [14-19]. Gasification reliability constraints especially tar formation and the need for gas cleaning are explicitly treated as availability and operating-cost drivers based on foundational and review literature [10], [11], [13]. ORC modeling is guided by techno-economic surveys and small-scale ORC reviews that document scale/temperature sensitivity [15], [16], while AD modeling follows widely cited digestion and co-digestion literature [17-19].

2.2. Functional Unit and System Boundary

The functional unit is 1 tonne of agricultural waste processed (as-received), enabling technology-neutral comparison of specific electricity yield (kWh/t) and efficiency across feedstocks with differing moisture content. The system boundary extends from feedstock reception at the plant gate to net electricity delivered at the generator terminals. Included processes are preprocessing (drying and size reduction where required), conversion, power generation, parasitic electricity use, and residue handling (ash/digestate). Upstream crop cultivation/harvesting is excluded because residues are treated as by-products, while downstream transmission/distribution beyond the plant is also excluded.

2.3. Feedstock Selection and Characterization

Nigeria-relevant agricultural wastes are grouped by moisture and conversion compatibility. Dry lignocellulosic residues (e.g., rice husk and palm kernel shell) are modeled under thermochemical conversion, supported by Nigeria-focused rice husk characterization and palm residue fuel studies [7], [22], [23]. Wet wastes (e.g., cassava processing residues and manure-rich organics) are modeled under AD based on moisture compatibility and biodegradability, consistent with Nigeria-focused cassava waste literature and digestion reviews [6], [17]–[19]. Each feedstock is characterized by moisture content MC, heating value (for thermochemical routes), or methane fraction/biogas energy potential (for AD).

2.4. Energy Modeling and Governing Equations

2.4.1. Energy input for thermochemical routes

For gasification–ICE and combustion–ORC, the energy input from as-received biomass is:

$$E_{in} = m \cdot LHV_{ar} \qquad (1)$$

where E_{in} is energy input (MJ), m is biomass mass (kg), and LHV_{ar} is as-received LHV (MJ/kg). When only dry-basis values exist, moisture correction is applied:

$$LHV_{ar} = LHV_{dry}(1 - MC) - 2.44\,MC \qquad (2)$$

where MC is moisture fraction (kg water/kg wet biomass) and 2.44 MJ/kg approximates the latent heat of water vaporization.

2.4.2. Biogas energy for anaerobic digestion

For AD, energy input is represented via biogas energy:

$$E_{bg} = V_{bg} \cdot LHV_{bg} \qquad (3)$$

where V_{bg} is biogas volume (Nm3). Biogas LHV is estimated from methane fraction:

$$LHV_{bg} \approx x_{CH_4} \cdot 35.8 \qquad (4)$$

where x_{CH_4} is methane volume fraction and 35.8 MJ/Nm^3 is methane LHV at standard conditions [17]–[19].

2.4.3. Net electricity and auxiliary loads

Net electricity exported is:

$$E_{el,net} = E_{el,gross} - E_{aux} \qquad (5)$$

Auxiliary electricity use is represented by:

$$E_{aux} = f_{aux}\, E_{el,gross} \qquad (6)$$

where f_{aux} is technology-dependent parasitic fraction (feed handling, pumps, blowers, gas cleaning, mixing, etc.).

2.4.4. Technology-specific gross electricity models

Gasification–ICE: Producer-gas chemical energy is estimated using cold gas efficiency:

$$E_{gas} = \eta_{CGE}\, E_{in} \qquad (7)$$

Gross electrical output is:

$$E_{el,gross} = \eta_{ICE}\, E_{gas} \qquad (8)$$

Tar formation and control requirements are treated as key constraints that influence auxiliary loads and availability, consistent with tar formation and mitigation literature [10], [11], [13].

Combustion–ORC: Thermal energy available from combustion is:

$$E_{th} = \eta_{boiler}\, E_{in} \qquad (9)$$

Gross electricity from ORC is:

$$E_{el,gross} = \eta_{ORC}\, E_{th} \qquad (10)$$

Small-scale ORC performance and feasibility are modeled using efficiency ranges and scale dependencies reported in ORC surveys and reviews [15], [16], while biomass CHP configurations follow catalogue guidance [14].

