WASTE REIMAGINED: BIOGAS ENERGY RECOVERY FROM ANIMAL DUNG IN THE ERA OF CIRCULAR ECONOMY

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Akatah, B.M.[1], Onungwe, I.[2] Oyetunji, A. B.[3,4], Bariture, L.C.[5], Eegbara, L.[1]

[1*] Civil Engineering Department, Kenule Beeson Saro-Wiwa Polytechnic, Bori, Rivers State, Nigeria
[2] Department of Civil Engineering, University of Birmingham, United Kingdom
[3] Department of Estate Management, Faculty of Environmental Sciences, University of Benin, Benin City, Nigeria
[4] Lancaster Environment Centre, Lancaster University, United Kingdom
[5] Industrial Safety and Engineering Department, Kenule Beeson Saro-Wiwa Polytechnic, Bori, Rivers State, Nigeria
Corresponding author's email: akatah.barry@kenpoly.edu.ng

Abstract

Most developing nations are faced with energy crisis and waste management problems. To solve these problems, a transition from sole dependence on fossil fuels due to their high cost, scarcity, and environmental pollution to a more circular, economy-based, and environmentally friendly source of energy that can promote sustainable waste management becomes promising. Therefore, the massive quantity of animal dung from animal husbandry provides a considerable amount of feedstock that can be accessed for biogas generation as a reimagined process for recovering energy from waste. The paper aimed at using dung from 368,557,554 livestock in Nigeria as a significant resource for energy generation. The emphasis is on dung, considering the amount of biogas produced from 1kg of dung and the energy volume that can be generated from biomass using excreta. This work primarily adopted secondary data to present Biogas as a significant fuel source in Nigeria. Based on statistical data, the methodology applied mathematical computation to ascertain the daily waste generation. The results revealed that the daily quantity of manure generated is 457,025.6 tons. The estimated total human waste per day is 250,463.4 tons, and the total amount of manure produced *daily by livestock is 206,562.2 tons; human excreta amount 12,523,170m^3 of biogas daily and 4,570,957,050m^3 annually, and livestock produces 7,939,294.6m^3 of biogas daily and 2,897,842,529m^3 annually indicating that Nigeria can generate 14,937,599,158m^3 of biogas from waste. The estimated thermal energy generated from manure as a resource for energy conversion in Nigeria equals 122,774,787.6kWh and 44,812,797,474kWh (44.813 billion kWh).*

Keywords: *Waste, Resource, Biogas, Renewable Energy, Circular Economy, Animal Dung*

1. Introduction

In an era characterized by increasing environmental imperatives and demands for sustainable energy solutions, biogas recovery from animal dung is a pivotal contribution to energy management and waste reduction. This paper points to the potential for integrating biogas systems within circular economy principles by elucidating the interdependent relationships among waste management, renewable energy generation, and environmental sustainability. Furthermore, the paper articulates how biogas energy recovery challenges traditional economic paradigms, thereby fostering a holistic, systemic transformation wherein biogas systems can be applied to implement animal dung to generate energy in circularity.

The global transition toward sustainability necessitates innovative approaches that address energy shortages and rethink waste management practices (Giurea et al., 2024). Biogas production from animal dung offers a multifaceted solution that aligns with circular economy principles, turning waste into a resource(Sadeghpour and Afshar, 2024). This paper seeks to theoretically contribute to the discourse on the circular economy by disseminating comprehensive insights into biogas energy recovery, examining its implications for systems thinking, and proposing a model that enhances efficacy in waste management and the energy sectors.

Most developing nations are faced with an energy crisis and waste management problems. Nigeria is no exception due to its severe energy crisis and waste mismanagement. To provide a solution to these problems, a transition from solely depending on fossil fuel (coal and crude oil) and natural gas as its sources of fuel is imperative due to the high cost, scarcity, and environmental pollution arising from industrial operations involving fossil fuel production, to a more circular economy based and environmentally friendly sources of energy conversion that can promote sustainable waste management. In this light, utilizing the dung from the rapid increase in animal husbandry in most countries, Nigeria alike, to create a considerable amount of feedstock that can be accessed for biogas generation as a reimagined process for recovering energy from waste becomes promising.

