Report

Anaerobic Digestion of Organic Wastes in Kenya: Biomethane Yields and Circular BioEconomy Opportunities

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1.0 Executive summary

Kenya generates significant volumes of organic waste from urban markets, households, livestock farms, and slaughterhouses, which pose serious environmental, health, and climate risks due to poor waste management. At the same time, these wastes represent untapped potential for clean energy production via anaerobic digestion. This study assessed the biomethane potential (BMP) of representative organic waste streams in Kenya to inform biogas investment, and circular economy transitions.

Through laboratory-based BMP assays, organic waste samples from Market, household and invasive plants in lake in Kisumu, Slaighterhouse in Isiolo, market in Embu, market and resturant in Nakuru, cattle farm in Nairobi, including fruit, vegetable, fish, food, household, and market wastes, water hyacinth, cattle manure, and slaughterhouse wastes, were analyzed for methane yield and digestate quality. The results revealed methane production ranging from 230 to 441 mL/g volatile solids (VS), confirming the high biodegradability and energy potential of these feedstocks. A combination of market (fruit and vegetable) waste and fish waste produced the highest methane yields, while co-digestion of market or food waste with fish waste or manure increased biogas output by up to 33%.

Feedstock composition analyses showed significant variation in carbon to nitrogen (C/N) ratios, volatile acids, and trace elements, reinforcing the importance of regular waste characterization and co-digestion to ensure stable digester performance. The absence of inhibitory elements such as chromium suggests that the feedstocks used were environmentally safe. The resulting digestate was nutrient-rich, supporting its potential as a biofertilizer for circular nutrient recycling.

These findings highlight the viability of anaerobic digestion as a circular economy solution for simultaneously addressing Kenya’s organic waste burden, promoting renewable energy and organic fertilizer access, and reducing greenhouse gas (GHG) emissions, particularly methane from landfills, open dumping and livestock manure. The study recommends further work on seasonal waste characterization, digester sizing, emissions reduction analysis, and economic feasibility to guide implementation and scale-up. Transforming organic waste into a valuable resource that advances a circular bioeconomy and sustainable food and energy systems aligns with Kenya’s climate goals under the Nationally Determined Contributions (NDCs), the Bioenergy Strategy, and the National Climate Change Action Plan (NCCAP 2023–2027).

2.0 Introduction

Large quantities of biodegradable food waste are discarded worldwide on a daily basis. The Food and Agriculture Organization (FAO) estimates that around 1.3 billion tonnes of food—worth 750 billion dollars—are wasted globally each year, accounting for a third of all food produced (FAO, 2017). Markets are, therefore, potential localized sources of food waste, with acute environmental and greenhouse gas (GHG) emission consequences if not properly managed. Animal production also generates large quantities of manure, which are often poorly managed through stockpiling and exposure to rain. This leads to nutrient loss and emissions of methane and nitrous oxide—both potent GHGs—particularly in developing countries. Additionally, large quantities of slaughterhouse waste generated daily in many African countries are left untreated, stockpiled, or discharged into streams (Ngwabie et al., 2019a; Ngwabie et al., 2019b). Poor management of organic waste—which forms a significant portion of the municipal waste stream—leads to decomposing matter in landfills that emits methane and foul odors, leaches nutrients and pathogens into waterways, and is often openly burned, releasing particulate pollution and short-lived climate pollutants (Cheng et al., 2019; Ngwabie et al., 2018; Sun et al., 2018). These issues not only threaten public health and the environment but also contribute to GHG emissions.

Kenya also faces critical challenges in managing its growing volumes of organic waste. Rapid urbanization has led to daily waste generation of 3,000–4,000 tonnes, primarily in cities (NEMA, 2023). In Nairobi alone, an estimated 2,400 tonnes of solid waste are produced each day, of which roughly 80% is organic (NEMA, 2023). Poor management of this waste—most of which ends up in open dumps like Dandora—causes serious environmental and health problems. The waste sector accounted for about 10% of global GHG emissions and 3–4% of Kenya's GHG emissions in 2020. Without intervention, waste-related emissions are expected to double by 2030.

The same organic waste causing these problems also represents a valuable resource with significant energy potential that remains largely untapped. Anaerobic digestion (AD) is widely regarded as a sustainable solution for managing organic waste (Vivekanand et al., 2018). In an oxygen-free digester, biodegradable material is converted by microbes into biogas—a combustible mixture of methane and CO_2—and a nutrient-rich residue known as digestate. Biogas can substitute for fossil fuels in cooking, heating, or electricity generation, while the digestate can be used as an organic fertilizer, returning nutrients to soils. By adopting AD at scale, Kenya could simultaneously address waste pollution, generate renewable energy, and reduce GHG emissions from decomposing waste and reliance on charcoal or wood fuel.

However, the AD of organic waste for biogas production is not without challenges. Food and market waste tends to be wet and rich in easily degradable carbohydrates, which can lead to rapid acidification in digesters and inhibit methane-producing organisms (Chen et al., 2008; He et al., 2024). Likewise, very high protein or nitrogen content—as found in manure or fish waste—can cause ammonia buildup, which is toxic to anaerobic microbes. Previous studies have noted issues like low pH and ammonium inhibition when digesting food waste alone. Co-digestion (combining multiple waste types) and pre-treatment are often proposed to overcome these challenges (Pilarska et al., 2023). For example, blending carbon-rich crop residues with nitrogen-rich food or animal waste can balance the carbon-to-nitrogen (C/N) ratio and improve process stability.

Indeed, the chemical composition of organic waste is highly variable—even “food waste” can differ greatly in moisture, fiber, fat, and nutrient content depending on the source and season. Previous studies (Moonsamy et al., 2024; Slopiecka et al., 2022) describe food waste as a “complex and variable composition” feedstock whose biogas yield can fluctuate widely. Edwiges et al. (2018) found the biomethane potential (BMP) of mixed fruit and vegetable waste ranged from as low as 288 to as high as 516 mL CH_4 per gram of volatile solids (VS), depending on the waste composition throughout the year. This variability underscores the need for local data—biogas yields reported in the literature cannot be assumed to apply universally.