AD–biogas engine: Gross electricity is:

$$E_{el,gross} = \eta_{bg,e}\, E_{bg} \qquad (11)$$

where $\eta_{bg,e}$ is biogas engine electrical efficiency [17]–[19].

2.4.5. Performance indicators

Specific net electricity yield per tonne is:

$$Y_{el} = \frac{E_{el,net}}{m_{tonne}} \qquad (12)$$

Electrical efficiency (thermochemical basis) is:

$$\eta_{el} = \frac{E_{el,net}}{E_{in}} \qquad (13)$$

For AD, efficiency is also reported on a biogas-energy basis:

$$\eta_{el,AD} = \frac{E_{el,net}}{E_{bg}} \qquad (14)$$

When useful heat is recovered and utilized (CHP), overall efficiency is:

2.4.6. $\eta_{overall} = \frac{E_{el,net}+E_{th,useful}}{E_{in}}$ *(15)*

Annual net electricity generation

Annual net electricity is computed as:

$$E_{ann} = P_{net} \cdot 8760 \cdot CF \qquad (16)$$

where $P_{net}$is net electrical capacity (kW) and $CF$is capacity factor.

2.5. Techno-Economic Analysis (TEA)

2.5.1. Cost structure

Total capital investment CAPEX_totincludes prime movers (gasifier/boiler/digester, engines/ORC), balance-of-plant, installation, civil works, and contingencies. Annual operating costs include fixed O&M (labor, routine maintenance), variable O&M (consumables, overhaul accrual), and feedstock logistics.

Fixed O&M is computed as:

$$OPEX_{fixed} = C_{FOM} \cdot CAPEX_{tot} \qquad (17)$$

Annual feedstock logistics cost is:

$$C_{feed,ann} = C_{log} \cdot \dot{m}_{ann} \qquad (18)$$

where $C_{log}$is logistics cost (USD/t) and $\dot{m}_{ann}$is annual throughput (t/yr).

2.5.2. Levelized cost of electricity (LCOE)

LCOE is computed using discounted cash flow:

$$LCOE = \frac{\sum_{t=1}^{N} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{N} \frac{E_t}{(1+r)^t}} \qquad (19)$$

where $C_t$includes OPEX, logistics, and replacements/overhauls; $E_t$is net electricity in year t; $N$is project lifetime; and $r$is discount rate.

2.5.3. Net present value (optional)

$$V = \sum_{t=0}^{N} \frac{(R_t - C_t)}{(1+r)^t}$$

where $R_t$includes electricity sales and any by-product revenue (e.g., digestate credit where applicable) [17-19].

2.6. Sensitivity Analysis

A one-at-a-time sensitivity analysis is conducted on the dominant feasibility drivers for small-scale WtE: CF, installed capital cost $CAPEX$, feedstock logistics C_{log}, moisture content MC(thermochemical routes), methane fraction x_{CH_4}(AD), auxiliary fraction f_{aux}, and conversion efficiencies η_{CGE}, η_{ICE}, η_{ORC}, and $\eta_{bg,e}$. Sensitivity outputs are reported as changes in Y_{el}, η, and LCOE relative to the base case, reflecting documented scale dependence for CHP/ORC and operational constraints for gasification and AD systems [10], [14-19].