The use of dung as a resource for biogas production in developing nations points to the application of circuitry (Lubańska and Kazak, 2023; Sibanda and Uzabakiriho, 2024). This process enhances sustainable waste management and renewable energy generation (Atchike et al., 2022). Due to the prevalence of livestock, animal dung is available in many rural regions(Herrero et al., 2013). Rather than considering the dung a simple waste product, biogas technology can be achieved through anaerobic digestion to transform such waste into methane-rich biogas (Hamzah et al., 2023; Alkhrissat, 2024). This will, in turn, reduce environmental pollution caused by the disposal of untreated animal dung and offer a sustainable energy source (Atchike et al., 2022; Khalil et al., 2019).

Studies show that biogas plants can produce large amounts of energy, which is advantageous to developing countries due to the lack of access to dependable energy sources (Yasar et al., 2017). The promising benefits of animal dung, which yields digestate, an organic fertiliser through anaerobic digestion and biogas for cooking and lighting, can be harnessed for various purposes (Roopnarain and Adeleke, 2017; Ahlberg-Eliasson et al., 2021). With the global demand for energy consumption projected to double by 2035 (Odgaard and Delman, 2014; Rawat et al., 2011); implementing biogas technology in developing countries on the premise of waste as a resource will facilitate socio-economic and environmental benefits leading to energy security, reduction in household energy costs, and health improvement outcomes from mitigating indoor air pollution due to traditional burning of biomass fuels (Surie, 2017; Jameel et al., 2024). In countries like India, the National Biogas Project has created local jobs, supported economic development, and empowered women by reducing their labour burden in fuel collection (Raha et al., 2014). Such can be replicated in other countries, such as Nigeria. However, several challenges are associated with the successful scaling and the sustainability of biogas systems in developing countries, including technological barriers, capital costs, level of awareness, lack of adequate policy support and government willpower, and stakeholders' engagement. If these challenges are overcome, the waste-to-energy initiative is seen to be a promising path to drive through sustainability opportunities (Muvhiiwa et al., 2017; Patinvoh and Taherzadeh, 2019).

A nation suffering from energy crises is regarded as underdeveloped because energy is a critical and essential amenity for the development and economic growth of any country (Anushiya, 2010; Rabah et al., 2010; Kabeyi and Olanrewaju, 2022). Nigeria had a significant energy source from fossil fuel, a finite resource bound to be exhausted with time. Also, fossil fuels are associated with greenhouse gases. Its continuous usage is detrimental to human health and the environment, leading to climate change, environmental pollution and degradation (Seyitoglu and Avcıoğlu, 2021; Ahmed et al., 2018), as well as high purchasing costs occasioned by the scarcity of the commodity (Budiyono et al., 2014). Therefore, the time is right to encapsulate and implement the ethos of circularity in achieving alternative energy sources, such as transforming animal dung through biomass production into a valuable resource to promote environmental sustainability, enhance energy access, and foster economic development in most developing countries, by transitioning from the use of fossil fuels, which have negative environmental impacts, to more reliable and sustainable energy sources (Sawle et al., 2018). However, many scholars have proposed the adoption of renewable energy sources, including solar power, hydropower, wind power, etc, which are eco-friendly (Choi et al., 2020; Stagnaro et al., 2020; Ayedun et al., 2023). These energy sources require substantial economic value and a technical workforce. (Anushiya, 2010; Olowoyeye, 2013). Hence, biogas is necessary as an alternative fuel source from vast waste materials. Biogas energy can be reliable, readily available, and economically viable for Nigeria. Countries like China, Georgia, and Malaysia have long identified this option.

The concept of circularity emphasizes rethinking waste not as outright discardable materials but as potentially valuable recoverable resources for reuse (Mukherjee et al., 2023; Onungwe et al., 2024; Palafox-Alcantar, 2022), constituting a paradigm shift crucial in addressing waste management and energy sustainability challenges. In this context, producing biogas from organic waste presents a viable solution that mitigates waste disposal issues while contributing to renewable energy generation (Khan and Kaneesamkandi, 2013; Kabeyi and Olanrewaju, 2022). Studies suggest that anaerobic digestion, the primary process for biogas production, can significantly reduce greenhouse gas emissions, which is a major environmental problem caused by fossil fuel, while offering a sustainable energy source (Moraes et al., 2017; Fusi et al., 2016).

