Journal of Energy in Southern Africa

Volume 35 • Number 1
2024

The feasibility of using biogas generated from livestock manure as an alternative energy source: A South African perspective

M. Moreroa*[1], **S.C. Motshekga**[2]

1. Institute for Catalysis and Energy Solutions, University of South Africa, Roodepoort, South Africa
2. Department of Chemical Engineering, University of South Africa, Roodepoort, South Africa

Abstract

Electricity usage has risen tremendously over the years, as has its price. This resulted in an increase in the quest for less expensive, viable, and ecologically acceptable means of producing energy for electricity. Currently, the primary source of power in South Africa is sourced from fossil fuels, which have negative environmental consequences. The use of biogas as an alternative can mitigate the impacts of using fossil fuels to generate power. This study has examined the availability and accessibility of waste that may be utilized to generate biogas using common South African livestock excrement. A typical South African home uses 31 kWh of power daily, which equates to 111.6 MJ of energy. According to calculations, about 30 m^3 of biogas is needed to produce enough energy to power a household. For the generation of mono-digestion biogas, 12 beef cows, 8 dairy cows, 3898 chickens, 156 pigs, 281 sheep and 300 goats would be needed to meet this need. Moreover, the livestock dung required to meet the daily requirement of 31 kWh is 713 kg for beef and dairy cows, 390 kg for chickens, 468 kg for pigs, 506 kg for sheep and 466 kg for goats. Co-digestion of various wastes is nonetheless a viable and advised method for enhancing the amount and quality of biogas.

Keywords: *animal manure; biogas value; biogas vs electricity; dung quantity; heating value*

Journal of Energy in Southern Africa 34(1),1–16

DOI: https://dx.doi.org/10.17159/2413-3051/2024/v35i1a17021

Published by the University of Cape Town   ISSN: 2413-3051   https://journals.assaf.org.za/jesa

Sponsored by the Department of Science and Innovation

Corresponding author: E-mail: emorerms@unisa.ac.za

Abbreviations and acronyms used

Carbon/nitrogen	C/N
Chemical oxygen demand	COD
Combined heat and power	CHP
Cubic metre	m^3
Degree Celsius	°C
Efficiency	η
Gram	g
Heating value	HV
Hour	h
Kilogram	kg
Kilogram of volatile solids per cubic metre per day	$kgVS/m^3.day$
Kilowatt-hour	kWh
Litre	L
Litre per gram of volatile solids	L/gVS
Megajoules	MJ
Microlitre	μL
Millilitre	mL
Millilitre per gram of volatile solids	mL/gVS
Millilitre per gram of volatile solids a day	mL/gVS.day
Normal millilitre	NmL
Normal litre of methane per kilogram of volatile solids	$L_NCH_4/kgVS$
Organic loading rate	OLR
Terawatt-hour	TWh
Total Kjeldahl nitrogen	TKN
Volatile solids per cubic metre a day	$VS/m^3.day$
Volatile solids	VS

1. Introduction

One of the most significant problems and possibilities in the global energy transition is universal access to inexpensive, reliable, plentiful, and sustainable energy. The demand for energy has increased globally since 1990 (Lerede and Savoldi, 2023), leaving about 580 million people in sub-Saharan Africa without electricity (Garg et al., 2022). Moreover, the high price of electricity, ZAR 1.8237 per kWh in South Africa (Mueni and Apindi, 2023) has become a challenge as the unemployment rate keeps rising. The highest unemployment rate reported globally in 2019 was in Africa, at 28.2% (Garg et al., 2022). In South Africa, one of Africa's most developed countries, the unemployment rate rose from 20% in 2003 to 29.81% in 2022 (Aaron O'Neill, 2023). As a result of the high unemployment rate and the high cost of living, alternative methods of energy generation need to be employed. Renewable energy such as solar, biomass, and wind have been on discussion tables in trying to resolve the energy crisis in Africa.

Biogas production for heat and power applications is an alternative way for local communities to have access to electricity. The technology has substantial positive impact on both people and the environment. The significant price hikes of high-quality petroleum products for households, commercial and agricultural activities have witnessed a drastic reduction of households and commercial industries meeting the levels to stay sustainably afloat. Hence, an urgent search for alternative, sustainable and renewable energy sources is required.

Significant research has been done on the generation of biogas as an alternative energy source, with success. Several substrates/feed, such as food waste (Singh et al., 2023), sheep manure (Sohail et al., 2022), rice straw and pig manure (Ji et al., 2022), aquatic plants (Moretti et al., 2023), municipal waste (Mrosso, Mecha and Kiplagat, 2023) and many others, have been explored. When anaerobically digested, such waste has the potential to produce biogas, which may be utilised to lessen the demand for expensive electricity.

In this research, the feasibility and use of animal waste as a substrate for the generation of biogas is being reviewed. The use of biogas generated from animal manure and other feedstock has been recorded, but there is scarce and scattered information about their feasibility and sustainability. This review aims to bring insight into the energy produced from biogas (in comparison to electricity), and the quantity of feedstock required to generate enough biogas to power an average household, which will further aid in digester-sizing.

2. Livestock wastes used to generate biogas

Animal waste has significant amount of nutrients that can be used as energy sources and has a potential to replace non-renewable energy sources. Given that most communities can produce significant amounts of these wastes per day, the production of biogas from this waste could provide a much-needed relief to accessing affordable energy, as the production of biogas does not require expensive equipment. Biogas is produced by the degradation of organic materials by the microorganisms involved at different stages of the process. The process involves four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. At different stages of the process, the process results in the production of methane, carbon dioxide, moisture, oxygen, hydrogen sulphide, and other trace gases. The wastes commonly used to produce livestock derived biogas are described below (Ya'aba and Ramalan, 2020).

2.1 Cow dung

Cow dung is the undigested waste material produced by cows as a result of their primarily plant-based diets. The features and quality of cow dung vary depending on the species, which might be dairy or meat cattle. Due to its abundance of nutrients and readily available microorganisms, cow dung is a frequent feedstock utilised in anaerobic digestion and is widely available (Ya'aba and Ramalan, 2020; McVoitte and Clark, 2019). Biogas is produced because of the aforementioned microorganisms. The makeup of the dung is additionally impacted by the kind of feed the cows ingest. For instance, the low total solids and high quantities of lignocellulose provide a risk because of the poor biodegradation and methane output. However, the materials are first prepared to facilitate successful breakdown, or co-digestion with other substrates is used as a solution to these problems (McVoitte and Clark, 2019).

Ya'aba and Ramalan (2020) reported that the anaerobic digestion of 260 g of cow dung resulted in the production of almost 13 180 mL of biogas on the fifteenth day of the process, with an average daily yield of 878.67 mL. These findings demonstrated the viability of using cow dung as a cheap and alternative energy source. Although they did not specify the concentration, the authors further confirmed that methane was present in the biogas. An investigation done by Elhenawy, et al. (2021) focused on the anaerobic digestion of cow manure in a floating digester to produce biogas. Over the course of 84 days, a total of 101.7 L of biogas was produced. They said that the volume of gas produced was very low, which could have been affected by the low temperatures used, which ranged from 18–28 °C. The study used 75.52 kg of cow dung over 84 days and produced an average of 19 L of biogas per week. Their results further indicated that the gas contained 60.9 % methane, 32.2% carbon dioxide, 0.1% hydrogen sulphide and 6.7% of carbon monoxide. They concluded that the low temperatures during their study affected the production of biogas, which the fermenter stopped producing after the 84th day. They suggested that a heat exchanger should be installed to increase the temperature of the fermenter and for effective gas production. Similar results were found by a study conducted by Matos et al. (2017), where they evaluated the production of biogas using dairy cattle manure under both organic and conventional systems. Their results showed that a cumulative biogas of 6.18 L for the organic system and 11.15 L for the conventional system was produced. The experiments were conducted over 30 weeks. The authors concluded that the difference in the produced biogas was due to the diet. Under the conventional system, the combination of concentrate and roughage was fed to the cattle and that could have facilitated a faster degradation of the waste, resulting in more biogas produced, whereas for organic system the diet did not include any concentrate and the biogas produced was less. These results were corroborated by similar studies, where adding concentrate in the diet reflected in the amount of biogas produced. A study by Chinwendu, Chibueze and Tochukwu (2013) evaluated the potential use of cow dung and swine dung in the production of biogas. The authors used similar conditions for the feedstocks, and their results showed that cow dung was superior to swine dung, as it produced more cumulative biogas, and the process was stable. From their analysis, the results showed that cow dung had high nutrient, energy and solids content which was enough for the biodegradation activity. And from these results, it was concluded that cow dung was an effective feedstock to significantly produce enhanced cumulative biogas under anaerobic digestion.