2.7. Data Sources and Parameter Justification (Traceability)

Model parameters were obtained from: peer-reviewed literature and established technical references for conversion performance and operational constraints, and scenario assumptions selected within literature-supported ranges to form a harmonized base case for comparative analysis. Thermochemical conversion principles and typical performance bounds were guided by Basu's standard gasification reference [9]. Gasification reliability constraints particularly tar formation and its impacts on producer-gas quality and engine protection were informed by foundational and review literature on tar formation and mitigation [10], [11], [13]. These sources justified the explicit inclusion of auxiliary load fractions and conservative availability treatment for the gasification pathway because tar control affects downtime and O&M intensity [10], [11], [13]. For combustion ORC, boiler efficiency and CHP configuration assumptions were guided by the U.S. EPA biomass CHP technology catalogue [14], while ORC efficiency ranges and small-scale feasibility were informed by ORC techno-economic surveys and reviews emphasizing scale and heat-source temperature sensitivity [15], [16]. Accordingly, CHP heat utilization is explicitly modeled through E_(th,useful)and overall efficiency (15). For AD, methane fraction assumptions and biogas energy relationships follow widely cited biogas literature [17], digestion process behavior follows digestion fundamentals [18], and co-digestion impacts are parameterized using evidence that substrate blending improves stability and methane yield [19]. Feedstock selection and characterization for Nigeria were supported using cassava waste literature [6], Nigeria-focused rice husk characterization [7], and palm kernel shell/palm residue studies for thermochemical fuels [22], [23]. Economic inputs (CAPEX/OPEX ranges, discount rate, and capacity factor bounds) were treated as scenario parameters due to strong site- and vendor-dependence of small-scale WtE costs. The base-case values were selected within literature-consistent ranges and subjected to sensitivity analysis to quantify uncertainty and identify dominant drivers of LCOE and feasibility [14-19].

Figure 1 Conceptual framework for comparative assessment of small-scale agricultural WtE pathways in Nigeria

2.8. Model Tables

Table 1 Technical Model Parameters (Energy Model Inputs)

Parameter	Symbol	Unit	Range used	Key references
Moisture content (dry residues)	MC	–	0.10–0.20	[7], [22], [23]
Moisture content (wet wastes)	MC	–	0.70–0.90	[6], [17-19]

Dry-basis LHV (rice husk)	LHV_{dry}	MJ/kg	13–18	[7]
Dry-basis LHV (PKS)	LHV_{dry}	MJ/kg	18–24	[22], [23]
Boiler efficiency	η_{boiler}	–	0.75–0.88	[14]
ORC efficiency	η_{ORC}	–	0.08–0.18	[15], [16]
Cold gas efficiency	η_{CGE}	–	0.60–0.75	[9]
ICE efficiency (producer gas)	η_{ICE}	–	0.20–0.30	[9], [10]
Biogas engine efficiency	$\eta_{bg,e}$	–	0.28–0.40	[17-19]
Methane fraction	x_{CH_4}	–	0.50–0.65	[17]
Auxiliary fraction (gasification)	f_{aux}	–	0.08–0.15	[10], [11], [13]
Auxiliary fraction (ORC)	f_{aux}	–	0.05–0.10	[14 -16]
Auxiliary fraction (AD)	f_{aux}	–	0.06–0.12	[17-19]

Table 2 Economic Parameters (TEA Inputs)

Parameter	Symbol	Unit	Range used
Project lifetime	N	years	15–20
Discount rate (real)	r	–	0.10–0.18
CAPEX (gasification–ICE)	$CAPEX$	USD/kW	2500–5000
CAPEX (combustion–ORC)	$CAPEX$	USD/kW	3000–7000
CAPEX (AD–biogas)	$CAPEX$	USD/kW	3000–6000
Fixed O&M	C_{FOM}	% of CAPEX/yr	4–8
Variable O&M	C_{VOM}	USD/kWh	0.005–0.030
Feedstock logistics	C_{log}	USD/t	5–20

Table 3 Base-Case Technical Inputs

Parameter	Unit	Gasification–ICE	Combustion–ORC	AD–Biogas engine
Feedstock type	–	Rice husk/PKS (dry)	Rice husk/PKS (dry)	Cassava waste + manure (wet)
Moisture content MC	–	0.12	0.15	0.85
LHV_{dry}	MJ/kg	15.0	15.0	–
Methane fraction x_{CH_4}	–	–	–	0.60
η_{CGE}	–	0.70	–	–
η_{ICE}	–	0.26	–	–
η_{boiler}	–	–	0.82	–
η_{ORC}	–	–	0.12	–
$\eta_{bg,e}$	–	–	–	0.35
Auxiliary fraction f_{aux}	–	0.12	0.08	0.10
Heat utilization fraction f_{heat}	–	0.20	0.40	0.15

