



Journal of Sustainable Engineering & Renewable Energy (JSERE)

VOLUME 2 ISSUE 2 (2026)



PUBLISHED BY
E-PALLI PUBLISHERS, DELAWARE, USA

Co-Digestion Performance of Chicken Droppings, Fruit and Vegetable Wastes, and Slaughterhouse Residues in Biogas Production

Joy Mwendwa Kimathi¹*, Bernard Orori¹, Lazare Etiégni¹

Article Information

Received: July 20, 2026

Accepted: September 26, 2026

Published: October 15, 2026

Keywords

Anaerobic Co-Digestion, Biogas Kinetics, Chicken Droppings, Fruit & Vegetable Waste, Methane Yield, Slaughterhouse Residue

ABSTRACT

Low practical uptake of biogas technology in Kenya is partly linked to limited knowledge of the range of substrates, beyond cattle manure, that can be digested individually or in combination. This study evaluated the co-digestion potential of chicken droppings (CHDR), fruit and vegetable wastes (FRVE) and slaughterhouse residue (SHRS), mixed alone and in binary and ternary combinations (CDFV, CDSH, FVSH, CFVS), for biogas production. Substrate mixtures were characterized for total solids (TS), volatile solids (VS), pH and chemical oxygen demand (COD) before and after digestion. Ten-litre batch digesters, without added inoculum, were monitored for 84 days, with biogas volume measured by water displacement, while parallel two-litre digesters were sampled every six days to quantify methane, carbon dioxide, nitrous oxide, ammonia and water vapour content using a Gasera One analyzer. Biogas yield was modelled using the first-order kinetic and modified Gompertz equations. Co-digestion of chicken droppings and fruit and vegetable wastes (CDFV) produced the most favourable substrate characteristics (near-neutral pH of 6.98, COD of 54,559 mg/L) and the highest cumulative biogas volume (28,856 mL), significantly outperforming all other mixtures ($p < 0.0001$) except SHRS, which ranked second (17,517 mL). The ternary mixture (CFVS) produced the least biogas (4,119 mL). The first-order model fitted CHDR, CDSH, and FVSH best ($R^2 = 0.87$ – 0.96 ; RMSE = 1.29–2.95 L), while the modified Gompertz model captured the extended lag phase evident in SHRS (11.2 days). SHRS produced the highest methane concentration (774,246 ppm), whereas FVSH produced the least. These findings identify chicken droppings/fruit-and-vegetable-waste co-digestion as the most promising combination for biogas volume, and slaughterhouse residue as the best source of methane-rich biogas, offering practical substrate-selection guidance for small- and medium-scale digester operators.

INTRODUCTION

Biogas offers a route to energy security while diverting organic waste from open dumping, yet its uptake in Kenya remains marginal. Biogas and bagasse together contribute only about 0.01% of the national renewable energy mix, far behind geothermal (44.6%) and hydropower (22.5%) (Lumadede *et al.*, 2021; Mudoga *et al.*, 2021). Slow adoption is largely attributed to limited awareness of which substrates, and which combinations of substrates, are suitable for digestion (Mittal *et al.*, 2018; Ngetuny *et al.*, 2025). Many operators rely almost exclusively on cattle manure; not everyone can own or sustain the cattle needed to feed a digester, so the system is often abandoned (Hamid & Blanchard, 2018).

Anaerobic co-digestion, the simultaneous digestion of two or more substrates, buffers the nutrient and structural limitations of a single feedstock and can raise both the quantity and stability of biogas production (Kipngetich *et al.*, 2018; Reyes *et al.*, 2015; Ćurčić *et al.*, 2025). Kenya's poultry sector alone generates an estimated 3.18 million kilograms of droppings daily (Anyona *et al.*, 2023; Manogaran *et al.*, 2022), while urban markets and abattoirs discard large volumes of fruit and vegetable waste and slaughterhouse residue that could otherwise be valorised (Food and Agriculture Organization of the United Nations [FAO], 2018; Kamau & Waswa,

2025). Slaughterhouse waste in particular has shown higher biogas potential than conventional cattle-manure feedstock (Pratima & Ale, 2016), and converting these residues into biogas can reduce dependence on firewood and charcoal in rural and peri-urban communities (Muhibbu-din *et al.*, 2021).

Despite this potential, no study has systematically compared chicken droppings, fruit and vegetable wastes and slaughterhouse residue, alone and in every binary and ternary combination, for biogas quantity, kinetics and quality. This study therefore evaluated the co-digestion potential of these three substrates with the specific objectives of (i) characterizing the substrate mixtures based on pH, total solids, volatile solids and chemical oxygen demand; (ii) determining biogas quantity with time and fitting first-order and modified Gompertz kinetic models; and (iii) determining the methane, carbon dioxide, nitrous oxide, ammonia and water vapour content of the biogas produced.