2.2 Goat and sheep manure

Similar to cow waste that is frequently used for the anaerobic digestion, goat and sheep waste are feedstocks that could be used for the process, but are rarely used. The waste is less expensive and easier to handle, with microbes that are beneficial for anaerobic digestion. The pelletised waste contains a relatively high amount of total solids and volatile solids (VS), which is a measure of the presence of organic material. Moreover, goat and sheep waste contain a relatively high total Kjeldahl nitrogen (TKN), which is slightly more or the same as that of cows. TKN is one of the performance indicators for anaerobic digestion, and its high values are beneficial for anaerobic microorganisms since nitrogen is required for the development of their methanogenic cell structure (Sanchez and Wilkie, 2017).

A study by Ndubuisi-Nnaji et al. (2023) evaluated the performance of anaerobic digestion of goat waste and poultry waste on the production of biogas. The study showed that the daily cumulative biogas yield of goat waste was significantly higher than that of poultry waste. The authors reported that they recorded the minimum biogas on the first day of the experiment for both wastes, which was 280 mL/gVS.day for poultry and 75 mL/gVS.day for goat waste and the maximum yield was recorded on day 23 at 1500 mL/gVS.day for poultry waste and 2450 mL/gVS.day for goat waste on day 45. Their results indicated that goat waste produced 1.05 times more biogas than poultry waste. The authors further showed that the performance indicators of the process, such as total solids, VS and pH of goat waste was significantly higher than that of poultry waste, which contributed to the stability of the process and continuous production of biogas. However, they also pointed out that at the end of the digestion process these performance indicators had decreased drastically, which might be the reason for low biogas quality in the beginning for goat waste, but as the degradation proceeded, more biogas was produced.

Sanchez and Wilkie (2017) conducted a study on the anaerobic digestion of goat and sheep waste for the production of biogas. They analysed the pelletised waste for total solids, VS, chemical oxygen demand (COD), pH, etc. The results indicated that the pH of each waste was within range, whereas the total solids, VS, and COD were also very high for both wastes, indicating that theoretically the wastes are capable of producing biogas. As anticipated, both wastes produced relatively high methane within the first 24 days of the process, with sheep waste producing a higher yield (198 L_NCH_4/kgVS) than goat waste (167 L_NCH_4/kgVS). The results showed that both goat and sheep waste are potential feedstocks for anaerobic digestion.

A study by Kaur and Kommalapati (2021) investigated the efficacy of co-digesting goat manure with cotton gin trash for methane production. The co-digestion was prompted by the poor carbon/nitrogen (C/N) ratio of goat manure, which was 15.7, whereas for the cotton gin trash it was found to be 36.3, which was conducive to anaerobic digestion. The cumulative methane produced by the mono-digestion of goat manure was 274.1 mL/g of VS. However, methane values of 261.4 and 262.6 mL/g of volatile solids were obtained for the co-digestion of goat manure with cotton gin trash of 10% and 20% respectively. These co-digestion results showed similar results as those of the mono-digestion, and it was observed that the quantity of the methane produced decreased gradually with more cotton gin trash added. Although the cotton gin trash was brought in to improve the C/N ratio, it was found that the optimum C/N ratio to support the digestion process in their study was between 15.7 and 19.8. With the results obtained to produce methane and the C/N ratio analysed, it could be argued that there was no need to add the cotton gin trash.

Otobrise, Udubor and Osabohien (2022) comparatively evaluated the anaerobic production of biogas using goat dung and pawpaw seeds. The results showed that goat dung produced more biogas (4943 mL) in comparison to the pawpaw seeds (4329 mL). However, the co-digestion of the two feedstocks produced an even greater biogas of 5872 mL.

According to Cestonaro et al. (2015), sheep-bedding is commonly used in sheep farming to mechanically improve the properties of sheep waste (pellets) as the sheep stomp over the pellets and bedding turning them into a homogeneous material. This is done in order to enhance the degradation yield of the pellets by increasing the available surface area for microbial activity. In their study, the authors used the sheep-bedding approach for sheep manure, which was anaerobically co-digested with cattle manure to improve the quality of biogas production. Different mixing ratios were used of both sheep and cattle manure, and it was found that biogas yield was improved with the addition of 50% cattle manure into the mixture, while addition beyond 50% did not yield any increase in biogas production. The authors stated that the significant biogas yield was due to the benefits of co-digestion as sheep manure alone produced less biogas and even with that it was stated that it is because of the high fibre content from the bedding and the presence of rice husks in the mixture. However, the benefits of co-digestion were not realised when Achinas et al. (2018) co-digested cow manure with sheep manure for biogas production. The mono-digestion of cow manure produced 104 NmL biogas after 24 days but only 89 NmL when co-digestion took place. The authors stated that the lower biogas yield during co-digestion could be due to the conflicting behaviours of the microbes found in each of the manures. A study conducted by Sankaran, Sivaprakasam and Velayutham (2019) co-digested municipal waste solids with sheep manure of different concentrations of 10%, 20% and 30%. The results revealed that the biogas yield increased with more sheep manure content: 256.45 mL/gVS for 10%, 385.65 mL/gVS for 20%, and 478.9 mL/gVS for 30%. Furthermore, the degradation of the organic materials started almost immediately, the process was stable, and the production of biogas increased significantly due to the exponential growth of the microbes and their ability to adapt to the process.

2.3 Pig manure

Another form of feedstock frequently fed into the digester for generating biogas is pig excrement. However, due to its physicochemical characteristics, this is constrained (Vanegas, Romani and Jiménez, 2022; Aranguren et al., 2021). Pig wastes are high in proteins, lipids, and cellulose, which makes biodegradation extremely difficult. Additionally, the manure has a low carbon content and C/N ratio and a high nitrogen content, which reduces its efficiency in the production of biogas. While the C/N ratio for pig manure was found to vary from 6 to 8, which is quite low for anaerobic digestion, the C/N ratio for optimal biogas generation has been predicted to be between 20 and 35. It has been argued that utilizing pig manure for mono-digestion is not the most efficient method of producing biogas due to its low C/N ratio. As a result, co-digestion is frequently used to produce biogas effectively and to maintain a balanced C/N ratio (Risberg et al., 2017; Tian et al., 2023; Toma et al., 2016; Gaworski et al., 2017). In emphasising the need for co-digestion, Gaworski et al. (2017) and Beily et al. (2023) have reported that pig manure alone is an inefficient feedstock to produce biogas, because of the high nitrogen concentration in comparison to the available organic carbon.

Co-digestion was shown to be effective in a study by Okareh, Adeolu and Shittu (2013), who found that co-digesting pig manure with certain crop wastes, such as peels (yam, cassava, and plantain) and bean husks, significantly increased biogas generation. The feedstock mixture produced 70.6% methane, 4.7% carbon dioxide, 5.3% hydrogen sulphide, 13.2% ammonia, and other trace gases which were very low. The authors also noted that utilising these feedstocks has the added benefit of reducing environmental waste and generating fertiliser with added value from the digestate. For process stability and to enhance the generation of biogas, Tian et al. (2023) carried out a co-digestion investigation using pig manure and rice straw. They conducted their studies in batch mode, varying the total solids, mixing ratios, and inoculum accounts. The results demonstrated that co-digestion produced a biogas production of 553.79 mL/gVS at 12% total solids content, 1:5 pig manure to rice straw mixing ratios, and 15% inoculum account. They also demonstrated that there were no ammonia nitrogen or acidification inhibitors in the co-digestion process, which was effectively stabilised. This was because volatile fatty acids were shown to progressively diminish while they were being digested by the microorganisms involved, and the pH of the system fluctuated within the stable range established as the self-buffering capabilities of anaerobic digestion.

The mono-digestion and co-digestion of swine waste and laying-hen waste at various mixing ratios and temperatures were assessed in a study by Pereira et al. (2023). A co-digestion ratio of 25:75 swine waste to hen waste produced more biogas than the other ratios when COD was removed at temperatures of 18 and 36 °C, respectively, generating 0.34 and 0.60 m^3 per kilogram of COD removed. The system outperformed mono-digestion, as evidenced by all of the co-digestion outcomes. According to the study, co-digestion of the two combinations has potential for both the creation of biogas and the management of waste.

2.4 Poultry waste

Poultry waste is a mixture consisting of chicken droppings, bedding, feathers, feed crumbs, dead skin scales, etc, that are associated with poultry farming. The exponential increase of poultry farming worldwide has significantly increased the generation of waste material, which has led to the advancement of anaerobic technology as a way of mitigating harmful environmental effects through waste management and the production of biogas using poultry waste. Poultry waste/chicken manure has highly degradable material, which is suitable for biogas production using anaerobic digestion (Busato et al., 2020; Arromdee, Nawalerskasama and Saewong, 2017; Rizzo et al., 2022; Wedwitschka et al., 2020). However, poultry waste has high nitrogen content due to undigested proteins and uric acid, and as a result their microbial degradation results in the production and possible accumulation of ammonia. Excess ammonia, especially in nitrogen-rich feedstocks is a crucial factor in anaerobic digestion as it inhibits microbial growth responsible for methane production. Hence, co-digestion of nitrogen-rich poultry waste with other feedstocks is widely practised (Busato et al., 2020; Elasri and El amin Afilal, 2016).