Table 4 Base-Case Scale and Operating Conditions

Parameter	Unit	Gasification–ICE	Combustion–ORC	AD–Biogas
Net electrical capacity P_{net}	kW	250	300	150
Capacity factor CF	–	0.75	0.75	0.85
Annual net generation E_{ann}	MWh/yr	1642.5	1971.0	1116.9
Lifetime N	years	15	15	15
Discount rate r	–	0.12	0.12	0.12

Table 5 Base-Case Economic Inputs

Parameter	Unit	Gasification–ICE	Combustion–ORC	AD–Biogas
Installed CAPEX	USD/kW	3500	4500	4000
Total CAPEX $CAPEX_{tot}$	USD	875,000	1,350,000	600,000
Fixed O&M C_{FOM}	%/yr	6%	5%	7%
Variable O&M C_{VOM}	USD/kWh	0.010	0.008	0.012
Feedstock logistics C_{log}	USD/t	10	10	8
Digestate credit (base case)	USD/t	–	–	0

Note: Base-case values are scenario assumptions selected within literature-supported ranges and are not claimed as measured plant data; uncertainty is addressed through sensitivity analysis [9], [14-19].

3. Results

3.1. Energy Analysis

Energy outputs were computed using the model equations and the base-case inputs. For thermochemical pathways, as-received fuel energy was determined using the moisture-corrected heating value, then gross electricity was obtained from the conversion chain and reduced by auxiliary consumption to give net exported electricity. For anaerobic digestion, biogas energy was computed from biogas volume and methane fraction, then converted to net electricity using generator efficiency and auxiliary load fraction.

Table 6 Energy Performance Results (Base Case, per tonne as-received)

Metric	Unit	Gasification–ICE	Combustion–ORC	AD–Biogas engine
As-received energy input, E_{in}	kWh/t	3585.3	3440.0	—
Biogas energy, E_{bg}	kWh/t	—	—	537.0
Net electricity yield, Y_{el}	kWh/t	574.2	311.4	169.2
Net electrical efficiency (fuel basis), η_{el}	%	16.0	9.1	—
Net electrical efficiency (biogas basis), $\eta_{el,AD}$	%	—	—	31.5

3.1.1. Energy-flow decomposition (per tonne)

Table 7 Energy Flow Breakdown (Base Case, per tonne as-received)

Pathway	Input energy basis	Prime-mover input (kWh/t)	Gross electricity (kWh/t)	Auxiliary use (kWh/t)	Net electricity (kWh/t)
Gasification–ICE	E_{in}	2509.7 (producer gas)	652.5	78.3	574.2
Combustion–ORC	E_{in}	2820.8 (thermal to ORC)	338.5	27.1	311.4
AD–Biogas engine	E_{bg}	537.0 (biogas)	188.0	18.8	169.2

3.1.2. Moisture sensitivity for thermochemical pathways

Table 8 Effect of Moisture Content on Net Electricity Yield (Thermochemical Routes; LHV_dry=15MJ/kg)

Moisture content, MC	E_{in}(kWh/t)	Gasification–ICE Y_{el}(kWh/t)	Combustion–ORC Y_{el}(kWh/t)
0.08	3779.1	605.3	342.1
0.12	3585.3	574.2	324.6
0.15	3440.0	551.0	311.4
0.20	3197.8	512.2	289.5

3.1.3. Methane fraction sensitivity for anaerobic digestion

Table 9 Effect of Methane Fraction on AD Net Electricity Yield (Base Case V_bg=90Nm^3/t)

Methane fraction, x_{CH_4}	Biogas energy E_{bg}(kWh/t)	Net electricity Y_{el}(kWh/t)
0.50	447.5	141.0
0.60	537.0	169.2
0.65	581.8	183.3

3.1.4. CHP heat results and overall efficiency

Useful heat was computed from the recoverable heat available after electrical conversion at the prime mover stage, multiplied by the base-case heat utilization fraction f_{heat}. For gasification–ICE and AD, recoverable heat was taken as the non-electrical fraction of the prime-mover input energy (producer gas to engine, or biogas to engine). For combustion–ORC, recoverable heat was taken as the post-ORC residual thermal output. Overall efficiency was then calculated as $\eta_{overall} = (E_{el,net} + E_{th,useful})/E_{in}$ for thermochemical routes and $\eta_{overall,AD} = (E_{el,net} + E_{th,useful})/E_{bg}$ for AD.