MATERIALS AND METHODS

Study area and substrate sourcing

The experiment was conducted in the Department of Forestry and Wood Science laboratories, University of Eldoret; biogas quality was analyzed at the International Centre of Insect Physiology and Ecology (ICIPE),

¹ Department of Forestry and Wood Science, University of Eldoret, P.O. Box 1125-30100, Eldoret, Kenya

* Corresponding author's e-mail: joykimathi639@gmail.com

Nairobi. All substrates were sourced from Uasin Gishu County (1,500–2,700 m a.s.l.; mean temperature 15–21 °C) (Busolo *et al.*, 2023; Nyongesa *et al.*, 2023). Chicken droppings were collected from a poultry farm in Kimumu Ward, fruit and vegetable wastes from Sogomo Market in Soy Ward, and slaughterhouse residue from the main Eldoret slaughterhouse.

Sampling and preparation

Chicken droppings were pooled from multiple cage locations and homogenized by coning and quartering (IUPAC, 2019). Fruit and vegetable wastes were collected from several market waste piles after the weekly market day, composited, sorted and blended into a uniform paste. Slaughterhouse residue was sampled across three separate days at peak slaughter activity to capture natural variation, composited, and held below 4 °C prior to use. All samples were transported to the laboratory in cooler boxes and screened by hand to remove inorganic material.

Experimental design and digester set-up

A completely randomized design was used, with the digesters replicated three times. Ten-litre plastic jerricans, fitted with brass outlet nozzles and sealed with silicone sealant, served as batch digesters operated under ambient laboratory conditions with no external inoculum, following Gomes (2022), to isolate the intrinsic biodegradability of each substrate mixture. Reactors were filled to 18% substrate content, leaving 40% headspace for gas accumulation (Angelidaki *et al.*, 2009; Holliger *et al.*, 2016). Seven treatments were tested (Table 1).

Table 1: Substrate mixtures and mixing ratios

Code	Composition	Mixing ratio
CHDR	Chicken droppings (sole)	100%
FRVE	Fruit and vegetable wastes (sole)	100%
SHRS	Slaughterhouse residue (sole)	100%
CDFV	Chicken droppings + fruit & vegetable wastes	50:50
CDSH	Chicken droppings + slaughterhouse residue	50:50
FVSH	Fruit & vegetable wastes + slaughterhouse residue	50:50
CFVS	Chicken droppings + fruit & vegetable wastes + slaughterhouse residue	33.3:33.3:33.3

Substrate characterization

Total solids and volatile solids were determined gravimetrically by oven drying at 105 ± 2 °C for 24 h and ignition at 550 ± 50 °C for 2 h, respectively (American Public Health Association *et al.*, 2017). PH was measured with a calibrated Hanna Instruments 211 microprocessor pH meter (Tiwari & Mahalpure, 2025). Chemical oxygen demand was determined by the closed reflux titrimetric

method using potassium dichromate digestion (American Public Health Association *et al.*, 2017). All parameters were measured in triplicate before and after digestion.

Measurement of biogas quantity

Biogas was collected every six days over 84 days by downward water displacement into a 2,000 mL graduated jar (Ramjani *et al.*, 2023).

Kinetic modelling

Cumulative biogas production was fitted to the first-order kinetic model (Equation 1) and the modified Gompertz model (Equation 2) (Arifan *et al.*, 2021):

$$V_t = V_m (1 - e^{-kmt}) \quad (1)$$

$$V_t = V_m \cdot \exp\{-\exp[(km \cdot e / V_m)(\lambda - t) + 1]\} \quad (2)$$

Where V_t is cumulative biogas yield at time t (d), V_m is the biogas production potential, km is the rate constant, and λ is the lag phase (d). First-order parameters were estimated by the Fujimoto graphical method and Gompertz parameters by the three-point method (Moharir *et al.*, 2020). Model fit was evaluated using R^2 , adjusted R^2 and root mean square error (RMSE), and predicted versus measured values were compared with paired t-tests.

Biogas quality analysis

Parallel two-litre digesters, prepared identically to the 10 L units, were connected to a Gasera One Ghg & Pulse analyzer (ICIPE, Nairobi) every six days for 8 weeks to quantify methane, carbon dioxide, nitrous oxide, ammonia and water vapour concentrations (ppm) (Omeoga, 2023).

Statistical analysis

Data were analyzed in SAS. One-way ANOVA tested differences in substrate characteristics among mixtures; two-way ANOVA tested the effects of substrate mixture and time on biogas quantity and quality, followed by post-hoc mean separation where significant differences were detected.