In addition to lowering greenhouse gas emissions, biogas is a helpful method of recovering energy from waste (Yi et al., 2018). It is an environmentally friendly energy source created when organic components, such as food waste, sewage sludge, and agricultural residues, are broken down anaerobically (Lin et al., 2018). Methane (CH4) and carbon dioxide (CO2), together with trace amounts of other gases, are the main components of the biogas process as microbes break down organic molecules in the absence of oxygen (Sivamani et al., 2021; Atelge et al., 2020). The methane in biogas can be harnessed for various applications, including electricity generation, heating, and as a vehicle fuel, thereby making biogas a versatile and sustainable alternative to fossil fuels (Korbag et al., 2020; Kabeyi and

Olanrewaju, 2022). The composition of biogas can vary significantly based on the type of feedstock used and the conditions of the anaerobic digestion process (Bharathiraja et al., 2018; Deepanraj et al., 2014). Typically, the methane content in biogas ranges from 50% to 70%, while the carbon dioxide content can range from 30% to 50% (Kabeyi and Olanrewaju, 2022; Koniuszewska et al., 2020; Tanigawa, 2017). The digestion byproduct, known as digestate, can also be utilised as a nutrient-rich fertiliser, thereby closing the loop in organic waste management and promoting a circular economy system (Peng and Pivato, 2019).

In other words, biogas is produced by an anaerobic digestion process. Biogas is a gas produced when bacteria degrade biological materials or organic matter without oxygen (Sambo et al., 1995,;Olowoyeye, 2013; Zupančič and Grilc, 2012). The breaking down process of the organic wastes (matters) in the absence of oxygen is called anaerobic digestion. Hence, biogas production requires anaerobic treatment of organic wastes (matters). This leads to the stabilisation of the materials and the gas release. Biogas is a mixture of methane, carbon dioxide and other gases, such as nitrogen and oxygen, in minimal quantities (Rabah et al., 2010; Cassidy et al., 2008; Pavičić et al., 2022). Biogas is rich in methane (50-75%) and can be used directly for heating, cooking, lighting power generation, etc (Kabeyi and Olanrewaju, 2022; Mydin et al., 2014). It is flammable and can produce heat having a temperature of up to 1400˚c (Gupta et al., 2023). Biogas usage has certain advantages over the use of fossil fuels. The benefits are low cost compared to fossil fuels, reduction of the greenhouse effect and global warming, pollution-free, low-scale production, etc. The other benefits of biogas include the treatment of feedstocks and the production of digestate, which is a beneficial organic fertilizer (Jurgutis et al., 2021; Kabeyi and Olanrewaju, 2022). Biogas is produced from organic wastes such as human faces, animal dung, chicken droppings, agricultural wastes, wastewater from treatment plant sludge, etc (Atelge et al., 2020; Abdeshahian et al., 2016). These wastes can be used as nutrients and fuel energy sources, which can be converted into energy as a supplement or alternative to fossil energy (Okoro et al., 2020; Mignogna et al., 2023). Nigeria has abundant waste for energy production (Abila, 2014, Sokan-Adeaga and Ana, 2015). According to (Oyeleke et al., 2003; Mshandete and Parawira, 2009), Nigeria can produce 227,500 tons of animal waste (dung) per day. This is a massive resource for solving Nigeria's energy crisis if adequately harnessed. The use of waste, mostly excreta, for energy production has been extensively studied. In most studies, excreta are used to produce biogas. Some excreta considered in those studies include chicken droppings (Tańczuk et al., 2019), goat excreta (Washaya and Washaya, 2023; Adeoti et al., 2014), cattle dung(Saleh and Jibrin, 2020), pig excreta (Wang et al., 2021; Silva et al., 2018), dog dung (Taylor, 2004; Okoroigwe et al., 2010), horse dung (Yusuf et al., 2011; Svanberg et al., 2018), human faeces (Donacho et al., 2023), and sheep manure (Osuhor et al., 2002; González et al., 2021). Their studies estimated the volume of biogas from 1kg of each excreta. Also, (Energypedia, 2010) estimated the equivalent quantities of diesel and thermal energy generated from 1m^3 biogas. According to their work, the thermal energy available from methane contained in biogas is about 6-8KWh/m^3, which corresponds to 0.5 litres of diesel. Considering the abundant waste in Nigeria and the available information, waste is a good resource for tackling the energy crisis in Nigeria. Also, the rapid increase in animal husbandry in most countries creates a considerable amount of feedstock that can be accessed for biogas generation as a reimagined process for achieving sustainable waste-to-energy (Khalil et al., 2019). Figure 1 diagrammatically presents the sequence of achieving renewable products through various processes, from livestock dung (Nehra and Jain, 2023).