According to Buivydas et al. (2022), co-digestion of pig fat and chicken manure was a feasible and justifiable utilisation of waste for biogas production. The authors conducted their experiments in a semi-continuous mode where they evaluated the influence of fat waste using different organic loading rates (OLR) from 3.0 to 4.5 kgVS/m^3.day. The results indicated that the biogas production yield increased and corresponded to the OLR of fat addition, demonstrating the benefits of co-digestion. For instance, at an OLR of 4.0 VS/m^3.day, the average biogas yield produced was 629.1 ± 29.9 L.kg/VS and for 4.5 VS/m^3.day it was 708.4 ± 14.5 L.kg/VS. A study by Lami, Chimdessa Egigu and Chimdessa (2017) evaluated and optimised different mixing ratios for co-digestion of poultry manure with orange peels for 21 days under mesophilic conditions. The mono-digestion of the individual feedstocks resulted in the highest biogas yield, of 659.33 mL and 218.33 mL for poultry manure and orange peels respectively. For co-digestion of 75:25 mixing ratio of poultry manure to orange peels, the cumulative biogas production observed was 768 mL. The authors indicated that increasing the concentration of orange peels above 25% resulted in a decrease in the produced biogas, total solids and volatile solids. They attributed this decrease to limonene, a chemical compound found in the peels of citrus fruits, which is reported to be harmful for anaerobic digestion. They noted that under mesophilic conditions, the compound could cause failure of the process with concentration of 400 μL/L and between 450 to 900 μL/L for thermophilic conditions. However, this chemical compound was not analysed in the study. Another study was conducted by Miah et al. (2016) where they evaluated the production of biogas from the co-digestion of poultry litter (chicken excreta of broilers, sawdust and rice hulls) with co-substrate of cow and poultry droppings. The experiments were conducted at room temperature over a period of 50 days using laboratory scale reactors marked as R1 (100% poultry litter), R2 (75% poultry litter and 25% cow dung), R3 (50% poultry litter and 50% cow dung), and R4 (70% poultry litter and 30% poultry dropping). The C/N ratio of poultry litter was found to be very low, at 7.5, which was inadequate for optimum biogas production. The results of the biogas revealed that for R1, which contained only poultry litter, the biogas production was 0.263 L/gVS. With the addition of cow dung in R2, the production was 0.460 L/gVS, which was the highest biogas production as compared to the other mixing ratios in the other reactors. It was also noted that cow dung had a higher C/N ratio, which could balance out the one of poultry litter for better performance. The biogas production yield was low in R3 at 0.419 L/gVS, which contained more dung, and even lower in R4, which contained poultry droppings at 0.221 L/gVS. Furthermore, it was also observed that the biogas production yield was very low in R1 and R4, which did not contain cow dung which stimulate the digestion with bacteria. Thus, it was revealed that poultry litter alone was not sufficient for optimum biogas production.

Busato et al. (2020) used a pilot-scale anaerobic membrane bioreactor, integrated with an ultrafiltration tube and an ammonia stripping system to prevent ammonia inhibition, to produce biogas using chicken manure under mesophilic conditions. Four different chicken manures were used with the organic loading rate gradually added from 1.0 to 7.6 kgVS/m^3.day and carefully reduced to evaluate the maximum load required for the process. The experiments showed that an organic loading rate of above 4.0 kgVS/m^3.day caused process instability, pH reduction, and the accumulation of volatile fatty acids; and even when the loading was reduced, the accumulated volatile fatty acids were not reversed by the system even over an extended period. With no ammonia-stripping system activated, the imbalance and concentration of volatile fatty acids were correlated to the inhibition of methanogenic bacteria by excess ammonia. However, the monitored and observed methane yield for the process was higher than 55% throughout, which indicated that the methanogenic bacteria were not completely inhibited. This showed that the production of biogas could greatly be enhanced with the reduction of ammonium concentration in the system. It was observed that the best system performance was with 1.4 to 2.0 kgVS/m^3.day organic loading and when an ammonia-stripping system was used. The methane production yield in the biogas was observed to be 60–70%.

3. Biogas-to-electricity system

Biogas is considered an environmentally friendly and an alternative, renewable source of energy, in comparison to non-renewable sources such as fossil fuels like coal. However, the application of biogas is often limited due to its chemical composition, which largely depends on the anaerobic digestion and the feedstock used. This implies that the type and origin of feedstock, treatment processes (digestion process), and the process parameters greatly affect the yield and quality of biogas. This shows that it is necessary for biogas to be treated to enhance its properties and remove unwanted impurities before using it for high-end applications. (with slight modifications), Figure 1 illustrates a typical process of how waste can be used to generate biogas (different applications of biogas are outlined later).

3.1 Fuel for transport

An estimated 21% or more of all greenhouse gas (GHG) emissions are attributed to transportation. This is because natural gas and fossil fuels are used most often in combustion for transportation equipment. A considerable reduction in these emissions may result from the use of biogas as a substitute for natural gas in vehicles and other equipment with combustion engines. Prior to being used as a transportation fuel, biogas, which is currently being used as such in various parts of the world (Mohanty, Mohanty and Ray, 2013; Abanades et al., 2022), must be concentrated and compressed, which requires converting it to biomethane. Biomethane is a desirable renewable energy source because of its remarkably low GHG emissions. In terms of economic value and environmental concerns, biomethane is a substantial substitute for fossil fuels (Mohanty, Mohanty and Ray, 2013; Ramírez and Gómez, 2015). It is envisioned that biomethane will serve as an alternative fuel for both light vehicles (passengers) and heavy-duty vehicles (including long-distance) in the near future (Ramírez and Gómez, 2015).

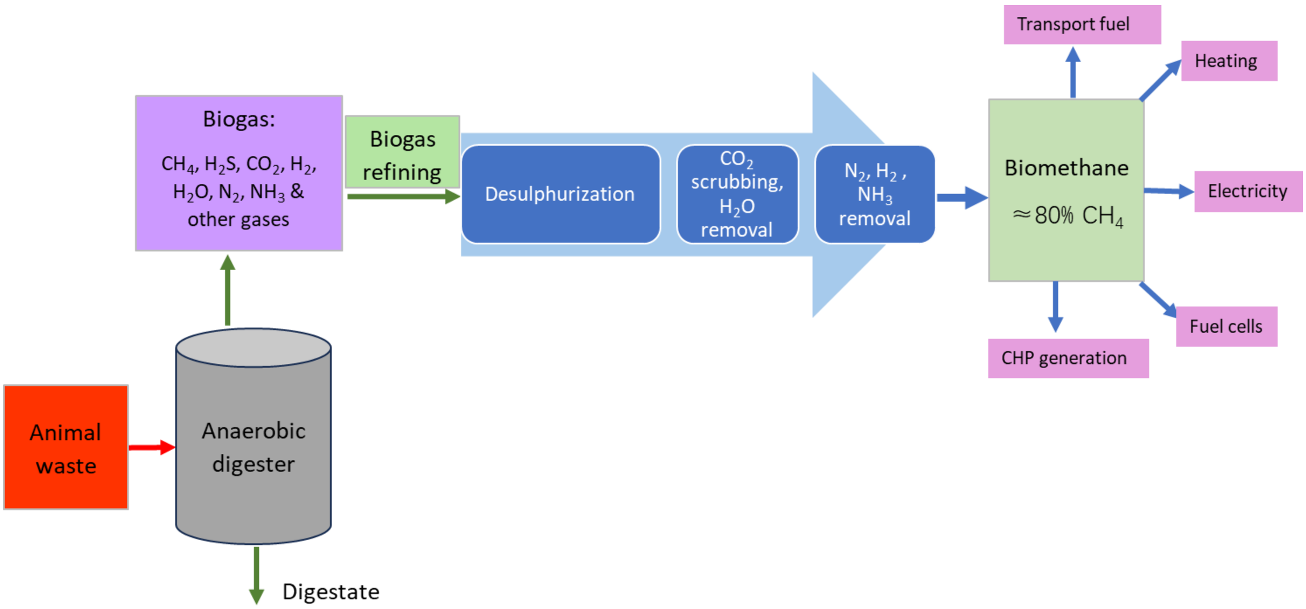

Figure 1: Process of obtaining energy from animal waste (modified from Moreroa et al., 2024).

3.2 Biogas for electricity

Due to the decline in the use of fossil fuels, the required reduction in GHG emissions, and the development of technology, the use of biogas for generating electricity is becoming more widespread andpopular globally. One benefit of biogas as a renewable energy source is its capacity to be stored and utilised later as a backup resource, as opposed to wind power which is available on a windy day or solar power which is accessible on a sunny day. It is possible to turn biogas into power that may be utilised either domestically or commercially on a big scale (Mohanty, Mohanty and Ray, 2013; Abanades et al., 2022).