Table 10 CHP Outputs and Overall Efficiency (Base Case)

Metric	Unit	Gasification–ICE	Combustion–ORC	AD–Biogas engine
Recoverable heat basis	—	Engine waste heat	Post-ORC residual heat	Engine waste heat
Recoverable heat, $E_{th,rec}$	kWh/t	1857.2	2482.3	349.0
Heat utilization fraction, f_{heat}	—	0.20	0.40	0.15
Useful heat, $E_{th,useful}$	kWh/t	371.4	992.9	52.4
Net electricity, $E_{el,net}$	kWh/t	574.2	311.4	169.2

Overall efficiency, $\eta_{overall}$	%	26.4 (fuel basis)	37.9 (fuel basis)	41.3 (biogas basis)

These results show that when useful heat demand exists, combustion–ORC produces the highest overall utilization of the as-received fuel energy under the assumed heat utilization fraction, despite having lower net electricity yield than gasification–ICE. The AD pathway shows high overall utilization when measured on the biogas-energy basis, while its per-tonne useful energy remains constrained by the biogas energy available per tonne of wet feedstock.

3.2. Techno-Economic Analysis

The levelized cost of electricity (LCOE) was computed using discounted cash flow with annual net generation fixed by plant scale and capacity factor. Annual costs include annualized capital cost, fixed O&M, variable O&M, and feedstock logistics.

Table 11 Techno-Economic Results (Base Case)

Metric	Unit	Gasification–ICE	Combustion–ORC	AD–Biogas
LCOE	USD/kWh	0.138	0.175	0.176
Total annual cost	USD/yr	225,999.9	344,772.2	196,319.9

Table 12 Annual Cost Components (Base Case)

Cost item	Unit	Gasification–ICE	Combustion–ORC	AD–Biogas
Annualized CAPEX	USD/yr	128,471	198,213	88,095
Fixed O&M	USD/yr	52,500	67,500	42,000
Variable O&M	USD/yr	16,425	15,768	13,403
Logistics cost	USD/yr	28,604	63,291	52,823
Total annual cost	USD/yr	225,999.9	344,772.2	196,319.9

Table 13 LCOE Sensitivity (±20% from Base Case)

Pathway	Base LCOE	CF −20%	CF +20%	CAPEX −20%	CAPEX +20%	Logistics −20%	Logistics +20%
Gasification–ICE	0.138	0.165	0.119	0.116	0.160	0.134	0.141
Combustion–ORC	0.175	0.209	0.152	0.148	0.202	0.169	0.181
AD–Biogas	0.176	0.205	0.156	0.152	0.199	0.166	0.185

3.3. Base-Case Scenario

3.3.1. Annual feedstock throughput requirement

TABLE 14 Base-Case Annual Throughput Requirement

Metric	Unit	Gasification–ICE	Combustion–ORC	AD–Biogas
Annual net generation, E_{ann}	MWh/yr	1642.5	1971.0	1116.9
Net electricity yield, Y_{el}	kWh/t	574.2	311.4	169.2
Implied annual throughput, $\dot{m}_{ann}$	t/yr	2860	6329	6603

3.3.2. Annual auxiliary electricity requirement

Table 15 Annual Gross Generation and Auxiliary Electricity (Base Case)

Pathway	Net generation (MWh/yr)	Gross generation (MWh/yr)	Auxiliary consumption (MWh/yr)
Gasification–ICE	1642.5	1866.5	224.0
Combustion–ORC	1971.0	2142.4	171.4
AD–Biogas	1116.9	1241.0	124.1

3.3.3. Comparative ranking indicators (model-based)

To add a clearer decision-oriented result, three normalized indicators were computed: cost competitiveness (LCOE), logistics burden (annual throughput), and robustness to availability (relative LCOE increase under CF −20%).