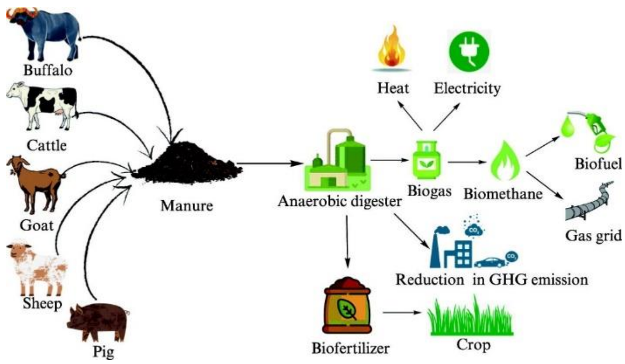

Figure 1: Renewable Products from Livestock Dung *(Nehra and Jain, 2023)*

2. Theoretical Framework

2.1 Reconceiving Waste in the Circular Economy and Agricultural Sustainability

Traditionally, waste has been viewed as an economic liability, but a circular economy reimagines waste as a valuable resource(Perey et al., 2018). This paradigm shift necessitates theoretical exploration of the waste-to-resource continuum, invoking concepts from ecological economics that support systems thinking and resource regeneration, emphasising how animal dung can be a source of sustainable energy generation bioeconomy (Bocken et al., 2016). Furthermore, biogas is critical in the energy transition because it epitomises the transition from conventional to renewable energy sources(Madheswaran et al., 2024). The ecological modernisation theory suggests technological advancements such as anaerobic digestion for decoupling economic growth from environmental degradation(Bergendahl et al., 2018). This paper will integrate this theory to illustrate how biogas systems can drive energy transitions and sustainable agricultural practices. In essence, biogas recovery can improve farm-level waste management and enhance energy security (Kumar et al., 2024). The conversion of animal waste to biogas can help to close nutrient loops by turning waste into energy and manure, offering farmers a cost-effective solution which can boost productivity and harvest yield (Sagar and Kartha, 2007, Cornelissen et al., 2012).

2.2 Environmental and Economic Benefits

Waste management reimagined through biogas systems provides a decentralised solution that significantly reduces the environmental burden of animal waste (Smith, 2023; Phillips, 2024). Based on the theoretical consideration of environmental considerations, this paper posits that biogas systems contribute to ecological resilience and should be considered crucial components of community-level waste management strategies. Integrating biogas into waste management techniques frameworks can redefine local economies by reducing waste treatment costs and enhancing local sanitation and environmental quality, thereby maximising the value of resources and minimising environmental impact (Lacy and Rutqvist, 2015). Biogas production reduces GHG emissions, mainly methane, and enhances waste management within the environment (Chojnacka and Moustakas, 2024).

2.3 Modelling Renewable Energy Contribution and Economic Policy Viability

From a systems perspective, biogas production offers a unique model of energy generation that not only reduces reliance on fossil fuels but contributes to energy security, particularly in rural areas(Iqbal et al., 2021; Kabeyi and Olanrewaju, 2022). This section will provide a theoretical model linking biogas energy recovery to energy resilience, incorporating metrics such as energy independence, local job creation, and sustainable agricultural practices while also addressing socio-economic implications for farming communities, of which Nigeria is considered one.

Also, integrating biogas systems requires supportive economic policies and innovative financing models. Research such as this will engineer policymakers to enact laws supporting sustainable animal dung treatment frameworks. Such can be explored through the theory of public-private partnerships, incentives for renewable energy production, and investment in green technologies, which aligns energy and agricultural sectors in the context of circular economy objectives (Uhunamure et al., 2021; Alengebawy et al., 2024).

However, the biomass waste-to-energy approach has known challenges and limitations, including technological limitations, investment costs, and social acceptance (Vrabie, 2021). Viewing these barriers within the context of innovation diffusion theory, network theory, and stakeholder theory points to strategies for overcoming these barriers through integrated collaboration and knowledge sharing, which aligns with effectively integrating biogas systems into the circular economy principle (Uhunamure et al., 2021; Rocha-Meneses et al., 2023).

3. Methodology

The data used in this study is primarily sourced from validated, updated, and reliable secondary sources. The data were collated, presented in tabular form, and analysed using mathematical principles to ascertain relevant results, as shown in the results section.