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While Kenya has a substantial livestock sector and many urban markets (all generating organic residues), there is limited empirical data on the actual methane yields and optimal co-digestion strategies for these diverse waste streams. Past assessments of biogas potential in Kenya (Nzila et al. 2010) have been largely theoretical or focused on single substrates (e.g. manure or crop residues). For instance, a national study estimated that 1,313 million m^3 of methane per year could be generated from agricultural residues and other biowastes (Nzila et al. 2010), but it did not examine site-specific waste mixtures or operational challenges. Until recently, little attention was given to market-specific waste blends (such as those from produce markets or slaughterhouses), which can have unique characteristics. A recent study in Nairobi’s food markets found that about 67% of the municipal market waste is organic and could yield approximately 144,774 m^3 of biogas per day—equivalent to replacing around 89,000 liters of petrol daily (Munga et al. 2025). Such data highlight the tremendous opportunity for waste-to-energy conversion, but also the need for research to tailor biogas solutions to local waste streams.

This study aims to address these gaps by experimentally assessing the biomethane potential of various organic wastes in Kenya and their combinations. We conducted biochemical methane potential assays on a range of representative wastes, including fruit and vegetable residues from open markets, household food waste, fish waste, water hyacinth (an invasive aquatic weed), slaughterhouse waste, and cattle manure. We also tested co-digestion of these materials (e.g., mixing market waste with fish waste or manure) to evaluate whether synergistic effects occur. Prior to anaerobic incubation, the composition of feedstocks (moisture, volatile solids, carbon-to-nitrogen ratio, hemicellulose, cellulose, and lignin fractions) was characterized to link waste characteristics to digestion performance. During and after digestion, we measured methane production kinetics and analyzed the resulting digestate for nutrients (nitrogen and phosphorus) to estimate its fertilizer value. By generating these data, the study seeks to inform the design and optimization of biogas systems in Kenya—identifying which waste streams have the highest energy potential, how blending substrates might improve yields, and what nutrient resources are recovered. Ultimately, the goal is to provide evidence that can help convert Kenya's organic waste burden into clean energy and organic fertilizer resources, supporting sustainable development and climate change mitigation efforts.

3.0 Materials and Methods

3.1 Feestock and experimental design

Feedstock samples were collected separately from seven different markets and from a slaughterhouse in Kisumu County, Kenya (Table 1). In addition, fresh cattle manure used as feedstock was collected from the farm of the International Livestock Research Institute (ILRI) in Nairobi, Kenya. The feedstock samples were stored in a cooler box to limit microbial activity and transported to the ILRI laboratory, where they were kept at 4 °C until the commencement of incubation experiments for biological methane potential (BMP) determination.

Table 1: Experimental design to investigate biomethane potential of organic wastes in Kenya

Experiment	Location	Composition	Number of BMP replicates
One	Kisumu, Kibuye market and household	Vegetable + fruits + household wastes	4
	Kisumu, Kondele market	Fruits + vegetable wastes	4
	Kisumu, Manyatta market	Vegetable + fruit waste	4
	Kisumu, Jubilee market	Vegetable + fruits + fish wastes	4
	Kisumu, Dunga market	Fish wastes + water hyacinth	4
		Control (microcrystalline cellulose)	4
		Blank (inoculum from digesters run with cow manure)	4
		Total	28
Two	Isiolo slaughterhouse	Meat scrap + goat/cow blood + ruminant feces + waste water	4
	Embu market	Food + market wastes	4
	Nakuru market	Market waste	4
	Nakuru restaurant	Food waste	4

Nakuru market with manure	Food + market wastes + cattle manure	4
International Livestock Research Institute (ILRI) farm, Nairobi	Cattle manure	4
	Control (microcrystalline cellulose)	4
	Blank (inoculum from digesters run with cow manure)	4
	Total	32

3.2 Proximate, nutrient and elemental analyses

Prior to incubation, proximate and ultimate analyses of feedstock samples (Table 1) were conducted using standard procedures. Dry matter (DM), volatile solids (VS), and ash content were analyzed according to (APHA, 2005; Telliard, 2001). Nitrate and ammonium were measured using the N-min method. Phosphorus was determined using the Olsen P method with 0.5 M $NaHCO_3$ as the extractant. Inductively coupled plasma mass spectrometry (ICP-MS) was used for metal concentration analysis in the digestate.

3.3 Feedstock preparations and incubation

The cow dung-based inoculum was obtained from a 6 m^3 fixed-dome anaerobic digester at ILRI, operated under ambient conditions. Each batch bottle (total volume: 526.5 mL) was filled with 140 mL of inoculum.

Feedstocks from different sources were blended and mixed as per Table 1. Except for blank and control samples, 0.60 g of each feedstock (based on VS content) was added to four replicates of serum bottles. The inoculum-to-substrate VS ratio was maintained at 2:1. Microcrystalline cellulose was added to the control bottles using the same ratio. Water was added to two-thirds of each bottle volume (351 mL). Bottles were purged with nitrogen gas for 3 minutes to remove oxygen, sealed with rubber septa and aluminum caps, and gently mixed. The bottles in experiment one were incubated at 37 °C for 62 days, while those in experiment two were incubated at 37 °C for 39 days.

