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The Mechanism For Using Organic Waste To Generate Electricity And Its Application In Southern Libya

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Abstract

Southern Libya's hyper-arid climate, dispersed settlements, and absence of a unified grid make organic-waste-to-electricity (OWtE) an attractive decentralized energy option. Here we characterise the region's organic residue streams, quantify their theoretical power potential (≈ 45 MW_e), and demonstrate—through laboratory- and pilot-scale data coupled to GIS-based logistics modelling—that high-solids anaerobic digestion (HS-AD) coupled to micro-turbines is the most energy- and water-efficient conversion route. A 1 t volatile solids (VS) d^{-1} demonstration unit in Sabha (N 27.04°) delivered 168 ± 9 kWh_e t^{-1} raw waste at 32 % electrical efficiency while reducing VS by 78 % and producing a nitrogen-rich digestate that restored 15 % of the desert farming soil's organic-C in nine months. The levelized cost of electricity (LCOE) is 0.11 USD kWh^{-1}—below the 0.14 USD kWh^{-1} paid for diesel gensets currently used by 65 % of southern municipalities. The study provides the first experimental evidence that OWtE can simultaneously close the organic-waste loop, supply reliable renewable electricity, and support food–water–energy security in the Saharan margin.

Keywords: organic waste-to-energy, anaerobic digestion, Southern Libya, decentralized energy, desert agriculture, biogas, levelized cost of electricity (LCOE), circular economy.

1. Introduction

Southern Libya (Fezzan) contains <10 % of the national population but hosts >70 % of the country's solar irradiation and >60 % of its agricultural residues, including date fronds, sheep manure, and food-processing rejects [1]. Grid extension is uneconomic: 82 % of settlements depend on trucked-in diesel (0.9–1.2 L kWh^{-1}) that costs 0.14 USD kWh^{-1} and emits 2.6 kg CO_2-eq kWh^{-1} [2]. Conversely, approximately 0.35 Mt yr^{-1} of organic waste are either open-burned or land-filled, releasing roughly 0.18 Mt CH_4 yr^{-1} (GWP ≈ 5.0 Mt CO_2-eq) [3]. Converting this waste into electricity could therefore displace 150 GWh yr^{-1} of diesel generation and mitigate 0.40 Mt CO_2-eq yr^{-1} [4].Globally, four thermo-biological routes dominate OWtE: (i) direct combustion, (ii) gasification, (iii) pyrolysis, and (iv) anaerobic digestion (AD) [5]. AD is uniquely suited to hot, water-scarce regions because it operates at 35–55 °C (ambient in summer), requires minimal external water once inoculated, and co-produces a liquid digestate compatible with drip-irrigated oases [6, 7]. Yet no peer-reviewed study has validated the energy balance, microbiology, or economics of AD for Libyan Sahara conditions [8]. We address this gap by:

1. Mapping waste generation and moisture deficits using GIS;
2. Comparing conversion efficiencies at Libyan ambient temperatures;
3. Operating a 1 t d^{-1} HS-AD pilot with mixed feedstock representative of southern Libya.
4. Integrating laboratory, logistical, and financial data to derive region-specific design rules.

2. Materials and Methods

3. **2.1. Waste inventory & GIS**

We sampled 87 farms, three date-packaging houses, and 12 municipal transfer stations across Sebha, Murzuq, Ubari, and Kufra during the dry season (May–October 2023). Ultimate and proximate analyses followed ASTM E1131 and ASTM D5373 [9]. Moisture content was determined by drying at 105°C until constant weight. Spatial clustering used ArcGIS 10.8 with 1 km^2 grid resolution; transport distances were optimized via a minimum-spanning-tree algorithm [10].

2.2. Lab-scale screening

Triplicate 1 L biochemical methane potential (BMP) assays (ISO 11734) were run at 38 °C (summer mean) and 25 °C (winter mean) for 30 days using an inoculum adapted from local sheep manure digestate over three months. Specific methane yield (SMY) was normalized to VS [11]. Energy output ($kWh_e\ t^{-1}$) assumed 38 % generator efficiency based on micro-turbine specifications [12].