3.1 Determination of animal and human population in Nigeria

The amount of organic material available must be known to calculate Nigeria's biogas production potential from human and animal waste. Therefore, the number of chickens, goats, cattle, sheep, horses, pigs, donkeys, giant rats, rabbits, camels, dogs, guinea pigs, and other birds was investigated. The animal population was obtained from the work carried out and published by (Bourn et al., 1994; FAOSTAT, 2021; FAJEMISIN, 2023). The United Nations population estimates report for Nigeria in 2024 determined the human population adopted for the current research.

3.2 Determination of the daily waste generation in Nigeria

The total waste generated per day by humans and livestock was analysed and estimated using Equation 1.

$$T_W = P * W_D \tag{3.1}$$

Where T_W = Total waste generated per day

W_D = Average daily waste generated per kilogram per head

P = Population of humans or livestock.

Determination of the volume of biogas

The total volume of biogas generated from waste (dung) was analysed and estimated using Equation 2.

$$T_V = T_W * V_b \tag{3.2}$$

Where T_V = Total volume of biogas generated from each waste type in m^3

V_b = Volume of biogas per kilogram from each waste type.

4. Results and Discussion

The results of the biogas and energy potentials of human and animal wastes in Nigeria are presented in the tables below. The tables consist of the livestock population, total waste generated from human and animal wastes per day, estimated total quantities of daily excreta generation, estimated volume of biogas produced from human and selected livestock wastes per day and calculated daily and yearly thermal energy from the estimated waste or manure.

Table 1: Nigeria livestock population estimates.

Livestock	Population	% Population
Cattle	21162929	5.73
Chicken	166564000	45.19
Goats	76292153	20.70
Sheep	48637013	13.20
Pigs	8092066	2.20
Dogs	4500000	1.22
Horses	107357	0.03
Donkeys	900000	0.24
Camels	293,915	0.08
Cats	3,300,000	0.90
Rabbits and hares	4939000	1.34
Guinea pigs	500000	0.14
Asses	1369121	0.37
Other Poultry	31900000	8.66
Total	**368557554**	**100**

Source: ***(Bourn et al., 1994, FAJEMISIN, 2023)***

Table 1 shows the livestock population in Nigeria. The information is based on the data provided by the 2021 Food and Agriculture Organization (FAO) of the United Nations. From the table, chickens have the highest population, with a value of 166,564,000, representing 45.19% of the livestock population. It is followed by goats, with 20.7 % of the population; sheep, with 13.5%; other birds, with 8.66%; cattle, with 5.74%; and other livestock, with 6.51%. A statistical presentation is shown in a pie chart in Figure 2.