3.4 Boigas production and biomethane calculations

The volume of biogas produced (Eq. 1) was monitored by measuring the overpressure (mbar) generated in sealed bottles using a digital pressure transducer (GMH 3161, Greisinger Electronic, Germany). The measured overpressure and the headspace volume in each digester were used to calculate the volume of biogas produced. The biogas volume was then normalized to STP (0 °C, 1 atm) using Equation 1 (Vivekanand et al., 2013).

$$BP = \left(\frac{\mathrm{P}}{1000}\right)\mathrm{V} * \frac{273}{273+\mathrm{T}}$$

……………………………………………………………………………………………………
…………..……Eq. 1

Where:
BP = Biogas produced (mL at STP)
P = Overpressure (mbar)

V = Headspace volume (mL)
T = Temperature in °C

Biogas samples were extracted into 20 mL vials. Bottles were then depressurized to 30 mbar. CH_4 and CO_2 concentrations (% by volume) were determined using a gas chromatograph (SRI 8610C, SRI Instruments, USA) with a thermal conductivity detector. Methane volume was calculated using Equation 2. The net volume of biogas produced by each feedstock was calculated as the difference between the measured production and that of the blank (inoculum alone).

$$Vol\ CH_4 = \left(\frac{\mathrm{BP}*\left(\frac{\mathrm{MCH_4}*100}{MCH_4+\mathrm{MCO_2}}\right)}{\mathrm{BP}}\right)$$

…………………………………………………………………..………………………
…..Eq. 2

Where:
Vol CH_4 = Methane volume (mL)
MCH_4 and MCO_2 = Volume fractions of CH_4 and CO_2 respectively
Average cumulative CH_4 was calculated for each quadruplicate and standardized by the initial VS. The CH_4 yield from the control was used for quality control (Filer et al., 2019).

3.5 Data analysis

Data were analyzed using the R statistical software. A nonlinear model was applied to standardized cumulative CH_4 yield using the modified Gompertz equation (Lay et al., 1997; Mulat et al., 2018) shown in Eq. 3.

$$B(t) = B_0 \exp\{-\exp\left[\frac{R_{max} * \mathrm{e}}{B_0}\right](\lambda - t) + 1$$

……………………………………………………………………………Eq. 3

Where:
B(t) = Cumulative CH_4 yield (mL CH_4/g VS)
B_0 = Biomethane potential (mL CH_4/g VS)
R_{max} = Maximum CH_4 production rate (mL CH_4/g VS/day)
λ = Lag phase (days)
t = Time (days)
e = Euler's constant (2.7183)

Correlational analysis was used to assess the influence of proximate and elemental parameters on BMP.

4.0 Results and Discussion

4.1 Characteristics of feedstock and digestate

Feedstock characteristics from Experiment One are shown in Tables 2–4, and dry matter (DM) and ash contents from Experiment Two are presented in Table 6. It was observed that the C/N ratio of the feedstock in experiment one showed a large variation from 13.73 to 28.69 (Table 2). The C/N ratio in Experiment One varied from 13.73 to 28.69 (Table 2). The optimal range for biogas production is 20–30 (Khanal et al., 2019). Lower C/N ratios suggest excess nitrogen, leading to ammonia buildup that inhibits anaerobic microbes (Tg et al., 2022). This was supported by significant negative correlations between C/N ratios and ammonium (r = -0.83, p = 0.08) and nitrate (r = -0.83, p = 0.07) levels in the digestate (Tables 2 and 5). Low C/N ratios may limit biogas and biomethane production from some feedstocks, highlighting the need to increase carbon content through co-digestion. Experiment One feedstocks had lower DM, while higher values were observed in Experiment Two (Table 6).

Table 2: Proximate analysis of different feedstock used for biogas production in Kenya for experiment one

Location	Composition	C	N	C/N	% DM	VS, % moist	% Ash	Hemi-cellulose (%DM)	Cellulose (%DM)	Lignin (%DM)
Kibuye market	Vegetable + fruits + household waste	34.59	1.5	23.05	11.86	8.45	3.41	7.46	11.65	14.54
Kondele market	Fruits + vegetable waste	44.04	1.54	28.69	6.09	5.54	0.55	5.93	11.86	4.51
Manyatta market	Vegetable + fruits waste	36.63	2.2	16.66	4.78	3.45	1.35	7.31	14.95	11.46
Jubilee market	Vegetable + fruits + fish waste	47.16	3.43	13.73	9.66	8.11	1.54	4.16	9.79	4.06
Dunga market	Fish waste + water hyacinth	40.49	2.11	19.15	9.35	8.42	1.11	7.95	15.52	5.78

The ratio of carbon-to-nitrogen-to-phosphorus-to-sulfur (C:N:P:S) nutrient requirements for optimal biogas production is recommended to be 600:15:5:1 (Vintiloiu et al., 2012; Weiland, 2010). Calculations from Experiment One, using data from Tables 2 and 4, yielded the following C:N:P:S ratios: 44.3:1.9:0.4:1 for Kibuye (vegetable + fruits + household wastes), 75.9:2.7:0.3:1 for Kondole (fruits + vegetable wastes), 66.6:4:0:1 for Manyatta (vegetable + fruit wastes), 73.7:5.4:0.5:1 for Jubilee (vegetable + fruits + fish wastes), and 47.1:2.5:0.1:1 for Dungaa (fish waste + water hyacinth). These significant variations—even among similar feedstock blends—highlight the need for continuous characterization and control of feedstocks to optimize methane production.

Large variations in volatile acid content were also observed across feedstocks, even within the same type of blend in Experiment One (Table 3). It is important to note that co-digestion with fish influenced the volatile acid content of the feedstock, with direct implications on the biogas and methane production (Nahar et al., 2024; Silva and Fragoso, 2023; Vivekanand et al., 2018). This further confirms the heterogeneous nature of food wastes and the importance of regular characterization for consistent and efficient biogas production. The propionic-to-acetic acid ratios calculated from Table 3 were all below 1.4, except for Manyatta market (vegetable + fruit wastes), which had a ratio of 2.4. This may indicate potential inhibition of methane production (Nahar et al., 2024).