RESULTS AND DISCUSSION

Substrate characteristics

Total solids, volatile solids, pH and COD differed significantly among the seven mixtures both before and after digestion ($p < 0.0001$ for TS, VS and COD; $p \leq 0.001$ for pH; Table 2). CHDR had the highest TS (30.05%) and CFVS the highest VS (96.28%) before digestion, while CDFV and SHRS achieved the greatest TS conversion (8.56% and 7.66%, respectively). CDFV recorded the highest initial COD (54,559 mg/L) and the largest COD reduction (73.9%). CDFV attained a near-neutral pH of 6.98, while FRVE and FVSH were acidic before digestion (pH 4.23 and 6.08, respectively) and became more acidic afterwards (3.44 and 4.31); SHRS was the only mixture whose pH rose after digestion (6.98 to 7.20), remaining near neutral to slightly alkaline.

Table 2: Substrate characteristics before and after biogas production

Mixture	TS before (%)	TS after (%)	VS before (%)	VS after (%)	COD before (mg/L)	COD after (mg/L)	COD reduction (%)	pH before	pH after
CHDR	30.05	24.45	78.82	74.75	52,041	29,429	43.5	7.56	5.49
FRVE	14.80	8.31	95.47	88.82	47,232	22,184	53.0	4.23	3.44
SHRS	20.14	12.48	88.84	78.05	54,292	19,129	64.8	6.98	7.20
CDFV	18.99	10.43	91.39	79.21	54,559	14,233	73.9	6.98	4.48
CDSH	23.45	20.29	92.39	90.74	48,036	38,622	19.6	7.43	5.10
FVSH	16.87	11.57	94.26	92.33	50,786	38,803	23.6	6.08	4.31
CFVS	20.15	18.39	96.28	94.84	51,639	44,557	13.7	6.90	4.83

Quantity and rate of biogas production

Biogas volume differed significantly by substrate mixture and by time ($p < 0.0001$ for both; Table 3, Figures 1–2). CDFV produced the highest cumulative volume (28,856 mL) and was statistically distinct from all mixtures except SHRS, which ranked second (17,517 mL). CHDR ranked third (13,242 mL), followed by FRVE (9,892 mL), CDSH (5,806 mL) and FVSH (5,298 mL); the ternary mixture CFVS produced the least biogas (4,119 mL) and ceased production earliest, by day 24. CDFV and FRVE peaked within the first six days (10,653 mL and 8,560 mL, respectively) before plateauing, whereas SHRS showed an extended lag before peaking on day 48 (535.5 mL/day) and continued producing gas through day 84, the only mixture to do so.

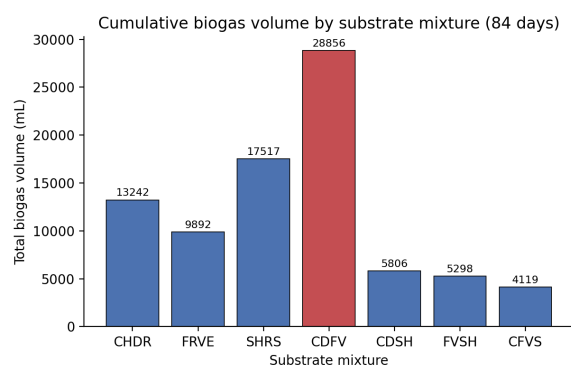


Figure 1: Cumulative biogas volume by substrate mixture over 84 days

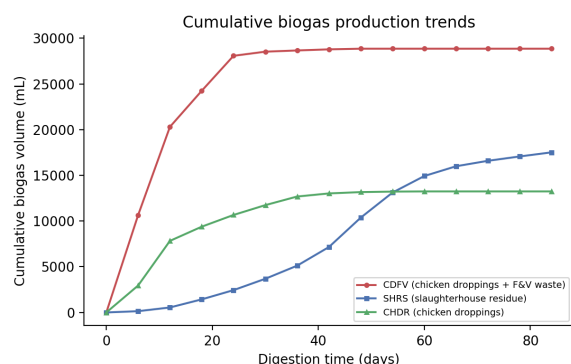


Figure 2: Cumulative biogas production trends for the three highest-yielding mixtures

Kinetics of biogas production

The first-order kinetic model described biogas production well for six of the seven mixtures ($R^2 = 0.86$ – 0.96 ; Table 4), with the tightest fit for CHDR ($R^2 = 0.96$) and the weakest for CDFV ($R^2 = 0.86$, RMSE = 5.07 L); the model could not describe SHRS because of its pronounced lag phase. The modified Gompertz model produced generally weaker fits ($R^2 = 0.36$ – 0.80) but was the only model able to capture SHRS's extended lag ($\lambda = 11.2$ d) and provided the closest fit for CHDR ($R^2 = 0.80$). FRVE showed the shortest lag phase ($\lambda = 0.83$ d) and among the highest rate constants, consistent with its rapid, short-lived production, while SHRS had the longest lag phase, reflecting the slower hydrolysis of its more fibrous, lignocellulosic composition. Predicted and measured cumulative volumes differed significantly for all mixtures examined ($p \leq 0.04$ – 0.0001), with both models tending to underestimate early-phase gas production.