A study by Arromdee, Nawalerskasama and Saewong (2017) showed the effectiveness of using chicken manure to produce biogas for electricity generation. In the study, 90 tons per day of chicken manure was processed using a plug flow anaerobic digester to produce 600 kW of electricity, while a completely stirred tank reactor produced 1 616 kW. Both systems showed significant investment efficiency and the electricity is distributed to small power plants producers. Furthermore, this study also showed that, of the different livestock (chicken, cow/buffalo, sheep/goat, swine, etc.) investigated in that year, chicken manure produce more gas than that of other livestock. Sutaryo et al. (2021) evaluated the co-digestion of dairy cow manure with cassava flour wastewater as the substrate for production of methane and further calculated the economic value of methane production by converting to electricity using a combined heat and power plant (CHP). The co-digestion treatment was observed to increase the methane yield by over 79.03%, and when the electricity generated from the CHP plant was connected to a small-voltage grid, the revenue increase was estimated to increase by USD 0.04 per ton of the substrate and USD 0.92 per ton of the substrate when connected to a high-voltage grid. A study by Arshad et al. (2022) estimated that one large cow can produce ±10 kg of dung per day and with an estimate of 42.4 million buffaloes and 51.5 million cows, a total of 92.53 million tons of dung could be collected to produce biogas of approximately 4.63 billion m^3, which is equivalent to a potential production of 19.79 terawatt-hour (TWh) of electricity per day for both cow and buffalo dung. The aforementioned demonstrate the almost limitless potential for livestock owners to generate electricity for residential purposes using biogas.

3.3 Biogas for heat generation

For heat generation, pristine biogas can be combusted in boilers. In farms, the generated heat is used for treating animal waste, heating farm buildings, operating digesters, and heating for equipment maintenance. In some farms it is used for drying, which adds a significant value to the agricultural sector. This also applies for households, where biogas is used for cooking, lighting, and heating of swimming pools. In comparison to other fuel combustion techniques, such as fossil fuels, biogas stoves emit low amount of GHGs when used appropriately. There have also been reports where biogas was used as heat energy for heating and operating distillation columns. Moreover, if there is enough heat generated, it could be sold to nearby commercial industries or districts (Abanades et al., 2022; Mohanty, Mohanty and Ray, 2013).

3.4 Injection into a natural gas grid

The composition of biogas is similar to that of natural gas, the difference being in the methane share.

However, for biogas to be supplied and used in the same infrastructure as natural gas, biogas must be processed and purified into biomethane in order to be compatible with the existing pipelines. Therefore, the conversion to biomethane is crucial source of energy that can be injected into the natural gas grid and reduce natural gas consumption and GHG emissions. The concentration and limits of biomethane will vary from country to country, as biogas upgrading is widely practised and used for different applications (Mohanty, Mohanty and Ray, 2013; Ramírez and Gómez, 2015; Abanades et al., 2022).

3.5 Combined heat and power generation

The production of combined heat and power (CHP) from biogas is a practical approach to improve the energy conversion of biogas. This approach is almost the same with that of generating electricity, but for production of CHP more investment is required for the installation of additional equipment. For these types of systems, more energy from the biogas is required, unlike when converting either heat or power, which requires fractional energy from the biogas. However, the production efficiency of this systems can be up to 90% for either heat or power, due to the cooling systems available for heat recovery (Mohanty, Mohanty and Ray, 2013; Ramírez and Gómez, 2015).

3.6 For fuel cells

Another attractive application of biogas is the generation of electricity using fuel cells. However, this approach is not widely practised, as it requires very costly fuel cells and the gas should also be very clean, so electricity from generators is more practical. In addition to specialised fuel cells, impurities such as sulphur compounds and carbon dioxide in the biogas must be removed to prevent catalyst toxicity, corrosion and an increase to gas energy capacity. Fuel cells by biogas are high-end applications as they result in low carbon dioxide and nitrogen oxides emissions, which make them suitable for power supply distributions and transport applications. Moreover, in order to further enhance their performance, fuel cells can easily be connected with other power-producing systems such as gas turbines (Mohanty, Mohanty and Ray, 2013; Ramírez and Gómez, 2015; Abanades et al., 2022).

3.7 Biogas for waste management in agriculture

Biogas is produced by the anaerobic digestion of agricultural waste, wastewater sludge, animal manure or any other organic material which provides a pathway for removing undesired and contaminating materials (Abanades et al., 2022). This is particularly important for landfills where the buildup of waste can cause explosions and release of toxic gases into the environment. Moreover, the digestate after biogas generation is considered a valuable fertilizer. The 'fertilizer', now easy to handle, with less odour, no harmful chemicals, cost-effective and environmentally friendly can easily be absorbed by more plants. This is a cost-effective way of ensuring that farm and agricultural waste is reduced and adds value through the production of biogas and later the digestate as a valuable material (Abanades et al., 2022).

4. Biogas components from different substrates

Biogas is a mixture of gases with methane and carbon dioxide as the main components. Other gases include nitrogen, hydrogen, and oxygen. There are often traces of ammonia, hydrogen sulphide, moisture, and siloxanes (Kuo and Dow, 2017; Lisowyj and Wright, 2020; Calbry-Muzyka et al., 2022; Kabeyi and Olanrewaju, 2022). Table 1 gives an example of some of the biogas compositions from different substrates. The composition of biogas largely depends on the type of feedstock used, operating conditions of the process, and the chemical composition that results from it. Hydrogen sulphide, moisture, nitrogen, oxygen, etc, are regarded as typical impurities found in biogas. Although they are present in trace amounts, their presence can cause adverse effects for biogas. Biogas is a very corrosive due to these impurities, so special materials are used for the construction of the production process, storage facilities and transportation (Lisowyj and Wright, 2020; Calbry-Muzyka et al., 2022). Additionally, the removal of these trace compounds is imperative for improving the properties, effective use and handling of biogas and is often done by pretreatment conditions. The potential application of biogas will determine how the biogas is purified (Ramírez and Gómez, 2015). The chemical composition of biogas is similar to that of natural gas, but the difference is the methane share which is higher for natural gas, at about 95-97%, while for biogas it is about 30-80% (Dimitrov et al., 2019). The quality of biogas depends on the effectiveness of the process and the feedstock used. Moreover, not all biogas processes will produce the same and equal compositions, as outlined in Table 1, which also shows that researchers are more likely to report on the quantity of methane alone and not report the other compositional elements of the biogas.

4.1 Methane

Methane is an odourless gas that is highly flammable and lighter than air. Its presence in biogas ranges from 30 to 80%. Although methane is not harmful, in confined spaces it can be a health threat due to asphyxiation owing to the displacement of oxygen. Moreover, concentrations ranging from 5 to 15%

Table 1. Typical biogas composition from various substrates

Feed-stock	*CH_4 (%)*	*CO_2 (%)*	*H_2S (%)*	*CO (%)*	*H_2 (%)*	*O_2 (%)*	*NH_3 (%)*	*N_2 (%)*	*H_2O (%)*	*Other gases (%)*	*Reference*
Cow dung	63	31	-	-	-	-	-	-	-	-	Rosenberg and Kornelius, 2017
	50.89	-	-	-	-	-	-	-	-	-	McVoitte and Clark, 2019
	67.9	27.2	0.1	4.7	-	-	-	-	-	-	Ukpai and Nnabuchi, 2012
	63.89	33.12	-	-	-	-	-	-	-	3	Abebe, 2017
	60.9	32.2	0.1	6.7	-	-	-	-	-	-	Elhenawy et al., 2021
	63.29	28.20	-	2.8	-	-	-	-	-	-	Ezekoye and Ezekoye, 2009
	61	-	-	-	-	-	-	2.32	95	-	Hamzah et al., 2023
	65.59	-	-	-	-	-	-	-	-	-	Alfa et al., 2014
	-	-	0.71	-	5.27	20.07	-	2.25	79.1	-	Nagy et al., 2019
Goat manure	53	-	-	-	-	-	-	-	-	-	Grimsby et al., 2016
	46	-	-	-	-	-	-	-	-	-	Sanchez and Wilkie, 2017
	64	12.5	-	-	-	6.2	-	-	-	-	Alham et al., 2022
Sheep manure	58	-	-	-	-	-	-	-	-	-	Nagy et al., 2019
	42	-	-	-	-	-	-	-	-	-	Sanchez and Wilkie, 2017
	66	8	-	-	-	6	-	2.0	-	-	Alma'atah, Al-zoubi and Alk-hamis, 2021
	50-60	40-50	-	-	-	-	-	-	-	-	Sankaran, Si-vaprakasam and Velayutham, 2019
	57	-	0.7	-	3.85	17.17	-	2.59	84.9	-	Nagy et al., 2019
Pig manure	69	-	-	-	5.56	-	-	-	-	-	Vanegas, Rom-ani and Jiménez, 2022
	69.43	23.22	2.00	-	-	0.4	1.6	2.2	1.15	-	Okewale and Ba-bayemi, 2018
	70.6	4.7	5.3	-	-	-	13.2	-	-	6.29	Okareh, Adeolu and Shittu, 2013
	50.83	12.62	-	-	0.017	1.97	-	-	-	-	Bertholt et al., 2021
	69	-	-	-	-B	-	-	-	-	-	Vanegas, Rom-ani and Jiménez, 2022