Table 3: Volatile acids composition of different feedstock used for biogas production in Kenya for experiment one

Location	Composition	Acetic acid (mg/L)	Propionic acid (mg/L)	Butyric acid (mg/L)	Iso-valeric acid (mg/L)	Valeric acid (mg/L)
Kibuye market	Vegetable + fruits + house hold waste	80.14	3.00	2.15	2.15	2.76
Kondele market	Fruits + vegetable waste	81.81	2.27	1.46	0.99	1.54
Manyatta market	Vegetable + fruits waste	1.31	3.17	0.89	0.64	0.97
Jubilee market	Vegetable + fruits + fish waste	92.78	4.33	1.42	0.83	0.55
Dunga market	Fish waste + water hyacinth	109.35	32.70	17.17	2.08	4.69

While trace elements were found at concentrations not detrimental to microbial activity (Table 4), it is worth noting the absence of chromium. Elevated chromium levels can inhibit anaerobic digestion and biogas production (Golub et al., 2022). Its absence also suggests that the feedstocks were unprocessed and free from industrial contamination.

Table 4: Elemental composition of different feedstock used for biogas production in Kenya for experiment one

Location	Composition	COD, mg/L	S, %w/w	P, mg/L	K, mg/L	Cu, mg/L	Zn, mg/L	Ca, mg/L	Pb, mg/L	Fe, mg/L	Cr, mg/L	N, mg/L
Kibuye market	fruits + vegetable waste	766	0.78	0.28	4.49	0.01	1.76	0.03	0.57	11.36	ND	441
Kondele market	Fruits + Vegetable + fish wastes	1068	0.58	0.16	4.13	0.01	2.96	0.02	0.11	1.98	ND	280
Manyatta market	Vegetable + fruit + house hold wastes	1232	0.55	ND	3.99	ND	1.85	0.02	0.99	2.36	ND	287
Jubilee market	Vegetable + fruit wastes	1212	0.64	0.31	4.31	0.02	0.47	0.03	0.04	4.05	ND	1610
Dunga market	Fish waste + water hyacinth	1212	0.86	0.06	4.27	ND	1.31	0.02	1.18	2.66	ND	826

ND: Not determined

Table 5: Characteristics of digestate resulting from biogas production from different feedstock in Kenya for experiment one

Location	Feedstock composition	Water content (%DW)	Ammonium (µg NH_4-N g^{-1} DW)	Nitrate (µg NO_3-N g^{-1} DW)	P (µg P g^{-1} DW)
Kibuye market	Vegetable + fruits + house hold waste	96.00	6433.93	125.48	7128.28
Kondele market	Fruits + vegetable waste	95.83	6199.83	78.45	6944.77
Manyatta market	Vegetable + fruits waste	96.09	8226.04	142.75	7511.94
Jubilee market	Vegetable + fruits + fish waste	95.84	11201.54	159.79	7498.87
Dunga market	Fish waste + water hyacinth	95.68	6871.90	95.24	6577.48

Table 6: Proximate analysis of different feedstocks used for biogas production in Kenya for experiment two

Location	Content of sample	Dry matter (%)	Ash (%) of fresh waste
Isiolo slaughterhouse	Meat scrapping	39.11	0.33
	Goat blood	8.17	0.46
	Cow blood	6.08	0.33
	Small ruminant feces	18.32	2.19
	Large ruminant feces	18.32	2.59
	Wastewater	2.55	0.43
Embu market	Market waste	9.59	1.01
	Food waste	32.54	2.97
Nakuru market	Food waste	29.91	5.09
	Market waste	18.99	6.82

4.2 Assessment of the biological biogas and biomethane potentials

The measured cumulative methane production and the modeled biomethane potentials for the different feedstocks conducted in the Experiment one are presented in Figure 1. For Experiment two, biogas composition (methane and carbon dioxide) was not measured; therefore, the data reported reflect the cumulative biological biogas potential (Figure 2). The results show that biogas and biomethane production began on the same day the incubation experiments were initiated, indicating highly biodegradable feedstocks with no observable lag phase. Slight variations in biomethane and biogas production, even for the same feedstock mixture (e.g., fruits and vegetables from the Kondele and Manyatta markets), could be attributed to differences in their composition and type. Different parts and species of fruits, vegetables, and fish wastes were collected from the various sources.