Table 3: Total biogas volume produced by substrate mixture over 84 days

Mixture	Total volume (mL)	Peak day	Production ceased (day)
CDFV	28,856	6	54
SHRS	17,517	48	84 (ongoing)
CHDR	13,242	12	60
FRVE	9,892	6	30
CDSH	5,806	6	72
FVSH	5,298	6	42
CFVS	4,119	6	24

Biogas quality

Methane concentration differed significantly among mixtures ($p = 0.001$) but not among time intervals ($p = 0.592$). SHRS produced by far the highest total methane (774,246 ppm), followed by CDSH (324,803 ppm); CFVS, CDFV, CHDR and FRVE formed a statistically

Table 4: Kinetic parameters for biogas production

Mixture	First-order Vm (L)	First-order km (d ⁻¹)	First-order R ²	Gompertz Vm (L)	Gompertz km (d ⁻¹)	Gompertz λ (d)	Gompertz R ²
CHDR	13.20	0.05	0.96	15.36	0.32	4.30	0.80
FRVE	9.80	0.15	0.92	9.94	0.04	0.83	0.36
SHRS	-	-	-	17.82	0.72	11.20	0.61
CDFV	28.80	0.04	0.86	28.86	0.44	6.00	0.53
CDSH	5.80	0.03	0.91	5.83	0.05	7.20	0.64
FVSH	5.30	0.03	0.87	5.51	0.08	7.50	0.62
CFVS	4.10	0.09	0.91	4.20	0.12	3.80	0.39

similar mid-range group, while FVSH produced the least methane (10,236 ppm; Table 5). Carbon dioxide production varied significantly with time ($p = 0.013$) but not among mixtures ($p = 0.729$), with CDSH recording the highest total (205,868 ppm). Nitrous oxide did not differ significantly among mixtures ($p = 0.502$) but varied significantly with time ($p = 0.001$), peaking during days 7–12; CFVS recorded

the highest cumulative concentration (9,976 ppm), driven by an anomalous spike on day 43–48. Ammonia concentration differed significantly among mixtures ($p = 0.001$), with FRVE far exceeding all others (2,292 ppm) while CHDR recorded the least (24 ppm). Water vapour differed significantly by both time ($p = 0.004$) and mixture ($p = 0.022$), with SHRS highest (124,720 ppm) and FRVE showing none.

Table 5: Total biogas quality parameters by substrate mixture over 8 weeks (ppm). Values in parentheses are the six-day intervals (days) in which each gas peaked

Mixture	Methane	Carbon Dioxide	Nitrous Oxide	Ammonia	Water Vapour
CHDR	115,126 (days 31–36)	109,704 (days 25–30)	342 (days 0–6)	24 (days 31–36)	68,133 (days 31–36)
FRVE	44,568 (days 7–12)	161,381 (days 25–30)	225 (days 0–6)	2,292 (days 0–6)	0 (none)
SHRS	774,246 (days 7–12)	119,481 (days 43–48)	276 (days 0–6)	66 (days 13–18)	124,719 (days 13–18)
CDFV	121,057 (days 25–30)	98,030 (days 19–24)	442 (days 7–12)	276 (days 25–30)	113,982 (days 31–36)
CDSH	324,803 (days 37–42)	205,868 (days 31–36)	214 (days 7–12)	83 (days 0–6)	85,026 (days 37–42)
FVSH	10,236 (days 43–48)	127,552 (days 43–48)	471 (days 0–6)	543 (days 43–48)	32,147 (days 31–36)
CFVS	175,950 (days 13–18)	167,472 (days 19–24)	9,976 (days 43–48)	61 (days 13–18)	47,702 (days 37–42)

Discussion

Co-digestion of chicken droppings and fruit and vegetable wastes produced the largest volume of biogas, consistent with earlier work reporting yield improvements of up to 31% when poultry manure was co-digested with municipal waste (Bres *et al.*, 2018) and with findings that a 50:50 chicken manure and food waste ratio maximizes biogas output (Mat Saad *et al.*, 2019). Co-digestion of these substrates appears to introduce complementary microbial populations that stabilize digestion and raise methane output (Ayantokun *et al.*, 2025); the resulting near-neutral pH (6.98) and high COD reduction (73.9%) in this study, higher than the 56.8% reduction reported for chicken manure and wheat straw co-digestion (Ahmad *et al.*, 2024), reflect this synergy. Slaughterhouse residue was the second-best biogas