Feed-stock	*CH_4 (%)*	*CO_2 (%)*	*H_2S (%)*	*CO (%)*	*H_2 (%)*	*O_2 (%)*	*NH_3 (%)*	*N_2 (%)*	*H_2O (%)*	*Other gases (%)*	*Reference*
Poultry waste	49.61	20.84	1.44	-	2.66	5.19	-	-	-	-	Zobeashia et al., 2022
	60.2	38.8	-	-	0	-	-	-	-	-	Elasri and El amin Afilal, 2016
	71	-	-	-	-	-	-	-	-	-	Miah et al., 2016
	66.69	-	-	-	-	-	-	-	-	-	Busato et al., 2020
	51.59	9.98	-		0.021	2.41	-	-	-	-	Bertholt et al., 2021
	61.71	-	-	-	-	-	-	-	-	-	Alfa et al., 2014

Key: Methane – CH_4, carbon dioxide – CO_2, nitrogen – N_2, hydrogen – H_2, oxygen O_2, ammonia – NH_3, hydrogen sulphide – H_2S, moisture (water) – H_2O

could form explosive mixtures with air. Methane is a powerful GHG, with a half-life of roughly 10 years in the atmosphere and is capable of obstructing the atmospheric heat almost 20 times more than carbon dioxide (Kabeyi and Olanrewaju, 2022). A high methane content in biogas denotes a significant amount of organic matter that can be broken down by biodegradation as well as significant activity by methane-producing microorganisms. The heating capacity of biogas is determined by the methane share in the biogas: the higher the methane content, the higher the heating value. As a result, if biogas is not treated for the removal of the impurities before use in some of the potential applications, the heating value of the biogas will reduce because of the lower calorific value of methane content which will result in environmental implications and health concerns. Moreover, the high concentration of carbon dioxide and other trace impurities reduces the potential applications of biogas, its heating value and economic value (Werkneh, 2022).

4.2 Carbon dioxide
Carbon dioxide which ranges from 25 to 40%, is the second main component in biogas after methane. It is produced during the anaerobic digestion in which it acts as an electron acceptor, as it is used by the methanogenic microbes (Werkneh, 2022). Carbon dioxide is colourless and odourless. The availability of carbon dioxide in biogas reduces the quality of other gases, especially methane, and this reduces the heating capacity of biogas (Bożym and Siemiątkowski, 2020). This impacts the economic value of biogas, in transportation and high-end applications. In addition, carbon dioxide does not have a combustion value and reacts with water to form carbonic acid, which causes damage to the processing equipment, as it is highly corrosive.

4.3 Hydrogen sulphide
Hydrogen sulphide is a colourless, flammable and harmful gas with a sharp odour of rotten eggs. It has adverse implications on human health and on the environment due to the emission of sulphur dioxide generated. It is formed during anaerobic digestion from the reduction of organic sulphur compounds and sulphates from the feedstock by microbial action. The gas reacts rapidly with metals, which makes it necessary to add fresh air to desulphurise the biogas and prevent any damage by hydrogen sulphide (Kuo and Dow, 2017; Bożym and Siemiątkowski, 2020). The presence and high concentration of the gas disrupts the effectiveness of the production of biogas directly or indirectly by inhibiting the microbial activity and precipitating essential trace metals (Ahlberg-Eliasson et al., 2021). Moreover, the gas can cause corrosion to the operating equipment, pipelines and biogas storage facilities, so it is imperative to reduce and control the concentration of hydrogen sulphide in the produced biogas (Werkneh, 2022). The concentration of hydrogen sulphide in the biogas can be expected to be 0 to 3%.

4.4 Siloxanes
Siloxanes are water-soluble and semi-volatile compounds that are considered an impurity in biogas. Their presence can result in the generation of siloxane dioxide particles that are abrasive and adhesive on the surfaces of metals, causing damage to the processing unit. Siloxanes contains silicon, which is widely used in household products such as detergents, food additives, cosmetics, etc. Siloxanes are found in biogas, as they are commonly found in wastewater sludge often used for anaerobic digestion (Kuo and Dow, 2017; Werkneh, 2022).

4.5 Oxygen, moisture and ammonia

Another undesirable ingredient in biogas is oxygen, which combines with hydrogen and slightly with carbon to generate hydroxides, oxides, and water. The concentration of oxygen in the biogas, on the other hand, has a favourable influence on the concentration of hydrogen sulphide, because it suppresses the hydrogen sulphide (Bożym and Siemiątkowski, 2020). Furthermore, biogas is frequently saturated with moisture, which can cause corrosion in gas pipes. The moisture content of biogas is affected by operational conditions, particularly temperature. Biogas also contains traces of ammonia which, when it reacts with water, forms ammonium hydroxide, which is corrosive to certain metals. As an end-product of biogas, the quality of ammonia depends on the feedstock and the pH in the digester.

5. Biogas energy value from various livestock manures

Several studies have reported the energy generated by biogas in kilowatt-hours (kWh) and MJ/m^3. The quantification of methane's energy value is commonly determined using its heating value (HV), typically expressed in megajoules per cubic metre (MJ/m^3). According to the literature, the heating value of methane in its pure form has been documented as 36 MJ/m^3, resulting in the production of 55.6 MJ/kg of energy (Haryanto et al., 2017; Kusmiyati et al., 2023). To determine the energy generated by a biogas generator, it is necessary to consider the efficiency (η) of the generator or engine. The reported efficiencies are 37% (Tateishi, 2016), 43% (ClarkeEnergy, 2024), and 35-45% (Marjolaine, 2017). To facilitate calculations, a uniform efficiency of 40% will be employed for further computations. Calculation of the electricity generated from a biogas generator was performed using Equation 1.

$$Electricity = \frac{\%CH_4}{100} \times HV \times \eta \quad (1)$$

where HV is the heating value (MJ/m^3) and η is the engine efficiency. The provided information has significance, as it facilitates the determination of the biodigester's dimensions and the quantity of feed necessary to generate an adequate amount of biogas. Moreover, the collected data will assist in assessing the feasibility of utilising a biodigester as a means of generating biogas in subsequent periods. The energy value of biogas is shown in Table 2.

This review evaluated the amount of energy (kWh) needed for use in a South African residence. This was accomplished by reviewing reports from Greater Good SA (2022) and Molekoa (2023). The findings of the research indicate that an average household in South Africa requires between 30 and 33 kWh of electricity per day. The average daily energy consumption per family was determined to be 31 kWh, which equates to 111.6 MJ. Considering the generator/engine efficiency, this value will be divided by η (40%) as discussed prior to Equation 1. The proceeding energy consumption per day will thus be as in Equation 2.

$$Av.en.consumption = \frac{111.6MJ}{\eta} = \frac{111.6MJ}{0.4} = 279\ MJ \quad (2)$$

Table 2 presents the quantitative data pertaining to the electrical generation derived from methane produced by different livestock animals. Based on the available evidence, it can be observed that an equivalent amount of biogas would be required to produce 111.6 MJ of electricity. This amount ranges between 28.1 and 30.3 m^3 per feedstock. The main difference will be the number of animals required to

Table 2: Energy value of biogas from different dung/manure sources.

Dung source	*Biogas yield (m^3/kg dung)*	*Methane content* (%)*	*Methane content (m^3)*	*Electricity (MJ/m^3)*	*Biogas required to produce 111.6 MJ (m^3)*
Cow	0.04 (Energypedia, 2016)	67.9 (Hamzah et al., 2023)	0.027	9.78	28.5
Chicken	0.07 (Energypedia, 2016)	71.0 (Miah, et al., 2016)	0.05	10.2	27.3
Pig	0.06 (Energypedia, 2016)	70.0 (Okareh, Adeolu and Shittu, 2013)	0.041	9.94	28.1
Sheep	0.058 (Olowoyeye, 2013)	66.0 (Alma'atah, Alzoubi and Alkhamis, 2021)	0.038	9.5	29.4
Goat	0.065 (Olowoyeye, 2013; Alham et al., 2022)	64.0 (Alham et al., 2022)	0.042	9.22	30.3

* Derived from the highest methane content reported in Table 1.

Table 3: Daily dung/manure production from livestock animals and the eventual biogas production.

Dung source	*Dung produced per day (kg)*[ǂ]	*Methane from daily manure (m^3)*	*Electricity from daily manure (MJ/m^3)*	*Dung required to produce 111.6 MJ/m^3 (kg)*	*Animals required*	*Reference*
Cow (beef)[§]	58	1.58	22.68	713	12	American Society of Agricultural Engineers, 2003
Cow (dairy) [§]	86	2.34	33.63	713	8	American Society of Agricultural Engineers, 2003
Chicken	0.1	0.005	0.07	390	3 898	Manogaran et al., 2022
Pig	3.0	0.124	1.79	468	156	Ngwabie, Chungong and Yengong, 2018
Sheep	1.8	0.069	0.99	506	281	Schoenian, 2021
Goat	1.55	0.065	0.93	466	300	Ogejo et al., 2010

[§] Calculations based on an adult cow with 1000 kg body mass.