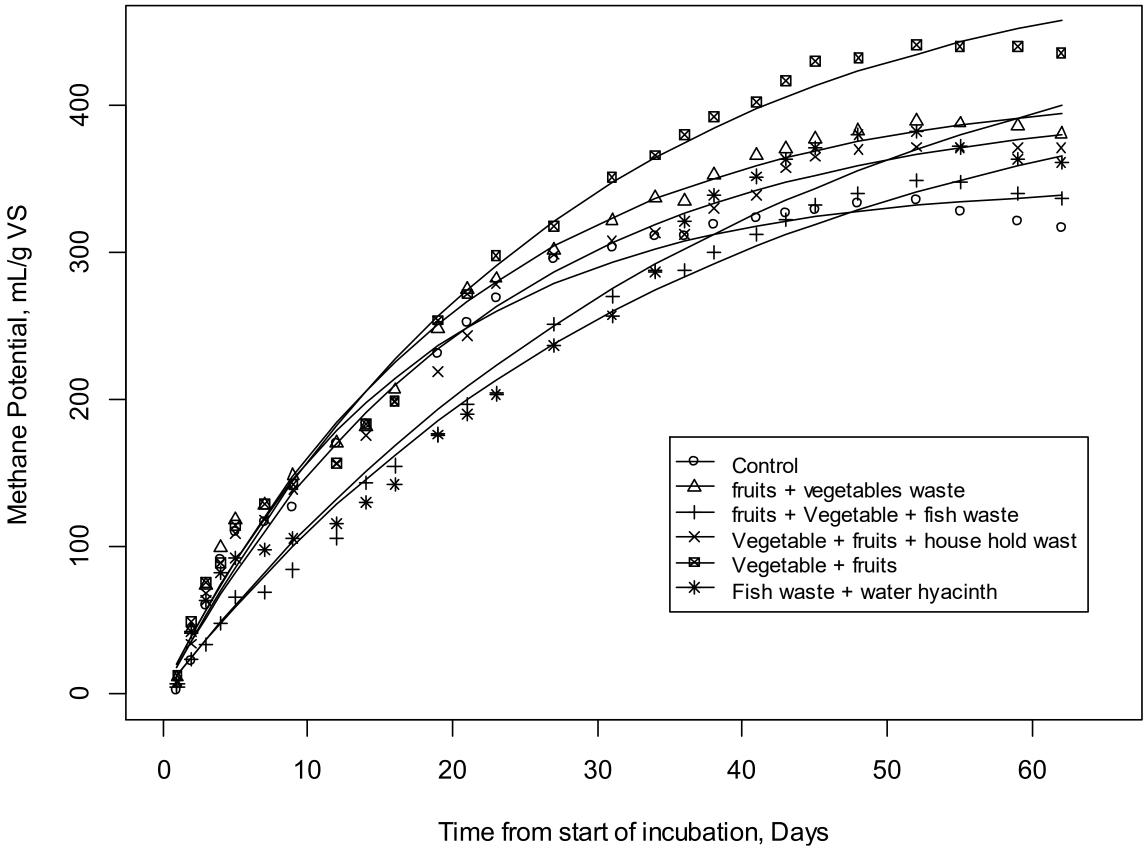

Figure 1: Cumulative measured and modelled methane yield from anaerobic co-digestion of different feedstock collected from Kisumu County – Kenya for experiment one

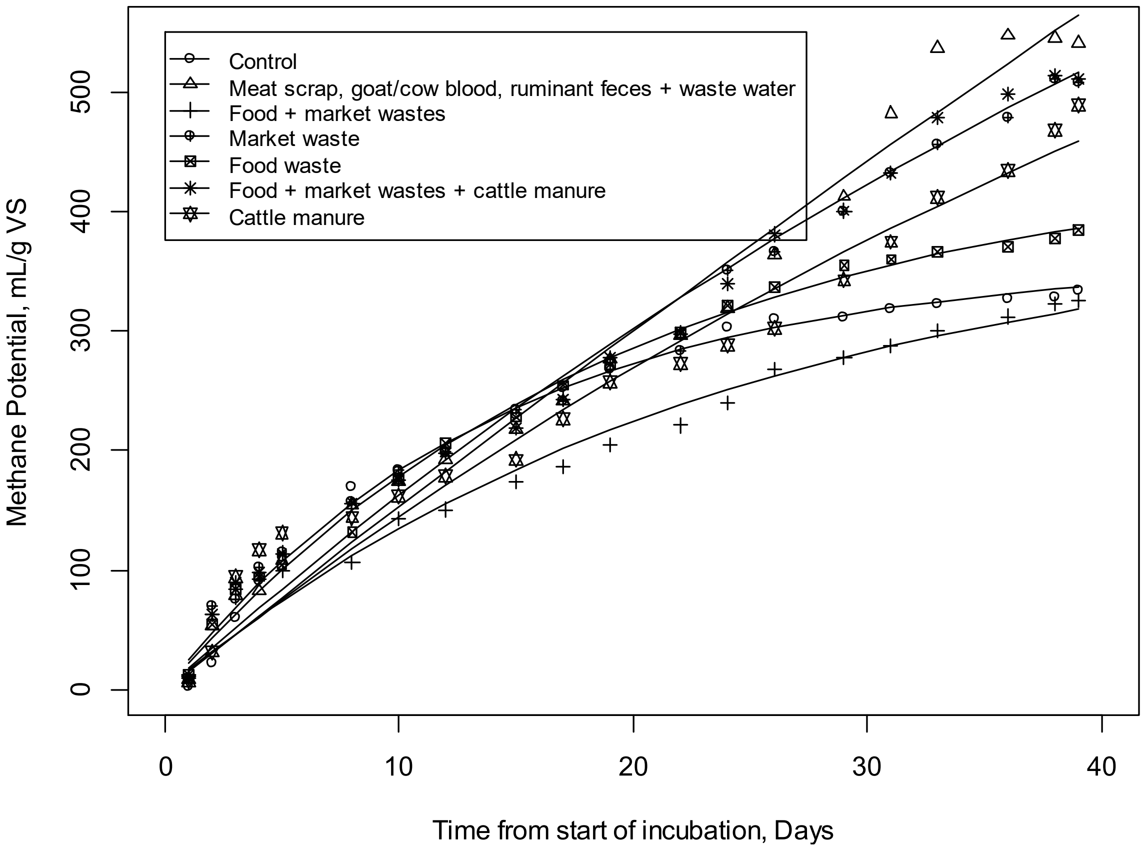

Figure 2: Cumulative measured and modelled methane yield from anaerobic co-digestion of different feedstock collected from Isiolo, Kiambu and Nakuru County – Kenya for experiment two

The biomethane and biogas potentials of the different feedstocks are presented in Figures 3 and 4 for both experiments, respectively. The biomethane potential for cellulose was above 333.9 mL/gVS, indicating an acceptable incubation process. Although it is expected to be in the range 351−419 mL/gVS, cellulose biomethane potential values in the range 340-366 mL/gVS have been measured elsewhere (Vivekanand et al., 2018; Wang et al., 2014). It was observed (Figures 3 and 4) that all the feedstock constituted good degradable substrates with biomethane potentials ranging from 230 to 441 mL/g mL/gVS. Since biogas composition was not measured in Experiment Two, we multiplied the biogas yield by an assumed methane composition of 60% to calculate the biomethane yield.

One of the central questions was whether co-digesting different wastes would enhance biomethane production. Our results show clear, if sometimes modest, benefits of co-digestion in most cases. Based on the results from experiment one, when just vegetables and fruit wastes were considered, the biomethane potentials were 349.3 and 371.9 mL/gVS from Manyatta and Kondele markets respectively, resulting to an average value of 360.5 mL/gVS. It can therefore be estimated that the addition of fish wastes to vegetable and fruit wastes (Jubilee market) increased the biomethane potential by 22% (from an average of 360.5 to 441.3 mL/gVS). In a similar assessment, the addition of household wastes to vegetable and fruit wastes (Kibuye market) increased the biomethane potential by 8% (from an average of 360.5 to 389.3 mL/gVS). These improvements are consistent with the idea that a more balanced substrate improves digestion. Fish waste provides extra protein and lipids which supply a higher energy content and possibly essential nutrients (like trace elements) that pure vegetable matter might lack. On the other hand, the fruit and vegetable waste supplies fiber and carbohydrates that help maintain a favorable C/N ratio when combined with high-nitrogen fish waste. Co-digestion of these components likely prevented excessive acid or ammonia accumulation and allowed the microbial community to degrade a wider range of compounds efficiently (Netshivhumbe et al. 2024).