Table 16 Decision Indicators and Rankings (Base Case)

Indicator	Unit	Gasification–ICE	Combustion–ORC	AD–Biogas
LCOE	USD/kWh	0.138 (1st)	0.175 (2nd)	0.176 (3rd)
Annual throughput	t/yr	2860 (1st)	6329 (2nd)	6603 (3rd)
Availability penalty index, Δ_{CF}	%	19.6	19.4	16.5
Net electricity yield	kWh/t	574.2 (1st)	311.4 (2nd)	169.2 (3rd)
Useful heat (CHP), $E_{th,useful}$	kWh/t	371.4 (2nd)	992.9 (1st)	52.4 (3rd)

Here, Δ_{CF} is calculated as $\Delta_{CF} = (LCOE_{CF-20\%} - LCOE_{base})/LCOE_{base} \times 100\%$. The indicators show that gasification ICE is most favorable for electricity-only outcomes under base-case assumptions, combustion ORC is most favorable where useful heat demand exists and can be reliably utilized, and AD's relative strength lies in wet-waste compatibility with a comparatively lower availability penalty index in the tested range.

4. Discussion

4.1. Electricity-Oriented Performance and Technology Trade-Offs

The results demonstrate clear differentiation among the three waste-to-energy pathways when evaluated on an electricity-only basis. Biomass gasification coupled with an internal combustion engine consistently delivers the highest net electricity yield per tonne and the lowest levelized cost of electricity (LCOE) under base-case assumptions. This outcome is primarily driven by the relatively high electrical efficiency achievable in the gasification-ICE conversion chain and the higher energy density of dry agricultural residues compared with wet organic wastes. Despite higher auxiliary electricity consumption associated with gas cleaning and feed handling, gasification-ICE maintains a net advantage due to its superior gross electricity output and lower feedstock throughput requirement per unit of electricity generated. In contrast, direct combustion integrated with an Organic Rankine Cycle exhibits significantly lower net electrical efficiency at the analyzed scale. This reflects the inherent limitation of ORC systems operating on moderate-temperature heat sources, where electrical efficiency is strongly constrained by thermodynamic factors and scale effects. Consequently, combustion-ORC systems require substantially higher feedstock throughput to achieve comparable annual electricity generation, which increases logistics burden and capital intensity. Anaerobic digestion with biogas-to-power demonstrates the lowest net electricity yield per tonne among the evaluated pathways. While the biogas engine itself operates at relatively high electrical efficiency, the overall electricity output is constrained by the limited biogas energy available per tonne of wet feedstock. This structural limitation explains why AD performs less favorably in electricity-only comparisons, despite offering advantages in feedstock compatibility and waste management.

4.2. Influence of Feedstock Quality on Energy Output

Sensitivity analysis confirms that feedstock quality is a dominant driver of energy performance across pathways. For thermochemical systems, increasing moisture content leads to nearly proportional reductions in net electricity yield for both gasification-ICE and combustion-ORC. This behavior highlights the importance of feedstock drying, storage, and seasonal moisture control in Nigerian agricultural contexts, where residues are often exposed to rainfall and high ambient humidity. Although gasification retains a higher absolute electricity yield across the tested moisture range, both thermochemical pathways exhibit similar relative sensitivity, indicating that moisture management is a shared operational challenge rather than a differentiating factor between them. For anaerobic digestion, methane fraction exerts a strong influence on net electricity output. Higher methane content directly increases biogas energy density and net electrical generation, underscoring the importance of substrate selection, co-digestion strategies, and process stability. In practical terms, AD systems deployed in Nigeria would need careful feedstock blending and operational control to sustain methane fractions at the upper end of the tested range to remain competitive.