producer, aided by high volatile solids content (88.84%), comparable to rumen waste values reported elsewhere (86.83%; Ihoeghian *et al.*, 2022). Native microorganisms in rumen material readily hydrolyze lignocellulosic biomass into volatile fatty acids that are subsequently converted to methane (Günel *et al.*, 2025), and the near-neutral to slightly alkaline conditions (pH 6.98–7.20) sustained throughout digestion in this study mirror earlier observations for rumen-derived waste (Omondi *et al.*, 2019). This pH stability, together with a pronounced lag phase (11.2 days) and continued gas production beyond day 84, is consistent with the slower breakdown of fibrous, lignocellulosic material relative to more readily degradable substrates (Shi *et al.*, 2017; Sarker *et al.*, 2019). Mono-digested chicken droppings ranked third, supported by an alkaline initial pH (7.56, comparable

to 7.80 reported by Buivydas *et al.*, 2022) and high total solids (30.05%, comparable to 22.5% reported by Miah *et al.*, 2016); production without added inoculum corroborates earlier findings that chicken manure can be digested successfully without inoculum addition (Wedwitschka *et al.*, 2020). Fruit and vegetable waste alone was more moderate, its acidic pH reflecting rapid acidification that can suppress microbial activity despite abundant volatile matter (Kalogiannis *et al.*, 2024).

Both remaining binary mixtures (CDSH, FVSH) and the ternary mixture (CFVS) underperformed their constituent mono-digested substrates. This is consistent with reports that mono-digestion of chicken manure can outperform its co-digestion with other wastes (Mapenzauswa *et al.*, 2024), likely because combining high nitrogen substrates raises ammonia concentrations that inhibit methanogenesis and allow acetate and propionate to accumulate, depressing pH further (Chen *et al.*, 2016). The lowest overall yield, from the ternary mixture, coincides with volatile solids concentrations above 75% across the combined substrates; overly concentrated organic loading can impair mixing and microbe-substrate contact, stalling digestion (Nkuna *et al.*, 2022).

Most mixtures peaked within the first six days, broadly matching a 2–5-day peak reported elsewhere (Kabaivanova *et al.*, 2022), reflecting the ready hydrolysis of starches and sugars relative to slower degrading fibrous material (Sarker *et al.*, 2019). SHRS methane output was correspondingly the highest recorded (774,246 ppm), consistent with reports that methane yield rises with the proportion of ruminal residue in a mixture (Meneses Queral & Pilamunga Hurtado, 2023), reflecting the cellulose degrading, volatile-fatty-acid-to-methane conversion capacity associated with ruminant-derived microbial communities (Karekar *et al.*, 2022). Low carbon dioxide relative to methane in SHRS suggests digestion progressed fully to the methanogenic stage, while negligible nitrous oxide and ammonia indicate minimal risk to biogas quality or downstream equipment (Werkneh, 2022; Angelidaki *et al.*, 2018).

The first-order kinetic model provided the better statistical fit overall (higher R^2 , lower RMSE) for CHDR, CDSH and FVSH, while the modified Gompertz model, though generally weaker, was the only model able to describe SHRS because it explicitly estimates a lag phase (Moharir *et al.*, 2020). The short lag phase and high rate constant recorded for fruit and vegetable waste (0.83 d), close to the 0.87 d reported for sugarcane peels (Abdulkhakeem & Lawal, 2020), point to a shorter required retention time and, correspondingly, the potential for smaller digester volumes when this substrate is used. Conversely, the extended lag recorded for slaughterhouse residue reflects the microbial acclimation period needed for lignocellulosic material (Veluchamy *et al.*, 2021), consistent with the general pattern that fibrous residues require longer retention for maximal biogas output (Shi *et al.*, 2017).

CONCLUSION

Co-digestion of chicken droppings with fruit and vegetable wastes produced the most favourable substrate characteristics (near-neutral pH, high organic content) and the highest biogas volume, with production beginning immediately and peaking within six days. Slaughterhouse residue, despite an extended lag phase, was the second-best volume producer and generated by far the highest methane concentration, making it the preferred substrate where biogas quality (energy content) is the priority. The first-order kinetic model gave the most reliable prediction of biogas volume for most mixtures, while the modified Gompertz model was necessary to capture the lag-phase behaviour of slaughterhouse residue.

Based on these findings, we recommend: (i) adopting chicken droppings-fruit and vegetable waste co-digestion where maximizing biogas volume is the priority, and slaughterhouse residue where high methane content is required; (ii) tapping biogas during the second week of digestion, when production is typically highest; (iii) further studies on alternative mixing ratios of chicken droppings and fruit and vegetable waste, on practical methods for reducing carbon dioxide and water vapour content in co-digested biogas, and on full-scale digester trials to confirm these laboratory-scale findings under field conditions; and (iv) further work on the purification, compression and containment of raw biogas to support its use as a commercialized energy product.