Experiment one also showed that co-digestion of fish wastes boosted the biomethane potential of water hyacinth which was 382.1 mL/gVS. Mono-digestion of water hyacinth as not directly tested in this study, but literature suggests a wide BMP range for this aquatic weed – from as low as ~185 mL/g VS up to ~440 mL/g VS (Nahar et al., 2024; Simbayi et al., 2023), depending on treatment and nutrient supplementation, which is on the higher end of the expected range. Fish waste has also been shown to significantly enhance methane production from water hyacinth by 33−103% (Nahar et al., 2024) (Table 7). This implies a synergistic effect: fish waste addition likely improved the degradation of the hyacinth, perhaps by providing extra enzymes or a better nutrient balance. Nahar et al. (2024) found the optimal water hyacinth:fish waste ratio was around 3:1 (on VS basis) for maximizing biogas, confirming that moderate inclusion of fish waste can significantly improve hydrolysis and methanogenesis for fibrous aquatic weeds. In practical terms, co-digesting invasive water hyacinth (a nuisance in Kenya's lakes) with proteinaceous waste could be a win-win: increased energy production and control of an invasive species (Netshivhumbe et al. 2024).

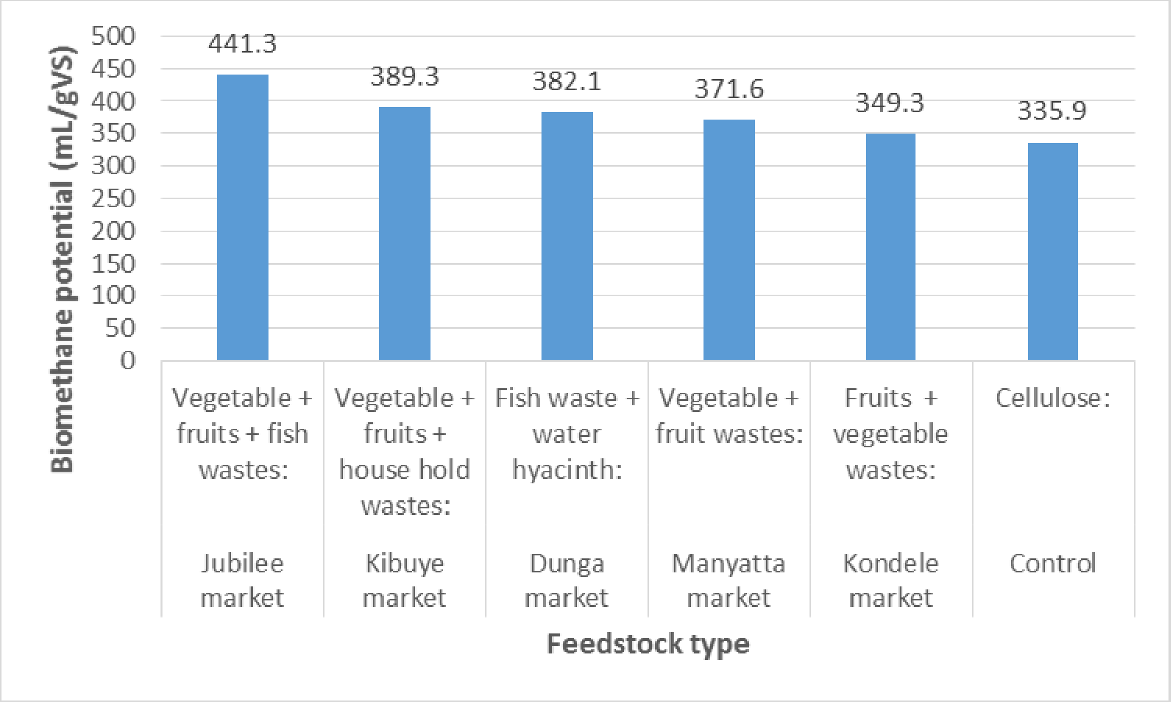

Figure 3: Biomethane potential from different feedstock collected from markets in Kisumu County – Kenya for experiment one

Results from Experiment Two showed that the biomethane potential of cow manure was lower than that of market and slaughterhouse waste. Since manure has already undergone partial digestion by cattle, it is expected to have a lower biogas potential. Notably, the methane yield from cattle manure in this study was 289.7 mL/g VS, which is compared to findings from other regions, as presented in Table 7. For instance, Abdallah et al. (2018) reported biomethane potentials in the range of 250–300 mL/g VS for different cow manures, and Wijaya et al. (2020) observed similarly low values in a tropical context.

It was observed that co-digestion of market and food wastes from Nakuru with cattle manure increased methane yield by 1, 33 and 4% compared to mono-digestion of market waste, food waste and cattle manure respectively (Figure 4). Co-digestion with cattle manure also showed some benefits, though more variable. Manure can act as a stabilizer in biogas process – it typically contains a dense microbial population (as inoculum) and high buffering capacity from its bicarbonate and ammonia content. Thus, adding manure might prevent excessive acidification when co-digesting easily fermentable food waste, thereby improving overall conversion. The relatively minor improvement for market waste could indicate that the market waste was already a balanced mixture (fruits, vegetables, some paper or yard waste). Still, even a neutral effect means co-digesting manure with market waste is viable and can be encouraged, since it allows treating multiple waste streams together for convenience without sacrificing yield.