4.3. Role of Combined Heat and Power Utilization

When useful heat recovery is considered, the comparative ranking of pathways changes substantially. Combustion-ORC achieves the highest overall energy utilization on a fuel basis due to the large quantity of recoverable residual heat and the assumed availability of a stable heat sink. This result confirms that the economic and energetic justification for combustion-ORC at small scale is strongly contingent on effective CHP integration. Without productive heat use, the pathway's low electrical efficiency dominates its performance and undermines its competitiveness. Gasification ICE also benefits from CHP operation, though to a lesser extent, as the quantity of recoverable engine waste heat per tonne is smaller. Anaerobic digestion exhibits high overall efficiency when measured on a biogas-energy basis; however, the absolute quantity of useful heat per tonne remains limited by the low energy density of wet feedstocks. These findings emphasize that CHP viability is highly site-specific and depends on the existence of continuous, year-round thermal demand such as crop drying, parboiling, or agro-industrial process heat.

4.4. Cost Structure and Economic Drivers

The techno-economic results indicate that annualized capital cost and fixed operation and maintenance expenses dominate the LCOE across all pathways. Gasification-ICE benefits from a combination of moderate specific capital cost and high electricity yield per tonne, resulting in the lowest LCOE among the base-case scenarios. Combustion-ORC and AD exhibit similar LCOE values despite differing technical characteristics, reflecting a trade-off between higher capital intensity (combustion-ORC) and higher feedstock throughput and logistics costs (AD). Sensitivity analysis further reveals that capacity factor is the most influential economic parameter for all pathways. A 20% reduction in capacity factor results in approximately 16–20% increases in LCOE, highlighting the critical role of operational reliability and sustained utilization. This finding is particularly relevant in the Nigerian context, where feedstock supply interruptions, maintenance challenges, and grid or demand uncertainty can significantly affect plant availability.

4.5. Feedstock Logistics and Scale Implications

The implied annual feedstock throughput requirements provide important insight into practical deployment constraints. Gasification-ICE requires less than half the annual feedstock mass needed by combustion-ORC and AD to achieve comparable electricity output. Lower throughput reduces risks associated with feedstock collection, transportation, storage, and seasonal variability, which are often decisive factors in decentralized energy projects. Anaerobic digestion, while well suited to wet wastes, requires the highest throughput and exhibits the greatest exposure to logistics costs relative to total annual cost. This characteristic suggests that AD systems are most viable where large, concentrated waste streams already exist such as cassava processing clusters rather than in settings where feedstock must be aggregated over long distances.

4.6. Implications for Decentralized Energy Deployment in Nigeria

Overall, the results indicate that no single pathway is universally optimal. Gasification-ICE emerges as the most attractive option for electricity-focused applications using dry agricultural residues, particularly where minimizing feedstock logistics and achieving competitive electricity costs are priorities. Combustion-ORC becomes favorable only in contexts with reliable and productive heat demand that can justify CHP operation. Anaerobic digestion is best suited to wet organic wastes and applications where waste treatment, sanitation benefits, and process stability are valued alongside energy production. These findings underscore the importance of aligning technology choice with feedstock characteristics, local energy demand profiles, and operational capabilities. For Nigeria's decentralized energy landscape, particularly in agro-industrial and rural settings, such alignment is essential to achieving both technical reliability and economic viability.

5. Conclusion

This study compared three small-scale agricultural waste-to-energy pathways gasification-ICE, combustion-ORC, and anaerobic digestion using a consistent techno-economic and energy analysis framework relevant to Nigeria. Gasification-ICE achieved the highest electricity yield per tonne and the lowest LCOE, making it the most suitable option for electricity-focused applications using dry agricultural residues. Combustion-ORC showed lower electrical efficiency but the highest overall energy utilization when productive heat demand exists, supporting its use in combined heat and power applications. Anaerobic digestion produced lower electricity output per tonne but remains best suited for wet wastes and offers additional waste-management benefits. Overall, the results highlight that effective WtE deployment in Nigeria requires matching technology choice to feedstock characteristics, heat demand, and operational reliability rather than relying on a single pathway for all contexts.

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