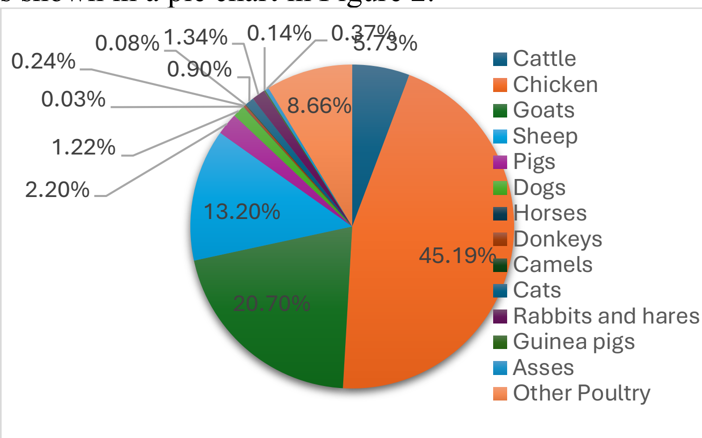

Figure 2: statistical presentation of Livestock Population in Percentage

Table 2: Total Waste Generated from Human and Animal Wastes per day in Nigeria

Human/ livestock	Population	Average daily waste generated per head (kg)	Total waste generated per day (ton)	References
Human	229152217	1.093	250,463.4	(Donacho et al., 2023)
Cattle	21162929	5.4	114,279.82	(Saleh and Jibrin, 2020, FAOSTAT, 2021)
Chicken	166564000	0.09	14,990.76	(Tańczuk et al., 2019, FAOSTAT, 2021)
Goats	76292153	0.38	28,991.02	(Washaya and Washaya, 2023)
Sheep	48637013	0.38	18,482.06	(Osuhor et al., 2002, FAOSTAT, 2021)
Pigs	8092066	3.33	26,946.58	(Wang et al., 2021, FAOSTAT, 2021)
Dogs	4500000	0.34	1,530	(Bourn et al., 1994, Taylor, 2004)
Horses	107357	12.5	1,341.96	(Yusuf et al., 2011, FAOSTAT, 2021)
Donkeys	900000	-	-	[(Bourn et al., 1994)
Camels	293,915	-	-	(FAOSTAT, 2021)
Cats	3,300,000	-	-	(Bourn et al., 1994)
Rabbits and hares	4939000	-	-	(Bourn et al., 1994)
Guinea pigs	500000	-	-	(Bourn et al., 1994)
Asses	1369121	-	-	(FAOSTAT, 2021)
Other Poultry	31900000	-	-	(FAJEMISIN, 2023)

Table 3: Estimated total Quantities of Daily Excreta Generated

Human and Livestock	Total waste Generated per Day (Tons)
Cattle	114,279.82
Chicken	14,990.76
Goats	28,991.02
Sheep	18,482.06

Pigs	26,946.58
Dogs	1,530
Horses	1,341.96
Total	206,562.20

Tables 2 and 3 show the average daily waste generated per head and the estimated total waste generated daily from humans and livestock in Nigeria. According to the table, the estimated total human waste per day is 250,463.4 tons (250,463,400kg). The estimated animal waste generated by the different livestock based on the available average daily waste generation per livestock data indicates that cattle produce 114,279.82 tons of dung, chickens produce 14,990.76 tons, goats produce 28,991.02 tons, sheep produce 18,482.06 tons, pigs produce 26,946.58 tons, dog produce 1,530 tons and horses produce 1,341.9 tons. The daily waste generation by other livestock was not determined as their average daily waste production rate was unavailable. From Table 3, the total quantities of manure produced daily by the livestock is 206,562.2 tons. Based on available statistics, the daily amount of manure generated in Nigeria is 457,025.6 tons.

Table 4: Quantity of Fresh Waste Produced daily in Nigeria in (Tons)

Fresh waste	Amount (Tons)
Animal waste	227500
Human faeces	250,463.4

Source: (Oyeleke et al., 2003, Rabah et al., 2010)

Table 4 shows the quantities of fresh waste produced per day in Nigeria. According to the table, Nigeria produces 227,500 tons of fresh animal waste each year and 250,463.4 tons of fresh human waste.

Table 5: Estimated Volume of Biogas Produced from Human and Livestock Wastes in Nigeria

Waste type	Total waste generated per day (Tons)	Volume of biogas produced per kilogram per day (m^3)	Estimated quantities of biogas per day from each excreta (m^3)	Quantities of biogas per year from each excreta (m^3)
Human excreta	250,463.40	0.05	12523170	4570957050
Cattle dung	114,279.82	0.04	4571192.8	1668485372
Chicken droppings	14,990.76	0.07	1049353.2	383013918
Goat excreta	28,991.02	0.03	869730.6	317451669

Sheep excreta	18,482.06	0.03	554461.8	202378557
Pig excreta	26,946.58	0.03	808397.4	295065051
Dog excreta	1,530	0.03	45900	16753500
Horse excreta	1,341.96	0.03	40258.8	14694462
Total			**20462464.6**	**14937599158**

Table 5 shows the volume of biogas that can be produced from excreta generated in Nigeria. From the result, human excreta can produce 12,523,170m^3 of biogas per day and 4,570,957,050m^3 annually. Livestock in Nigeria can produce 7,939,294.6m^3 per day of biogas and 2,897,842,529m^3 annually. By implication, if this resource is correctly harnessed, Nigeria can generate 14,937,599,158m^3 of biogas from dung. This, in actual application, will provide alternative renewable energy and promote environmental sanitation in the context of waste management based on the circular economy principle.