It is worth noting that the co-digestion of food waste and market waste from one location (Embu) yielded the lowest BMP (~326 mL/g VS), which was lower than either waste alone in other cases. This suggests that not all combinations are inherently beneficial – the specific characteristics of the wastes matter. The Embu wastes may both have had low C/N (excess nitrogen, no measurement) or other limiting factors.

Slaughterhouse waste gave the highest methane yield, indicating a promising oppoturnity for its management through renewable energy production and fertilizer production using biogas technology.This can be attributed to its high content of fats and proteins (from animal offal and blood) which have higher energy density than carbohydrates (Pagés-Díaz et al. 2014). Our result aligns with those findings (Ware & Power, 2016), suggesting that slaughterhouse waste, if properly managed in a digester, could be extremely productive. The trade-off is that such wastes also carry a risk of inhibition if the loading is too high (excess fats can cause long-chain fatty acid accumulation, and proteins yield ammonia). In our batch BMP assay, inhibition was not observed – likely because the substrate-to-inoculum ratio was chosen to be low enough – but any continuous system treating slaughter waste would need co-digestion with other feedstock and careful monitoring.

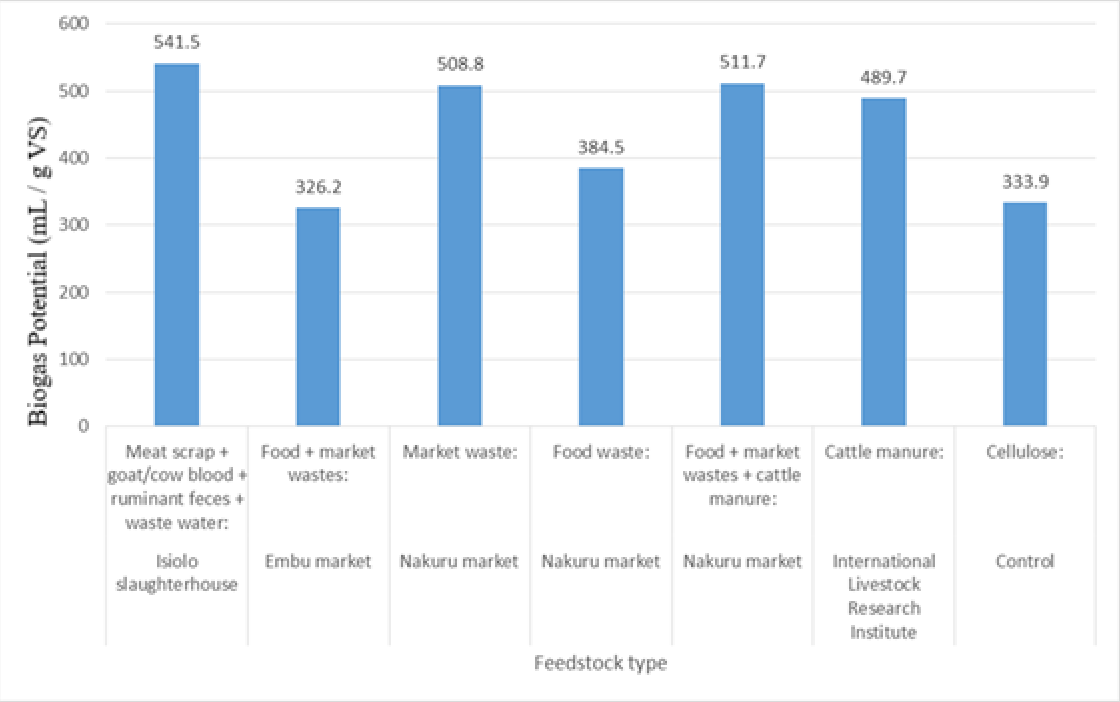

Figure 4: Biogas potential from different feedstocks in Kenya for experiment two

The biomethane potential of organic and especially food-related wastes in the present study (Figure 3 and 4) showed large variations, with higher values in some cases when compared to measurements reported in other studies (Table 7). Such variations are expected given the differences in feedstock composition and feedstock combinations, even when sourced from the same area (Moonsamy et al., 2024; Slopiecka et al., 2022). These results present a great opportunity for the utilization of biodegradable organic wastes in Kenya for biogas production, with the added advantage of waste management, GHG reduction, odour reduction and bio-fertilizer production.

Table 7: Reviewed biochemical methane potentials for different waste substrates

Current study	Literature values		
Biomethane potential (mL/g VS)	Waste type	Biomethane potential (mL/g VS)	Source
NA	Fish ensilage	691 ± 6	(Vivekanand et al., 2018)
	Fish waste	610	(Nahar et al., 2024)
382.1	Fish waste + water hyacinth	585−890	
NA	Water hyacinth	280.15 and 440	(Gbiete et al., 2024; Nahar et al., 2024)
231*	Food waste (South Africa)	357	(Matobole et al., 2019)
	Italian food waste	219 and 534	(Luz et al., 2021)
305-349*	Fruits and vegetable wastes	294 and 360	(Edwiges et al., 2018; Seswoya et al., 2019)
294*	Dairy cattle manure (Canada)	300-350	(Godbout et al., 2010)
	Beef cattle manure (Canada)	190-210	
	Cattle manure (Thailand)	175.79	(Wijaya et al., 2020)
	Dairy cattle manure (United Arab Emirates)	148−216	(Abdallah et al., 2018)
	Dairy cattle manure	147 ± 9	(Vivekanand et al., 2018)
325*	Slaughterhouse Waste: Ruminal residue (Ecuador)	232.2 – 250.8	(Meneses Quelal and Pilamunga Hurtado, 2023)
	Swine slaughter waste	711−1076	{Renggaman, 2021 #731; Yoon, 2014 #732}

NA: Not available as it was not measured

* For experiment two, biomethane was calculated from the biogas volume presented in Figure 4, assuming a methane composition of 60%.