REFERENCES

- Abdulkhakeem, N. H., & Lawal, A. (2020). Kinetics of anaerobic co-digestion of paunch manure and sugarcane peels using cow dung as inoculum. *Arid Zone Journal of Engineering, Technology and Environment*.
- Ahmad, R. M., Javied, S., Aslam, A., Alamri, S., Zaman, Q. uz, Hassan, A., & Noor, N. (2024). Optimizing biogas production and digestive stability through waste co-digestion. *Sustainability*, 16(7), 3045. <https://doi.org/10.3390/SU16073045>
- American Public Health Association, American Water Works Association, & Water Environment Federation. (2017). Standard methods for the examination of water and wastewater (23rd ed.). *American Public Health Association*.
- Angelidaki, I., Alves, M., Bolzonella, D., Borzacconi, L., Campos, J. L., Guwy, A. J., Kalyuzhnyi, S., Jenicek, P., & van Lier, J. B. (2009). Defining the biomethane potential (BMP) of solid organic wastes and energy crops: A proposed protocol for batch assays. *Water Science and Technology*, 59(5), 927–934. <https://doi.org/10.2166/wst.2009.040>
- Angelidaki, I., Treu, L., Tsapekos, P., Luo, G., Campanaro, S., Wenzel, H., & Kougias, P. G. (2018). *Biogas upgrading and utilization: Current status and perspectives. Biotechnology Advances*, 36(2), 452–466. <https://doi.org/10.1016/j.biotechadv.2018.01.011>
- Anyona, D. N., Musyoka, M. M., Ogolla, K. O., Chemuliti,

- J. K., Nyamongo, I. K., & Bukachi, S. A. (2023). Characterization of indigenous chicken production and related constraints: Insights from smallholder households in rural Kenya. *Scientific African*, 20, e01717. <https://doi.org/10.1016/J.SCIAF.2023.E01717>
- Arifan, F., Abdullah, A., & Sumardiono, S. (2021). Kinetic study of biogas production from animal manure and organic waste in Semarang City by using anaerobic digestion method. *Indonesian Journal of Chemistry*, 21(5), 1221. <https://doi.org/10.22146/ijc.65056>
- Ayantokun, A. S., Matambo, T. S., Rashama, C., Van der Merwe, I., & Van Niekerk, J. A. (2025). A critical review of food waste and poultry manure anaerobic co-digestion: An eco-friendly valorization for sustainable waste management and biogas production. *Frontiers in Sustainable Food Systems*, 9, 1695945. <https://doi.org/10.3389/FSUFS.2025.1695945>
- Bres, P., Beily, M. E., Young, B. J., Gasulla, J., Butti, M., Crespo, D., Candal, R., & Komilis, D. (2018). Performance of semi-continuous anaerobic co-digestion of poultry manure with fruit and vegetable waste and analysis of digestate quality: A bench scale study. *Waste Management*, 82, 276–284. <https://doi.org/10.1016/J.WASMAN.2018.10.041>
- Buivydas, E., Navickas, K., Venslauskas, K., Žalys, B., Župerka, V., & Rubežius, M. (2022). Biogas production enhancement through chicken manure co-digestion with pig fat. *Applied Sciences*, 12(9), 4652. <https://doi.org/10.3390/app12094652>
- Busolo, T. A., Koech, M. K., & Wemali, E. (2023). Climate variability adaptation strategies used by small-scale maize farmers in Uasin Gishu County, Kenya. *African Journal of Climate Change and Resource Sustainability*, 2(1), 153–170. <https://doi.org/10.37284/ajccrs.2.1.1400>
- Chen, H., Wang, W., Xue, L., Chen, C., Liu, G., & Zhang, R. (2016). Effects of ammonia on anaerobic digestion of food waste: Process performance and microbial community. *Energy & Fuels*, 30(7), 5749–5757. <https://doi.org/10.1021/acs.energyfuels.6b00715>
- Ćurčić, S., Miličević, D., Kilibarda, N., & Peulić, A. (2025). Assessing biogas production potential from organic waste and livestock byproducts in a Serbian municipality: Implications for sustainable food systems. *Sustainability*, 17(7), 3144. <https://doi.org/10.3390/SU17073144>