[ǂ] Differences within species according to usage exist.

produce the quantity of biogas, based on the dung they produce per day. This is further discussed in the subsequent section.

6. Viability of biogas usage

Most families in the rural areas of South Africa own livestock, whose manure can be used to generate biogas for home use. These include chickens, pigs, sheep, cows, and goats. While some families utilise them to ensure their food security, others use them as a means of revenue. The typical livestock animals present in South Africa were evaluated for their capacity to generate biogas in order to determine the amount of animal waste needed to power a home. Table 3 displays the biogas yield that may be produced using various types of animal dung. Equation 3 was used to calculate the dung required to meet daily requirement.

$$Dung\ req. = \frac{Dung\ Produced\ P.D \times Daily\ energy\ req.}{Electricity\ produced} \quad (3)$$

where *Dung req.* is the amount of dung required to meet the daily energy requirement of 31 kWh (kg); *Dung produced P.D* is the dung produced per animal per day (kg); *Daily energy req.* is the daily energy required by each household (MJ/m^3), which is 111.6 MJ/m^3; and *Electricity produced* is the electricity produced from the daily manure per animal (MJ/m^3).

In addition, Table 3 presents the amount of methane that may be produced from the daily excrement of livestock animals. This was calculated using Equation 4.

$$CH_4\ P.D = Dung\ P.D \times Biogas\ Yield \times \frac{\%CH_4}{100} \quad (4)$$

where $CH_4\ P.D$ is the methane produced from daily excrement (m^3); *Dung P.D* is the dung produced per animal per day (kg); Biogas Yield is the typical biogas produced from various substrates (m^3/kg dung); and $\%CH_4$ is the methane content from various substances.

7. Quantification of livestock for biogas generation

Each livestock animal was assessed for its daily excrement, to determine the number of animals one would require to obtain sufficient biogas in a day. The quantification was done by converting the biogas to methane, which was further converted to kWh and eventually compared with the daily energy requirement of 31 kWh, as shown in Table 3. Equation 5 was used to calculate the number of animals required to meet the daily energy requirement of 31 kWh or 111.6 MJ/m^3.

$$Animals\ req. = \frac{Dung\ req.}{Dung\ produced\ P.D} \quad (5)$$

where *Animals req.* is the number of animals required to produce 31 kWh of energy from biogas; and *Dung produced P.D* is the amount of dung produced by each animal per day (kg).

It seems that one would be able to produce enough biogas to power a home by owning a herd of 8 dairy cows or 12 beef cows. Given that the majority of cattle livestock owners own more than 10 cows and their calves at a time, this figure is highly plausible. Regarding the chickens, it appears that the choice is “go big or go home”, as the majority of homes would not raise many chickens at once. However, those that keep chickens for business purposes may be able to afford this amount (3 898). The number of pigs, sheep and goats required to generate sufficient energy for a day is also high for small-scale farmers or even a typical owner of livestock in their home. It seems that it is only feasible for commercial farmers to produce enough biogas to generate 31 kWh of energy per day. On a positive note, the figures presented in Table 3 are for mono-digestion, where most households would possess a few of each type of animal and also have access to other feedstock, such as kitchen waste and other biodegradable matter. Co-digestion or merging several waste types as one feedstock for the biodigester, may assist in obtaining more feedstock and thus generating more biogas.

8. Conclusions

Organic waste can be effectively exploited to create biogas, which can then be used as a source of energy. Due to the strong odour when decaying, waste like animal manure is a burden. When employed as an alternative energy source, the utilisation of such waste, which is available to the majority of low-income households, as biogas can alleviate socioeconomic issues. The two main uses of power in every household are cooking and heating, and biogas made from such waste may be used safely for both. Excess methane generated from the biodigester may also be compressed into cylinders and stored for future use. Currently, it seems like a large number of livestock is needed to produce enough biogas to power a house, but if engine efficiency is raised, these numbers can be lowered. Therefore, it is recommended that additional studies be conducted to enhance the efficiency of biogas generators.

References

Aaron O’Neill. 2023. *South Africa: Unemployment rate from 2003 to 2022*, *Statista*. https://www.statista.com/statistics/370516/unemployment-rate-in-south-africa/ (Accessed: 16 December 2023).

Abanades, S., Abbaspour, H., and Ahmadi, A. 2022. A critical review of biogas production and usage with legislations framework across the globe. *International Journal of Environmental Science and Technology*. Springer Science and Business Media Deutschland GmbH, pp. 3377–3400. https://doi.org/10.1007/s13762-021-03301-6.

Abebe, M.A. 2017. Characterisation of fruit and vegetable waste with cow dung for maximizing the biogas yield. *International Journal of Scientific Engineering and Science*, 1(1), pp. 26–32. https://www.academia.edu/33195394/Characterisation_of_Fruit_and_Vegetable_Waste_with_Cow_Dung_for_Maximizing_the_Biogas_Yield (Accessed: 1 February 2024).

Achinas, S., Li, Y., Achinas, V. and Euverink, G. 2018. Influence of sheep manure addition on biogas potential and methanogenic communities during cow dung digestion under mesophilic conditions. *Sustainable Environment Research*, 28(5), pp. 240–246. https://doi.org/10.1016/j.serj.2018.03.003.

Ahlberg-Eliasson, K., Westerholm, M., Isaksson, S. and Schnürer, A. 2021. Anaerobic digestion of animal manure and influence of organic loading rate and temperature on process performance, microbiology, and methane emission from digestates. *Frontiers in Energy Research*, 9. https://doi.org/10.3389/fenrg.2021.740314.

Alfa, M.I., Adie, D.B., Igboro, S.B., Oranusi, U.S., Dahunsi, S.O. and Akali., D.M. 2014. Assessment of biofertilizer quality and health implications of anaerobic digestion effluent of cow dung and chicken droppings. *Renewable Energy*, 63, pp. 681–686. https://doi.org/10.1016/j.renene.2013.09.049.

Alham, N.R., Siregar, I.R., Prabowo, B.D., Margono, W.C., Azhari, U.L. and Larasati, T.D. 2022. Utilization of goat manure towards PLTB (biogas) prototypes in simple way. In International conference on tropical studies and its applications, pp. 1–8. https://e-journals2.unmul.ac.id/index.php/ictrops6th/article/download/91/73/521 (Accessed: 22 November 2023).

Alma’atah, B.M., Alzoubi, A.I. and Alkhamis, T.M. 2021. Biogas production from sheep manure by a simulated underground burial system heated with cascade-controlled solar water heated system, as an indicator of biomass potential contribution to power mix in Jordan. *Journal of Environmental Protection*, 12(02), pp. 125–140. https://doi.org/10.4236/jep.2021.122009.

American Society of Agricultural Engineers, A. 2003. *ASAE D384.1 FEB03 Manure production and characteristics*. http://large.stanford.edu/publications/coal/references/docs/ASAEStandard.pdf (Accessed: 1 February 2024).

Aranguren, D.D., Acosta, M.T., Rodríguez, M.O., Seirra, R., Gordillo, R., and Gordillo, G. 2021. Analysis of the potential biogas production from pig manure in pig farms located in Colombia. In *29th European Biomass Conference and Exhibition*, pp. 600–604. https://doi.org/10.5071/29thEUBCE2021-2CV.3.13.

Arromdee, P., Nawalerskasama, A. and Saewong, N. 2017. Economic analysis of electricity generation from chicken manure by plug flow anaerobic digester and CSTR anaerobic digester. *Silpakorn University Journal of Social Sciences*, 17(3), pp. 27–50. https://thaiscience.info/Journals/Article/SUIJ/10988630.pdf (Accessed: 16 December 2023).

Arshad, M., Ansari, A.R., Qadir, R., Tahir, M.H., Nadeem, A., Mehmood, T., Alhumade, H. and Khan, N. 2022. Green electricity generation from biogas of cattle manure: an assessment of potential and feasibility in Pakistan. *Frontiers in Energy Research*, 10, p.911485. https://doi.org/10.3389/fenrg.2022.911485.

Beily, M.E., Young, B.J., Bres, P.A., Riera, N.I., Wang, W., Crespo, D.E. and Komilis, D. 2023. Relationships among physicochemical, microbiological, and parasitological parameters, ecotoxicity, and biochemical methane potential of pig slurry. *Sustainability*, 15(4), p.3172. https://doi.org/10.3390/su15043172.

Bertholt, S.S.H., Kewir, T.J., Merlain, D.K.B., Tchoumboue, N.K., Alexi, L.K., Jospin, T.G. and Leonel, N.W.B. 2021. Characterization of wet mesophilic biomethanization of three types of materials: chicken dung, rabbit poop and pig slurry. *International Journal of Sustainable and Green Energy,* 10 (4), p.145-154. 10.11648/j.ijrse.20211004.14

Bożym, M. and Siemiątkowski, G. 2020. Assessment of composition changes, stability degree and the potential of biogas formation of sewage sludge composts during maturation process. *Waste and Biomass Valorization*, 11(8), pp. 4081–4091. https://doi.org/10.1007/s12649-019-00736-4.