5.0 Conclusion and Recommendations

Using laboratory BMP experiments, this study evaluated the potential for producing biomethane from a variety of Kenyan organic wastes, such as household food, market (fruit, vegetable, fish), livestock manure, and slaughterhouse wastes, as well as water hyacinth. The findings demonstrate that these wastes are highly degradable and can produce significant volumes of biogas and biomethane. All types of feedstocks were found to be good substrates for biogas production, and measured biomethane yields varied between approximately 326 and 541 mL CH_4/g VS. Kenya's organic waste streams offer a good opportunity to be converted into a renewable energy source thanks to their high biomethane potential. Co-digestion, in particular, has been demonstrated to increase methane outputs. By reducing process inhibitors, combining nitrogen-rich or high-calorific wastes (such as fish offal and food waste) with carbon-rich wastes (such as water hyacinth) can increase overall gas production. In our experiments, for instance, adding fish waste raised the methane yield by 20% or more, and co-digesting market trash with manure enhanced output and stability. According to the findings, anaerobic digestion is a circular solution to address Kenya's issues with disposing of organic waste, lowering pollution, health hazards, and greenhouse gas emissions while generating nutrient-rich fertilizer and sustainable energy. Since biogas technology tackles several sustainable development issues (clean cooking energy, waste recycling, environmental pollution and health risks, and climate change mitigation), this is in line with national waste management and climate goals (Munga et al. 2025).

Based on these results, we suggest a number of areas for additional study and action to effectively implement biogas systems in Kenya:

- **Characterization of the composition of waste across seasons:** Conduct studies on seasonal variations in waste generation volume and composition. Festivals, harvest seasons, and rainy vs dry spells can all affect the availability and composition of wastes. Planning the feedstock supply for biogas plants will be made easier with an understanding of these trends (e.g., maintaining sufficient storage or alternative feeds during lean seasons). As demonstrated before with fruit and vegetable waste (Edwiges et al. 2018) , ongoing monitoring over a year can show how BMP and feedstock composition and BMP changes over time.
- **Digester sizing and design:** Create specifications for biogas digester sizing that take into account energy requirements and waste availability locally. To find the best digester type and volume for a particular market or farm, our data can be fed into engineering models. For example, a medium-sized digester could be needed to handle the approximately five tonnes of organic waste produced daily by a municipal market. Target gas usage and peak waste periods (based on the seasonal data above) should also be taken into account when sizing.
- **Baseline energy use and displacement:** To estimate how biogas could replace conventional fuels, collect data on baseline energy consumption and cooking fuel use in target populations (market vendors, surrounding homes, slaughterhouses or farms). One can calculate the amount of biogas (in m^3) required each day to meet those needs by calculating the current usage of firewood, charcoal, LPG, or grid electricity for cooking, lighting and heating. This also establishes a baseline for comparing emissions; for instance, using biogas to replace a specific quantity of firewood can result in tonnes of CO_2 and the avoidance of deforestation.
- **Analysis of GHG emissions reduction:** Perform a detailed emissions reduction potential assessment for biogas projects. This would involve comparing GHG emissions with and without the biogas system. Without biogas, the waste would decompose aerobically or anaerobically in dumps, releasing methane and CO_2, and people might use kerosene or wood for cooking. With biogas, methane is captured and burned for energy. Additionally, organic waste is diverted from dumps, cutting landfill methane. Quantifying this difference will support Kenya’s climate commitments. For instance, Kenya’s solid waste management NAMA aimed for a 0.49 $MtCO_2e$ reduction by 2022 through better waste handling – similar calculations can be made for expanding biogas systems (Climate Action Tracker for Kenya, 2022). Future research should measure methane emissions directly at dumpsites and compare with emissions from properly managed digesters (including any digestate storage emissions).
- **Optimization of digestate use:** Investigate digestate's amount, nutritional value, and safe use in different situations. According to our research, the digestate is high in phosphorus and nitrogen (ammonium); additional laboratory testing can provide

specific macro and micronutrient profiles for every waste mix. The digestate's fertilizer value might subsequently be evaluated in pilot studies using forages and crops that are often grown in Kenya. Determining the right application rates is crucial to meeting crop nutrient needs without producing runoff, as is making sure that any pathogens in wastes—particularly those from manure or slaughter—are removed. To enhance digestate's handling and safety, research may look into straightforward post-treatment techniques (such as drying, composting, or pasteurization). In the end, creating a market for the digestate as an organic fertilizer might boost sustainable agriculture and the profitability of biogas facilities.

- **Feasibility and Business Models:** Carry out a cost-benefit analysis of biogas systems in peri/-urban market and rural livestock settings. This should include capital and operating costs of digesters (which can vary from low-tech plastic tubular digesters to high-tech stirred tanks), as well as the monetized benefits: savings on cooking fuel or electricity, potential revenue from selling excess biogas or electricity, carbon credits from emissions reductions, and the value of biofertilizer replacing synthetic fertilizers. Socio-economic factors such as job creation in building/maintaining digesters and reduced healthcare costs from cleaner air could also be considered. It will be crucial to streamline biogas adoption into policies such as Kenya's NDCs, LT-LEDS, Bioenergy Strategy, Climate Change Action Plan, and energy access programs, which are beginning to acknowledge biogas as a clean cooking option.

In conclusion, Kenya's efforts to convert organic waste into biogas and organic fertilizer have great potential to concurrently address waste management goals, energy security, agricultural productivity and climate change. The results of this study offer promising proof of the large biogas and organic fertilizer yields that may be achieved as well as useful information (such the advantages of co-digestion and the requirement for C/N balance) that can direct implementation on the ground. Stakeholders can strengthen their knowledge base to optimize biogas systems year-round and optimize their economic and environmental benefits by following the suggested research areas. What is currently considered "waste" in Kenya can increasingly be turned into a useful resource with the help of encouraging laws and ongoing innovation. This will help to reduce pollution and promote a more circular economy while supplying households and businesses with renewable energy. Kenya will be able to fully utilize biomethane and organic fertilizer from its plentiful organic resources if these research findings are translated into pilot projects and subsequently expanded deployments.

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