- Food and Agriculture Organization of the United Nations. (2018). *The state of food and agriculture 2018: Migration, agriculture and rural development*.
- Günel, G., İnce, O., Uzun, Ö., Erdem, E. I., & İnce, B. (2025). Enhancing biomethane production from cattle manure by integrating rumen bacteria: A microbial analysis with next-generation sequencing and quantitative PCR. *Biomass Conversion and Biorefinery*, 15(23), 30359–30373. <https://doi.org/10.1007/S13399-025-06783-3>
- Hamid, R. G., & Blanchard, R. E. (2018). An assessment of biogas as a domestic energy source in rural Kenya: Developing a sustainable business model. *Renewable Energy*, 121, 368–376. <https://doi.org/10.1016/J.RENENE.2018.01.032>
- Holliger, C., Alves, M., Andrade, D., Angelidaki, I., Astals, S., Baier, U., Bougrier, C., Buffière, P., Carballa, M., de Wilde, V., Ebertseder, F., Fernández, B., Ficarra, E., Fotidis, I., Frigon, J.-C., de Lacroix, H. F., Ghasimi, D. S. M., Hack, G., Hartel, M., . . . Wierinck, I. (2016). Towards a standardization of biomethane potential tests. *Water Science and Technology*, 74(11), 2515–2522. <https://doi.org/10.2166/wst.2016.336>
- Ihoeghian, N. A., Amenaghawon, A. N., Ajieh, M. U., Oshoma, C. E., Ogofure, A., Erhunmwunse, N. O., Edosa, V. I. O., Tongo, I., Obuekwe, I. S., Isagba, E. S., et al. (2022). Anaerobic co-digestion of cattle rumen content and food waste for biogas production: Establishment of co-digestion ratios and kinetic studies. *Bioresource Technology Reports*, 18, 101033. <https://doi.org/10.1016/j.biteb.2022.101033>
- IUPAC. (2019). Coning and quartering. In *The IUPAC compendium of chemical terminology*. International Union of Pure and Applied Chemistry. <https://doi.org/10.1351/goldbook.C01265>
- Kabaivanova, L., Petrova, P., Hubenov, V., & Simeonov, I. (2022). Biogas production potential of thermophilic anaerobic biodegradation of organic waste by a microbial consortium identified with metagenomics. *Life*, 12(5), 702. <https://doi.org/10.3390/LIFE12050702>
- Kalogiannis, A., Diamantis, V., Eftaxias, A., & Stamatelatou, K. (2024). Long-term anaerobic digestion of seasonal fruit and vegetable waste using a leach-bed reactor coupled to an upflow anaerobic sludge bed reactor. *Sustainability*, 16(1), 50. <https://doi.org/10.3390/SU16010050>
- Kamau, M. J., & Waswa, G. A. (2025). *Sustainable management of organic waste in municipalities: Pathways to bio-energy, bio-fertilizer production, and climate action*. South Eastern Kenya University Repository. <http://repository.seku.ac.ke/xmlui/handle/123456789/8063>
- Karekar, S., Stefanini, R., & Ahring, B. (2022). Homo-acetogens: Their metabolism and competitive relationship with hydrogenotrophic methanogens. *Microorganisms*, 10(2), 397. <https://doi.org/10.3390/MICROORGANISMS10020397>
- Kipnetich, L., Njogu, P., & Kamau, J. (2018). Biogas energy potential from co-digestion of avocado pulp with cow manure in Kaitui Location, Kericho County, Kenya. *International Research Journal of Innovations in Engineering and Technology*, 2, 28–34.
- Lumadede, H. M., Wangai, L. K., & Khalifa, J. (2021). Biogas technology in Kenya: A review. *Journal of Environmental Science, Computer Science and Engineering & Technology*, 10(3). <https://doi.org/10.24214/ijecet.A.10.3.36981>
- Manogaran, M. D., Shamsuddin, R., Mohd Yusoff, M. H., Lay, M., & Siyal, A. A. (2022). A review on treatment processes of chicken manure. *Cleaner and Circular*