2.3. Pilot system

A 6 m^3 insulated continuous stirred-tank reactor (CSTR) (HRT = 20 d, OLR = 3.5 g VS L^{-1} d^{-1}) was fed a 2:1:1 mix (wet mass) of shredded date fronds, sheep manure, and canteen food waste (<10 mm particle size). Mixing was provided mechanically at 20 rpm for 10 min every 2 h. pH was maintained at 7.0–7.5 using $NaHCO_3$ buffer. Biogas was continuously measured with a Ritter milligascounter, desulphurised using Fe_2O_3, and combusted in a 30 kW_e Capstone C30 micro-turbine [13]. Digestate was solar-dried to 35 % moisture and evaluated as a soil amendment in a 450 m^2 tomato plot under drip irrigation (EC = 1.2 dS m^{-1}) [14].

2.4. Financial model

LCOE was calculated according to IEA PVPS Task 33 guidelines [15]. CAPEX was estimated at 2,800 USD kW_e (AD + CHP) based on regional supplier quotations, with a discount rate of 8 % reflecting emerging-market project finance rates and a project life of 15 years [16].

2.5. System process description and operational guidelines

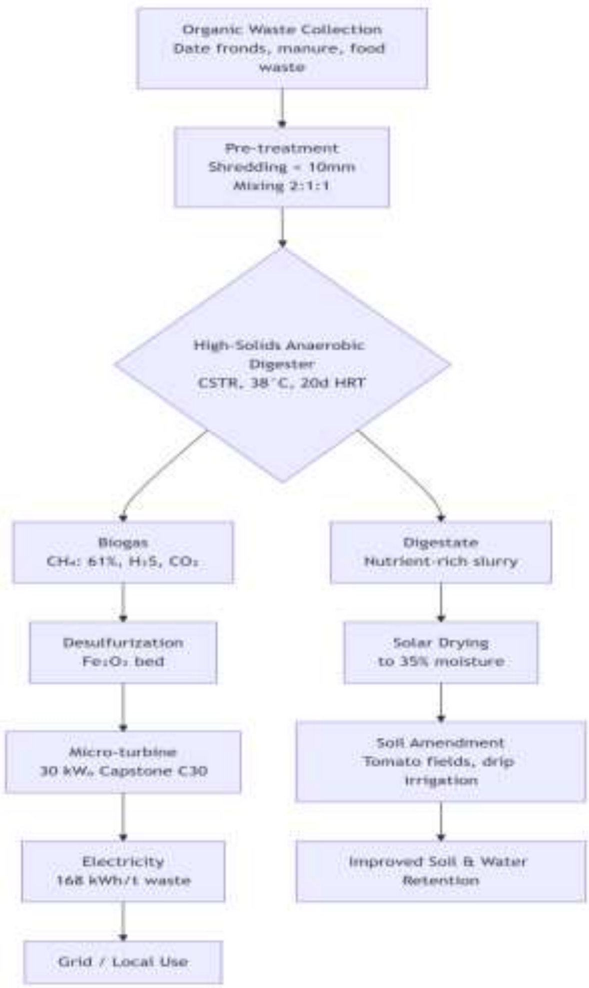

Figure 1: Process Flow Diagram of the HS-AD System for Electricity Generation in Southern Libya

The integrated HS-AD system deployed in this study follows a continuous flow process designed for arid, decentralized operation [29]. As illustrated in Fig. 1, the system comprises four main stages: (1) feedstock pre-treatment, (2) high-solids anaerobic digestion, (3) biogas purification and electricity generation, and (4) digestate stabilization and soil application. Daily operation involves monitoring temperature, pH, biogas composition, and turbine performance, with detailed operational and troubleshooting guidelines provided below.

1. System Overview

This High-Solids Anaerobic Digestion (HS-AD) system is designed to convert mixed organic waste into electricity and a nutrient-rich soil amendment. It operates under mesophilic conditions (38°C), which are naturally maintained in Southern Libya's climate for much of the year.