Table 6: Estimated daily and yearly Thermal Energy from Excreta in Nigeria

Waste type	**Total Volume of biogas produced per from each waste type day (m^3)**	**Thermal energy per cubic meter of biogas (kWh)**	**Estimated daily total thermal energy (kWh)**	**Estimated yearly total thermal energy (kWh)**
Human excreta	12523170	6	75139020	27425742300
Cattle dung	4571192.8	6	27427156.8	10010912232
Chicken droppings	1049353.2	6	6296119.2	2298083508
Goat excreta	869730.6	6	5218383.6	1904710014
Sheep excreta	554461.8	6	3326770.8	1214271342
Pig excreta	808397.4	6	4850384.4	1770390306
Dog excreta	45900	6	275400	100521000
Horse excreta	40258.8	6	241552.8	88166772
Total			**122774787.6**	**44812797474**

Table 6 shows the estimated daily and yearly thermal energy that can be generated from using excreta as a resource for energy generation in Nigeria. From the table, 122,774,787.6 kWh of thermal energy can be generated daily in Nigeria. This generates 44,812,797,474 kWh (44.813 billion kWh) of thermal energy annually.

Table 7: Estimated Daily and yearly Equivalent Quantities of Diesel from Excreta in Nigeria

Waste type	**Total Volume of biogas produced per from each waste type day (m^3)**	**quantity of diesel per cubic meter of biogas (Liter)**	**Estimated daily total quantities of diesel (Liter)**	**Estimated yearly total quantities of diesel (Liter)**
Human excreta	12523170	0.5	6261585	2285478525
Cattle dung	4571192.8	0.5	2285596.4	834242686
Chicken droppings	1049353.2	0.5	524676.6	191506959
Goat excreta	869730.6	0.5	434865.3	158725834.5
Sheep excreta	554461.8	0.5	277230.9	101189278.5
Pig excreta	808397.4	0.5	404198.7	147532525.5
Dog excreta	45900	0.5	22950	8376750
Horse excreta	40258.8	0.5	20129.4	7347231
Total			**10231232.3**	**3734399790**

Table 7 shows the estimated daily and yearly equivalent quantities of diesel that can be produced using excreta as a resource for energy generation in Nigeria. Based on Table 7, 10,231,232.3 litres equivalent of diesel can be produced per day from excreta produced in Nigeria, which amounts to 3,734,399,790 litres equivalent of diesel annually.

Exploring biogas as a resource in the context of circular economy principles highlights its critical role in efficient waste management and renewable energy generation (Ellacuriaga et al., 2021, Mutezo, 2021). The massive production of animal dung in developing countries presents both a challenge and an opportunity. By leveraging biogas technology, these countries and Nigeria alike can transform agricultural waste into a valuable energy source, alleviating reliance on fossil fuels and mitigating environmental impacts (Audu et al., 2020, Kabeyi and Olanrewaju, 2022, Nwankwo et al., 2024).

The dual benefits of reducing waste and providing an alternative energy supply underscore the significance of biogas in fostering sustainable development (Olawale and Oladapo, 2024). Simultaneously, implementing biogas systems addresses pressing energy needs and enhances agricultural productivity by giving bio-fertilizers (Ibarra-Esparza et al., 2023). Moreover, waste-to-energy, in general, promotes rural development and job creation, contributing to socioeconomic stability (Yong et al., 2019, Jagun et al.).

The transition to a biogas-oriented framework requires strategic policies, investment in technology, and stakeholder engagement to realise its full potential (Huttunen et al., 2014, Gustafsson and Anderberg, 2021). Integrating waste-to-energy solutions like biogas into national energy strategies is imperative for achieving energy resilience and advancing circular economy objectives. Ultimately, harnessing animal dung as a resource can enhance transformative changes in energy generation, waste management, and environmental sustainability in developing countries, thereby paving the way for a more sustainable future within a liveable environment (Brahmi et al., 2024, Atchike et al., 2022).

The theoretical framework for reimaging waste within the context of a circular economy and agricultural sustainability shifts the traditional perspective of waste as an economic liability to viewing it as a valuable resource (Perey et al., 2018). This transition emphasises systems thinking and resource regeneration, particularly in using animal dung for biogas production, which serves as a renewable energy source while promoting sustainable waste management. The theoretical framework draws from ecological modernisation theory, highlighting how technologies like anaerobic digestion can mitigate environmental degradation while enhancing farm-level waste management and energy security (Bocken et al., 2016)By converting animal waste into biogas, farmers can effectively manage nutrients and improve productivity and harvest yield, exemplifying the benefits of integrating waste recovery within agricultural systems (Sagar and Kartha, 2007, Cornelissen et al., 2012).