- Bioeconomy*, 2, 100013. <https://doi.org/10.1016/J.CLCB.2022.100013>
- Mapenzauswa, C. F., Hoko, Z., & Misi, S. (2024). Optimization of substrate mixing ratios for the anaerobic digestion of chicken manure and slaughterhouse waste: A case study of Irvine's Zimbabwe (Pvt) Ltd, Zimbabwe. *Biofuels*, 15(1), 47–56. <https://doi.org/10.1080/17597269.2023.2216955>
- Mat Saad, M. F., Abdul Rahman, N. A., & Mohd Yusoff, M. Z. (2019). Hydrogen and methane production from co-digestion of food waste and chicken manure. *Polish Journal of Environmental Studies*, 28(4), 2805–2814. <https://doi.org/10.15244/pjoes/83670>
- Meneses Quelal, O., & Pilamunga Hurtado, D. (2023). Anaerobic fermentation of slaughterhouse waste - Codigestion with wheat straw to determine methane biochemical potential and kinetic analysis. *Fermentation*, 9(8), 726. <https://doi.org/10.3390/FERMENTATION9080726>
- Miah, M. R., Rahman, A. K. M. L., Akanda, M. R., Pulak, A., & Rouf, M. A. (2016). Production of biogas from poultry litter mixed with the co-substrate cow dung. *Journal of Taibah University for Science*, 10(4), 497–504. <https://doi.org/10.1016/j.jtusci.2015.07.007>
- Mittal, S., Ahlgren, E. O., & Shukla, P. R. (2018). Barriers to biogas dissemination in India: A review. *Energy Policy*, 112, 361–370. <https://doi.org/10.1016/j.enpol.2017.10.027>
- Moharir, S., Bondre, A., Vaidya, S., Patankar, P., Kanaskar, Y., & Karne, H. (2020). Comparative analysis of the amount of biogas produced by different cultures using the modified Gompertz model and logistic model. *European Journal of Sustainable Development Research*, 4(4), em0141. <https://doi.org/10.29333/ejosdr/8550>
- Mudoga, H. L., Mbithi, V. A., Kwach, S., & Wangai, L. (2021). Biogas technology in Kenya: A review. *Journal of Environmental Science, Computer Science and Engineering & Technology*, 10(3). <https://doi.org/10.24214/jecet.A.10.3.36981>
- Muhibbu-din, I., Adebayo, G., Odedele, S., & Ajibulu, O. O. (2021). Review on environmental effect of biogas production. *Malaysian Journal of Applied Sciences*, 6(2), 93–104. <https://doi.org/10.37231/MYJAS.2021.6.2.290>
- Ngetuny, J., Baldauf, T., & Zörner, W. (2025). Optimizing feedstock selection for sustainable small-scale biogas systems using the analytic hierarchy process. *Energies*, 18(7), 1739. <https://doi.org/10.3390/EN18071739>
- Nkuna, R., Roopnarain, A., Rashama, C., & Adeleke, R. (2022). Insights into organic loading rates of anaerobic digestion for biogas production: A review. *Critical Reviews in Biotechnology*, 42(4), 487–507. <https://doi.org/10.1080/07388551.2021.1942778>
- Nyongesa, G. M., Makokha, G., & Mbuthia, S. (2023). The extent to which rainfall variability has affected small-scale dairy farmers in Uasin-Gishu County, Kenya. *International Journal of Research and Innovation in Social Science*, 7(10), 1319–1338. <https://doi.org/10.47772/ijriss.2023.701102>
- Omeoga, U. N. (2023). *Reduction of greenhouse gas emissions using biochar and wood residues* [Unpublished manuscript].
- Omondi, E. A., Njuru, P. G., & Ndiba, P. K. (2019). Anaerobic co-digestion of water hyacinth (*E. crassipes*) with ruminal slaughterhouse waste for biogas production. *International Journal of Renewable Energy Development*, 8(3), 253–259. <https://doi.org/10.14710/ijred.8.3.253-259>
- Pratima, K., & Ale, B. (2016). Production of biogas from slaughterhouse waste in Lalitpur Sub-metropolitan City. *Journal of the Institute of Engineering*.
- Ramjani, S. A., Gunasekar, J. J., & Ramachandran, J. (2023). Evaluation of biogas production potential from waste coconut water. *International Journal of Environment and Climate Change*, 13(12), 1383–1391. <https://doi.org/10.9734/IJECC/2023/V13I123863>
- Reyes, I. P., Díaz, J. P., & Horváth, I. S. (2015). Anaerobic biodegradation of solid substrates from agroindustrial activities - Slaughterhouse wastes and agrowastes. In *Biodegradation and bioremediation of polluted systems - New advances and technologies*. InTech. <https://doi.org/10.5772/60907>
- Sarker, S., Lamb, J. J., Hjelme, D. R., & Lien, K. M. (2019). A review of the role of critical parameters in the design and operation of biogas production plants. *Applied Sciences*, 9(9), 1915. <https://doi.org/10.3390/AP9091915>
- Shi, X. S., Dong, J. J., Yu, J. H., Yin, H., Hu, S. M., Huang, S. X., & Yuan, X. Z. (2017). Effect of hydraulic retention time on anaerobic digestion of wheat straw in the semicontinuous continuous stirred-tank reactors. *BioMed Research International*, 2017, 2457805. <https://doi.org/10.1155/2017/2457805>
- Tiwari, R., & Mahalpure, G. S. (2025). A detailed review of pH and its applications. *Journal of Pharmaceutical and Biopharmaceutical Research*, 6(2), 492–505. <https://doi.org/10.25082/JPBR.2024.02.001>
- Veluchamy, C., Kalamdhad, A. S., & Gilroyed, B. H. (2021). Evaluating and modelling of plug flow reactor digesting lignocellulosic corn silage. *Fuel*, 287, 119498. <https://doi.org/10.1016/J.FUEL.2020.119498>
- Wedwitschka, H., Gallegos Ibáñez, D., Schäfer, F., Jenson, E., & Nelles, M. (2020). Material characterization and substrate suitability assessment of chicken manure for dry batch anaerobic digestion processes. *Bioengineering*, 7(3), 106. <https://doi.org/10.3390/bioengineering7030106>
- Werkneh, A. A. (2022). Biogas impurities: Environmental and health implications, removal technologies and future perspectives. *Heliyon*, 8(10), e10929. <https://doi.org/10.1016/j.heliyon.2022.e10929>