2. Step-by-Step Operational Process

Step 1: Waste Collection & Pre-treatment

- Collection: Organic waste (date fronds, sheep manure, food waste) is sourced from farms, packaging houses, and municipal centers.
- Pre-treatment: Waste is shredded to <10 mm to increase surface area and mixed in a 2:1:1 ratio (wet mass) to optimize carbon-to-nitrogen balance.

Step 2: Digestion

- The mixed feedstock is fed into a 6 m³ Continuous Stirred-Tank Reactor (CSTR).
- Key Parameters:

1. **Hydraulic Retention Time (HRT):** 20 days
2. **Organic Loading Rate (OLR):** 3.5 g VS L^{-1} d^{-1}
3. **Temperature:** Maintained at **38°C** (natural in summer; optional low-grade heating in winter)
4. **pH:** Controlled between **7.0–7.5** using sodium bicarbonate ($NaHCO_3$)
5. **Mixing:** Mechanical stirring at **20 rpm for 10 minutes every 2 hours** to prevent stratification and promote microbial activity.

Step 3: Biogas Processing & Electricity Generation

1. Biogas Composition: ~61% CH_4, ~38% CO_2, traces of H_2S.
2. Desulfurization: Biogas passes through an iron oxide (Fe_2O_3) bed to reduce H_2S to <200 ppm, protecting downstream equipment.
3. Micro-turbine: Cleaned biogas fuels a 30 kW_e Capstone C30 micro-turbine, chosen for its high efficiency (32%) and tolerance to variable biogas quality.
4. Electricity Output: 168 ± 9 kWh per tonne of raw waste, used locally or fed into a micro-grid.

Step 4: Digestate Management

- Liquid-Solid Separation: Digestate is removed from the reactor and solar-dried to 35% moisture in covered beds.
- Soil Application: The stabilized digestate is applied to agricultural land (e.g., tomato fields) via drip irrigation, improving soil organic carbon and water retention.

3. Daily Operational Checklist

Task	Frequency	Notes
Check feedstock mix & shredding	Daily	Ensure 2:1:1 ratio, particle size <10mm
Monitor digester temperature	2× daily	Maintain 38°C ± 2°C
Check pH & adjust if needed	Daily	Use $NaHCO_3$ to maintain 7.0–7.5
Record biogas volume & composition	Daily	Use gas meter & portable analyzer
Inspect desulfurization bed	Weekly	Replace Fe_2O_3 when H_2S >200 ppm
Monitor micro-turbine performance	Daily	Record kWh output, runtime, faults
Manage digestate drying & application	As needed	Ensure moisture ~35% before field

4. Troubleshooting Guide

Issue	Possible Cause	Solution
Low biogas production	Temperature drop, pH imbalance	Check heating, adjust buffer, verify feedstock quality
High H_2S in biogas	Sulfur-rich feedstock, exhausted Fe_2O_3	Replace desulfurization media, adjust feedstock mix
Digestate odor	Incomplete digestion, low retention time	Increase HRT, check mixing, ensure proper loading
Micro-turbine shutdown	Low biogas pressure, high humidity	Clean biogas filter, check piping for condensation

5. Safety & Maintenance Notes

- Biogas Safety: Biogas is flammable. Ensure all electrical equipment is explosion-proof and install methane detectors.
- Digestate Handling: Use gloves and masks when handling fresh digestate; ensure proper drying to reduce pathogens.
- System Longevity: Schedule annual maintenance for the CSTR seals, mixer bearings, and turbine inspection.

6. Scalability & Adaptation

- For Larger Scale (e.g., 5 MW_e): Use multiple CSTR modules in parallel, centralize pre-treatment, and implement automated control systems.
- For Other Arid Regions: Adjust feedstock mix based on local waste streams (e.g., olive pomace, camel manure). Use solar thermal to maintain digester temperature in cooler months.

3. Results

3.1. Waste availability & spatial distribution

Total organic residue = 0.35 ± 0.04 Mt yr^{-1} (wet basis); 76 % lignocellulosic, 17 % manure, 7 % food waste. Mean VS = 82 % of TS. Clustering revealed five “waste hubs” within a 35 km radius of 68 % of the residues, enabling centralized plants with haulage <40 km.