Buivydas, E., Navickas, K., Venslauskas, K., Žalys, B., Župerka, V. and Rubežius, M. 2022. Biogas production enhancement through chicken manure co-digestion with pig fat. *Applied Sciences*, 12(9), p.4652. https://doi.org/10.3390/app12094652.

Busato, C.J., Da Ros, C., Pellay, R., Barbierato, P. and Pavan, P. 2020. Anaerobic membrane reactor: biomethane from chicken manure and high-quality effluent. *Renewable Energy*, 145, pp.1647-1657. https://doi.org/10.1016/j.renene.2019.07.088.

Calbry-Muzyka, A., Madi, H., Rüsch-Pfund, F., Gandiglio, M. and Biollaz, S. 2022. Biogas composition from agricultural sources and organic fraction of municipal solid waste. *Renewable Energy*, *181*, pp.1000-1007. https://doi.org/10.1016/j.renene.2021.09.100.

Cestonaro, T., de Mendonça Costa, M.S.S., de Mendonça Costa, L.A., Rozatti, M.A.T., Pereira, D.C., Lorin, H.E.F. and Carneiro, L.J. 2015. The anaerobic co-digestion of sheep bedding and⩾ 50% cattle manure increases biogas production and improves biofertilizer quality. *Waste Management*, 46, pp.612-618. https://doi.org/10.1016/j.wasman.2015.08.040.

Chinwendu, S., Chibueze, U. and Tochukwu, E. 2013. Anaerobic digester considerations of animal waste. *American Journal of Biochemistry*, 2013(4), pp. 93–96. https://doi.org/10.5923/j.ajb.20130304.02.

ClarkeEnergy. 2024. *CHP efficiency for biogas*, *Biogas*. https://www.clarke-energy.com/2013/chp-cogen-efficiency-biogas/ (Accessed: 29 January 2024).

Dimitrov, R., Ivanov, Z., Zlateva, P. and Mihaylov, V. 2019. Optimization of biogas composition in experimental studies. In E3S Web of Conferences (Vol. 112, p. 02007). EDP Sciences. https://doi.org/10.1051/e3sconf/201911202007.

Elasri, O. and El amin Afilal, M. 2016. Potential for biogas production from the anaerobic digestion of chicken droppings in Morocco. *International Journal of Recycling of Organic Waste in Agriculture*, 5(3), pp. 195–204. https://doi.org/10.1007/s40093-016-0128-4.

Elhenawy, Y., El-Kadi, S., Elsawy, K., Abdelmotalip, A. and AbdelrahmanIbrahim, I. 2021. Biogas production by anaerobic digestion of cow dung using floating type fermenter. *Journal of Environmental Treatment Techniques*, 9(2), pp.446-451. https://doi.org/10.47277/JETT/9(2)451.

Energypedia. 2016. *Electricity Generation from Biogas*. *Energypedia*. https://energypedia.info/wiki/Electricity_Generation_from_Biogas#:~:text=In%20most%20cases%2C%20biogas%20is,design%20of%20an%20electric%20motor. (Accessed: 26 June 2023).

Ezekoye, V.A. and Ezekoye, B.A. 2009. Characterization and storage of biogas produced from the anaerobic digestion of cow dung, spent grains/cow dung, and cassava peels/rice husk. *The Pacific Journal of Science and Technology*, 10(2), pp. 898–904. http://www.akamaiuniversity.us/PJST.htm.

Garg, S., Attia, B., Handler, B. and Bazilian, M. 2022. Demand in the dark: Estimating the true scale of unmet electricity demand in Sub-Saharan Africa. *The Electricity Journal*, 35(8), p.107189. https://doi.org/10.1016/j.tej.2022.107189.

Gaworski, M., Jabłoński, S., Pawlaczyk-Graja, I., Ziewiecki, R., Rutkowski, P., Wieczyńska, A., Gancarz, R. and Łukaszewicz, M. 2017. Enhancing biogas plant production using pig manure and corn silage by adding wheat straw processed with liquid hot water and steam explosion. *Biotechnology for biofuels*, 10, pp.1-13. https://doi.org/10.1186/s13068-017-0922-x

Greater Good SA. 2022. *Average Electricity Consumption Per Household in South Africa*, *Greater Good*. https://www.myggsa.co.za/how-much-kwh-does-a-house-use-in-south-africa/ (Accessed: 2 June 2023).

Grimsby, L.K., Gulbrandsen, L., Eik, L.O., Msalya, G. and Kifaro, G.C. 2016. The prospect of biogas among smallholder dairy goat farmers in the Uluguru Mountains, Tanzania. *African Journal of Food, Agriculture, Nutrition and Development*, 16(1), pp.10723-10737. https://doi.org/10.18697/ajfand.73.15650.

Hamzah, A.F., Hamzah, M.H., Man, H.C., Jamali, N.S., Siajam, S.I. and Ismail, M.H. 2023. Effect of organic loading on anaerobic digestion of cow dung: Methane production and kinetic study. *Heliyon*, 9(6), p. e16791. https://doi.org/10.1016/j.heliyon.2023.e16791.

Haryanto, A., Marotin, F., Triyono, S. and Hasanudin, U. 2017. Developing a family-size biogas-fueled electricity generating system. *Int. Journal of Renewable Energy Development*, 6(2), pp.111-118. https://doi.org/10.14710/ijred.6.2.111-118.

Ji, J.L., Chen, F., Liu, S., Yang, Y., Hou, C. and Wang, Y.Z. 2022. Co-production of biogas and humic acid using rice straw and pig manure as substrates through solid-state anaerobic fermentation and subsequent aerobic composting. *Journal of Environmental Management*, 320, p.115860. https://doi.org/10.1016/j.jenvman.2022.115860.

Kabeyi, M.J.B. and Olanrewaju, O.A. 2022. Biogas production and applications in the sustainable energy transition. *Journal of Energy*, 2022, pp. 1–43. https://doi.org/10.1155/2022/8750221.

Kaur, H. and Kommalapati, R.R. 2021. Optimizing anaerobic co-digestion of goat manure and cotton gin trash using biochemical methane potential (BMP) test and mathematical modelling. *SN Applied Sciences*, 3(8). https://doi.org/10.1007/s42452-021-04706-1.

Kuo, J. and Dow, J. 2017. Biogas production from anaerobic digestion of food waste and relevant air quality implications. *Journal of the Air and Waste Management Association*, 67(9), pp. 1000–1011. https://doi.org/10.1080/10962247.2017.1316326.

Kusmiyati, K., Wijaya, D.K., Hartono, B.R., Shidik, G.F. and Fudholi, A. 2023. Harnessing the power of cow dung: Exploring the environmental, energy, and economic potential of biogas production in Indonesia. *Results in Engineering*, 20, p.101431. https://doi.org/10.1016/j.rineng.2023.101431.

Lami, M., Chimdessa Egigu, M. and Chimdessa, M. 2017. Biogas Production from co-digestion of poultry manure and orange peel through thermal pre-treatments in batch fermentation. *Technology, and Sciences (ASRJETS) American Scientific Research Journal for Engineering*, 38(2), pp. 226–246. http://asrjetsjournal.org/.

Lerede, D. and Savoldi, L. 2023. Might future electricity generation suffice to meet the global demand?. *Energy Strategy Reviews*, 47, p. 101080. https://doi.org/10.1016/j.esr.2023.101080.

Lisowyj, M. and Wright, M.M. 2020. A review of biogas and an assessment of its economic impact and future role as a renewable energy source. *Reviews in Chemical Engineering*, 36(3), pp. 401–421. https://doi.org/10.1515/revce-2017-0103.

Manogaran, M.D., Shamsuddin, R., Yusoff, M.H.M., Lay, M. and Siyal, A.A. 2022. A review on treatment processes of chicken manure. *Cleaner and Circular Bioeconomy*, 2, p.100013. https://doi.org/10.1016/j.clcb.2022.100013.

Marjolaine. 2017. *Electricity and heat production from biogas CHP: discover technologies*, *Biogas World*. https://www.biogasworld.com/news/biogas-chp-discover-technologies/ (Accessed: 29 January 2024).

Matos, C.F., Paes, J.L., Pinheiro, É.F. and De Campos, D.V. 2017. Biogas production from dairy cattle manure, under organic and conventional production systems. *Engenharia Agrícola*, 37, pp.1081-1090. https://doi.org/10.1590/1809-4430-eng.agric.v37n6p1081-1090/2017.

McVoitte, W.P.A. and Clark, O.G. 2019. The effects of temperature and duration of thermal pretreatment on the solid-state anaerobic digestion of dairy cow manure. *Heliyon*, 5(7). https://doi.org/10.1016/j.heliyon.2019.e02140.