Moreover, biogas systems present significant environmental and economic advantages, particularly in decentralised waste management strategies that alleviate the burden of animal waste. Integrating biogas production can redefine local economies by lowering waste treatment costs and improving sanitation and environmental conditions while reducing greenhouse gas emissions, mainly methane (Chojnacka and Moustakas, 2024). The theoretical model proposed in this framework links biogas recovery to energy resilience and local economic development. It underscores the need for supportive economic policies and innovative financing to encourage the adoption of biogas systems, addressing both technological challenges and social acceptance. Employing theories such as innovation diffusion and stakeholder engagement makes it evident that collaborative efforts and comprehensive policy frameworks are essential to overcoming barriers and ensuring the effective integration of biogas systems within a circular economy (Uhunamure et al., 2021).

5. Conclusion

This article aims to contribute to the theoretical discourse on the intersection of waste management, renewable energy, and circular economies by presenting a nuanced understanding of biogas energy recovery from animal dung. It underscores the need for a systems-oriented approach recognising the interdependencies between ecological sustainability and economic viability. By leveraging theoretical frameworks and successful case studies, we advocate for a paradigm shift that views waste not merely as a problem but as an integral resource in the quest for sustainable energy solutions.

The current research underscores a significant opportunity for Nigeria to transform its massive waste resources into a sustainable energy solution. With a population exceeding 200 million and livestock around 368 million, Nigeria can generate biogas from human and animal waste. The study's results reveal that the daily generation of manure totals approximately 457,025.6 tons, complemented by an estimated daily production of 250,463.4 tons of human waste.

This substantial waste output translates into the potential for generating around 14.94 billion m^3 of biogas per year, showcasing the untapped opportunities within Nigeria's current waste management landscape. Specifically, human excreta have a daily biogas production potential of approximately 12,523,170 m^3, while livestock contributes roughly 7,939,294.6 m^3. The energy conversion statistics are equally compelling, with the potential to generate approximately 122,774,787.6 kWh of thermal energy daily, amounting to nearly 44.81 billion kWh annually. These figures underscore the potential of biogas derived from waste to revolutionise waste disposal and environmental degradation, offering a promising solution to these pressing issues.

Embracing biogas energy recovery aligns seamlessly with circular economy principles, where waste is resourcefully repurposed rather than ineffectively disposed of. Encouraging a mindset shift toward viewing organic waste as a viable resource can drastically alter the waste management landscape. Instead of overwhelming landfills and polluting environments, waste converted to biogas can yield valuable renewable energy, reduce reliance on fossil fuels, and ultimately contribute to a cleaner, healthier ecosystem.

Moreover, the environmental implications of adopting biogas as an energy source are profound. By converting waste into usable energy, Nigeria can significantly reduce methane emissions, a potent greenhouse gas from traditional waste disposal practices. Lowering these emissions is pivotal in mitigating climate change and achieving global sustainability goals. Significantly, sustainable energy production from waste reduces environmental impact and enhances food security and agricultural sustainability by providing nutrient-rich organic fertilisers through the digestate byproduct of biogas production, thereby closing the loop on waste and farming practices.

However, the transition to biogas energy recovery is not without challenges. Initial implementation costs, the need for technological expertise, and the development of supportive policies are critical factors that require strategic attention. Nigeria must engage in stakeholder collaborations involving government entities, private investors, academic institutions, and local communities to capitalise on the biogas potential fully. This synergy can help foster research and innovation, promote technical training, and stimulate public awareness campaigns about the benefits of biogas technologies.

To realise this potential, it's essential to establish a robust regulatory framework that incentivises biogas projects while retaining investor confidence. Policies promoting renewable energy sources, waste-to-energy initiatives, and sustainable agricultural practices will significantly help foster a favourable environment for biogas adoption. By prioritising funding production and development, building infrastructure for biogas production, and facilitating access to financing for farmers and entrepreneurs venturing into this sector, Nigeria can lay the groundwork for a resilient biogas industry.

The findings presented in this study illuminate a promising path for Nigeria to reimagine waste management through biogas energy recovery. The potential derived from its significant daily waste outputs can foster job creation, energy security, and environmental sustainability. By transforming perception and viewing waste as not merely refuse but as a unique opportunity for innovation, Nigeria can harness its waste resources to regenerate the economy while contributing to a cleaner, more sustainable future. The journey toward this biogas-powered vision calls for collective efforts, informed policymaking, and a commitment to embracing the principles of a circular economy, ultimately leading to a more sustainable, energy-secure Nigeria.

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