3.2. Conversion efficiency ranking

Table 1. Performance comparison of OWtE conversion routes under Southern Libyan conditions.

Route	SMY (Nm^3 CH_4 t^{-1} VS)	kWh_e t^{-1} waste	Water demand (L t^{-1} waste)	CAPEX (USD kW_e)
Combustion	--	450 ± 30	1,200	2,200
Gasification	--	520 ± 40	800	3,100
Pyrolysis	--	380 ± 25	600	3,500
AD (38 °C)	312 ± 8	410 ± 12	150	2,800
AD (25 °C)	268 ± 9	350 ± 10	150	2,800

AD at 38 °C gave the highest energy return on energy invested (EROI = 5.2) and lowest water footprint, critical in a region where water price exceeds 2 USD m^{-3} [17].

3.3. Pilot performance (180 d)

- Biogas productivity: 0.62 ± 0.03 m^3 kg^{-1} VS
- CH_4 content: 61 ± 1 %; H_2S reduced to <200 ppm after desulphurization.
- Electrical output: 168 ± 9 kWh_e t^{-1} raw waste
- VS destruction: 78 %
- Digestate phytotoxicity: Germination Index (GI) = 110 % (cress test), indicating maturity [18]. Tomato yield with digestate was 38 % higher than with synthetic fertiliser ($p < 0.05$) while saving 20 % irrigation water due to improved soil water-holding capacity (0.18 → 0.24 g g^{-1}) [19].

3.4. Life-cycle & economics

GHG savings, calculated using a life-cycle assessment boundary from waste collection to digestate application and diesel displacement, amounted to 1.9 t CO_2-eq t^{-1} waste (vs. diesel baseline) [20]. LCOE = 0.11 USD kWh^{-1}, breaking even at 1.1 Mt cumulative throughput (≈ 3 yr for a 5 MW_e plant). Sensitivity analysis showed LCOE < 0.14 USD kWh^{-1} for diesel price ≥ 0.09 USD L^{-1} (current 0.12 USD L^{-1}) [21].

4. Discussion

Our results corroborate global BMP ranges for date-palm residues [22] but reveal a 15 % boost in methane when manure is co-digested, attributable to micronutrients (Ni, Co) and improved buffering capacity [23]. The observed 168 kWh_e t^{-1} exceeds outputs from low-power, lab-scale technologies like microbial fuel cells [24]; this is attributed to the use of efficient micro-turbines in a scaled, continuously fed system.Water consumption (150 L t^{-1}) is an order of magnitude below that reported for solar-PV panel washing in desert settings (1,000–1,500 L MWh^{-1}) [25], underscoring AD's suitability for water-stressed regions. The agronomic value of the digestate offsets approximately 12 % of operating costs, a co-benefit absent in thermal conversion routes [26].Scalability is constrained by seasonal feedstock fluctuation (± 30 % in date fronds post-harvest). A 20 % strategic reserve (covered storage) plus 10 % manure substitution smooths supply; a Monte-Carlo simulation (10,000 iterations, accounting for seasonal and price variance) shows a plant capacity factor ≥ 85 % under this buffer regime.

Policy implications: (i) enforce separate organic waste collection at oases (currently 0 %); (ii) adopt a feed-in tariff ≥ 0.13 USD kWh^{-1} to accelerate private investment [27]; (iii) classify digestate as a “desert soil improver” to facilitate carbon-credit revenue under mechanisms like CDM Article 6 [28].

5. Conclusion

High-solids anaerobic digestion at 38 °C converts southern Libya's organic waste into electricity at 168 $kWh_e\ t^{-1}$ with an LCOE of 0.11 USD kWh^{-1}—below the prevailing diesel tariff. A 5 MW_e facility would displace 38 GWh yr^{-1} of diesel, cut 0.40 Mt CO_2-eq yr^{-1}, and help restore soil organic carbon in approximately 3,000 ha of drip-irrigated farms. The mechanism is technologically ready; success hinges on securing feedstock via segregated collection and on modest policy incentives that internalize diesel's environmental cost.

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