Miah, M.R., Rahman, A.K.M.L., Akanda, M.R., Pulak, A. and 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), pp.497-504.

Mohanty, M.K., Mohanty, R.C. and Ray, N.H.S. 2013. A Study on application of biogas as fuel in compression ignition engines. *International Journal of Innovations in Engineering and Technology*, 3(1), pp. 1–8. https://www.researchgate.net/publication/330701506.

Molekoa, K. 2023. *Hydro electricity dispersed through a complex national grid system of high initial investments and maintenance*. https://riseint.org/ritc2018/wp-content/uploads/sites/4/gravity_forms/11-668ee6dabb93228a6b74b6d0fd14787c/2019/01/15-Kenny-Molekoa.pdf (Accessed: 2 June 2023).

Moreroa, M., Malematja, T.P. and Ijoma, G.N. 2024. Integrating the circular economy model into the management and treatment of Fischer–Tropsch effluents—a conversion of waste to energy (biogas) opportunity. *IET Renewable Power Generation*, pp. 1–13. https://doi.org/10.1049/rpg2.12976

Moretti, E.R., Roston, D.M., da Silva, A.J. and Reyes, I.P. 2023. Biogas from aquatic plants: A bioenergetics incentive for constructed wetlands usage. *Heliyon*, *9*(2). https://doi.org/10.1016/j.heliyon.2022.e12537

Mrosso, R., Mecha, A.C. and Kiplagat, J. 2023. Characterization of kitchen and municipal organic waste for biogas production: Effect of parameters. *Heliyon*, 9(5), p. e16360. https://doi.org/10.1016/j.heliyon.2023.e16360.

Mueni, P. and Apindi, C. 2023. *Prepaid electricity rates in South Africa 2023: how does it work?*, *Briefly*. https://briefly.co.za/105425-prepaid-electricity-rates-south-africa-work.html (Accessed: 27 June 2023).

Nagy, G., Takács, A. and Kállay, A.A. 2019. The energy aspects of biogas production from sheep manure. *Carbon*, *29*, pp.37-70.

Ndubuisi-Nnaji, U.U., Ofon, U., Asira, A.E., and Dickson, N.J. 2023. Anaerobic digestion of untreated manure: Environmental risk assessment of resultant digestates. *World Journal of Applied Science & Technology*, 14(1b), pp. 73–79. https://doi.org/10.4314/wojast.v14i1b.73.

Ngwabie, N.M., Chungong, B.N. and Yengong, F.L. 2018. Characterisation of pig manure for methane emission modelling in Sub-Saharan Africa. *Biosystems Engineering*, 170, pp. 31–38. https://doi.org/10.1016/j.biosystemseng.2018.03.009.

Ogejo, J.A., Wildeus, S., Knight, P. and Wilke, R.B. 2010. Estimating goat and sheep manure production and their nutrient contribution in the Chesapeake Bay watershed. *Applied engineering in agriculture*, 26(6), pp.1061-1065. https://doi.org/10.13031/2013.35912.

Okareh, O.T., Adeolu, A.T. and Shittu, O.I. 2013. Enrichment of pig dung with selected crop wastes for the production of biogas. *International Research Journal of Medicine and Medical Sciences*, 04(04). https://doi.org/10.14303/irjm.2012.093.

Okewale, A.O. and Babayemi, K.A. 2018. Anaerobic co-digestion of pig and poultry droppings with elephant grass for the production of biogas. *Journal of Renewable Energy and Smart Grid Technology*, 13(1), pp. 50–64.

Olowoyeye, J. 2013. Comparative studies on biogas production using six different animal dungs. *Journal of Biology, Agriculture and Healthcare*, 3(15), pp. 7–12. www.iiste.org.

Otobrise, C., Udubor, C.W. and Osabohien, E. 2022. Kinetics of biogas production from goat dung and pawpaw seed. *Oriental Journal Of Chemistry*, 38(4), pp. 914–923. https://doi.org/10.13005/ojc/380411.

Pereira, F.E.D.A., Rosa, A.P., Borges, E.S., Otenio, M.H., Souza, L.D.D., do Nascimento, J.E. and Borges, A.C. 2023. Anaerobic co-digestion of swine and laying hen waste for biogas generation and digestate quality. *Engenharia Agrícola*, *43*, p.e20220124.

Ramírez, M., Gómez, J.M., Cantero, D., Ramírez, M., Gómez, J. and Cantero, D. 2015. Biogas: sources, purification and uses. *Hydrogen and Other Technologies*, *11*(12), pp.296-323.

Risberg, K., Cederlund, H., Pell, M., Arthurson, V. and Schnürer, A. 2017. Comparative characterization of digestate versus pig slurry and cow manure–Chemical composition and effects on soil microbial activity. *Waste management*, 61, pp.529-538.

Rizzo, P.F., Salinas, M.C., Della Torre, V., Diez, J.P., Sallesses, L.F., Riera, N.I., Pathauer, P.S., Komilis, D. and Sánchez, A. 2022. Effect of poultry manure-derived compost on the growth of eucalypts spp. hybrid clones. *Processes,* 10(11), pp.2182.

Rosenberg, L. and Kornelius, G. 2017. Experimental investigation of biogas production from feedlot cattle manure. *Journal of Energy in Southern Africa*, 28(4). https://doi.org/10.17159/2413-3051/2017/v28i4a1753.

Sanchez, C. and Wilkie, A.C. 2017. Bioenergy production potential from small ruminant manure. *Journal of Undergraduate Research*, 18(3), pp. 1–4.

Sankaran, S., Sivaprakasam, S. and Velayutham, T. 2019. Biogas production by co-digestion of municipal solid waste generated from vegetable market area and sheep dung. *Journal of Emerging Technologies and Innovative Research*, 6(5), pp. 386–397. www.jetir.org.

Schoenian, S. 2021. *A beginner's guide to raising sheep*, *Sheep 201*. https://www.sheep101.info/201/ (Accessed: 27 November 2023).

Singh, D., Tembhare, M., Machhirake, N. and Kumar, S. 2023. Biogas generation potential of discarded food waste residue from ultra-processing activities at food manufacturing and packaging industry. *Energy*, *263*, pp.126138.

Sutaryo, S., Adiwinarti, R., Abi Sudrajad, M., Sari, T.Y.K., Khayati, L.N., Ward, A.J. and Purnomoadi, A. 2021. Enhancing methane production of dairy cow manure by co-digestion with modified cassava flour waste water. *Analytical methods*, *120*(4.24), pp.13-59.

Tateishi, T. 2016. *Development of High Efficiency BP-G 300kW-Class Biogas Co-Generation System*, *Yanmar Energy System*. https://www.yanmar.com/global/about/technology/technical_review/2016/0727_1.html#:~:text=The%20BP%2DG%20power%20generation,23.3MJ%2FNm3). (Accessed: 29 January 2024).

Tian, P., Gong, B., Bi, K., Liu, Y., Ma, J., Wang, X., Ouyang, Z. and Cui, X. 2023. Anaerobic co-digestion of pig manure and rice straw: Optimization of process parameters for enhancing biogas production and system stability. *International Journal of Environmental Research and Public Health*, *20*(1), pp.804.

Toma, L., Voicu, G., Ferdes, M. and Dinca, M. 2016. Animal manure as substrate for biogas production. *Engineering for Rural Development*, *25*(27), pp.5.

Ukpai, P.A. and Nnabuchi, M.M. 2012. Comparative study of biogas production from cow dung, cow pea and cassava peeling using 45 litres biogas digester. *Advances in Applied Science Research*, 3, pp. 1864–1869.

Vanegas, M., Romani, F. and Jiménez, M. 2022. Pilot-Scale anaerobic digestion of pig manure with thermal pretreatment: stability monitoring to improve the potential for obtaining methane. *Processes*, 10(8), pp. 1602. https://doi.org/10.3390/pr10081602.

Wedwitschka, H., Ibanez, D.G., Schafer, F., Jenson, and Nelles, M. 2020. Material characterization and substrate suitability assessment of chicken manure for dry batch anaerobic digestion processes. *Bioengineering*, 7(3), pp. 1–16. https://doi.org/10.3390/bioengineering7030106.

Werkneh, A.A. 2022. Biogas impurities: environmental and health implications, removal technologies and future perspectives. *Heliyon*. Elsevier Ltd, pp. 1–16. https://doi.org/10.1016/j.heliyon.2022.e10929.

Ya'aba, Y. and Ramalan, A.S. 2020. Isolation, identification and characterization of some bacteria associated with biogas production from cow dung. *Equity Journal of Science and Technology*, 7(2), pp. 91–99. www.equijost.com.

Zobeashia, S.S.T., Abioye, O.P., Ijah, U.J.J. and Oyewole, O.A. 2022. Physicochemical parameters and microbial community in anaerobic digestion of organic wastes. *Advance in Environmental Waste Management & Recycling*, 1(1), pp. 1-12.