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Investigation of Biogas Yield Composition From Agricultural Waste

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Abstract

In addition to solving the problems associated with agricultural waste management, the creation of biogas from agricultural waste provides an environmentally responsible and sustainable way to meet the Nigeria energy needs. The goal of this study is to produce and assess the composition of biogas from a specific set of agricultural waste, such as food scraps and animal manure, that comes from agricultural production and processing operations. Using a 30-liter plastic digester, the agricultural waste was anaerobically digested without oxygen to produce the biogas. A portable gas meter was used in the lab to test the biogas produced by the anaerobic digestion process, and statistical analysis was performed on the experimental data generated. These were the findings of the compositional analysis: 25.15% carbon dioxide (CO_2), 1.95% carbon monoxide (CO), 69.25% methane (CH_4), 1.05% hydrogen sulphide (H_2S), 2.35% water vapor (H_2O), and other gases present as 0.25%. With a good yield of methane content, the analysis's conclusion shows that used agricultural waste is a viable feedstock for the production of renewable energy.

Keywords: Investigation, Biogas yield, Composition, Methane, Agricultural waste, Energy

1. INTRODUCTION

In a world where pollution and the effects of climate change are felt on a daily basis, it is critical to assess the situation and look for potential ways to lessen these effects. This is where waste management comes into play, posing a worldwide problem due to its direct effects on the environment and public health. In order to maintain a sustainable balance for future generations, proper waste management will lessen pollution, preserve natural resources, and slow down global warming [1-4]. Raising awareness of how people manage solid waste both individually and collectively and what can be done to reduce, recycle, and reuse it in our daily lives is a critical first step [5-7]. An estimated 2.24 billion tons of solid waste are produced annually by humans, whether from residences, workplaces, industries, institutions, or public areas; 931 million tons of this waste is food waste alone, which usually ends up in rivers and oceans, with only 55% of it being processed in controlled facilities [8-10]. Urban solid waste generation is predicted to increase from roughly 2.3 billion tons in 2023 to 3.8 billion tons by 2050, according to data from the United Nations Environment Program's Global Waste Management Outlook 2024 report [9]. In light of the aforementioned factors, as well as the energy crisis, ineffective waste management, and climate change, biogas has emerged as a viable and effective substitute [7, 11]. Because the production of biogas from organic waste offers a multifaceted approach to addressing global waste management challenges and the transition toward a more sustainable energy model, this renewable gas, which is produced by the anaerobic digestion of organic matter in the absence of oxygen [12-18], not only helps to reduce waste and polluting emissions but also represents a significant opportunity for economic and technological development in strategic sectors, such as agriculture and forestry [19-25]. The forestry and agricultural industries are thought to produce over 1.3 billion tons of solid organic waste a year [23, 24], which makes effective public policies and lower initial implementation costs even more important. In addition to reducing the environmental impact, turning this biomass into biogas and biofertilizers maximizes resource utilization, enhancing biodiversity and soil quality through more sustainable farming methods [25-30].

Biogas is a flammable gas that is created when organic materials, such as manure, agricultural waste, and industrial effluents, undergo biological fermentation in an anaerobic (oxygen-deficient) environment. This process produces methane, carbon dioxide, and trace amounts of hydrogen sulfide [31-35]. Methane and carbon dioxide are byproducts of the breakdown of complex organic compounds by bacteria and archaea during digestion. Biogas is a valuable renewable energy source since its main component, methane, is highly flammable [36-40]. One viable path toward sustainable energy solutions and effective waste management practices is the creation of biogas from animal waste and biodegradable trash [41-44]. Methane (CH_4) and CO_2 make up the majority of biogas, a renewable energy source with enormous potential for use. Because of its adaptability, it can be used to inject natural gas into networks, heat buildings, power automobiles, and even generate electricity [45-47]. Anaerobic digestion, raw material collection and pretreatment, and the separation of digestate, a nutrient-rich by-product that can be utilized as organic fertilizer, and biogas are some of the steps involved in its production. Because of their potential to lessen reliance on fossil fuels and combat climate change, these processes have drawn increasing attention from the scientific community and the energy industry [48-50]. There are still issues with its widespread application, though. The economic and environmental feasibility of biogas in comparison to other renewable energy sources can be influenced by various factors, including the anaerobic digestion process's efficiency, the waste's variability, and operational circumstances [51-55]. Analyzing the present obstacles to its advancement and identifying creative solutions that promote its uptake are therefore crucial.

In the end, the generation of biogas not only converts trash into a clean energy source but also plays a significant role in combating climate change and promoting the circular economy [56]. Biogas is becoming a crucial component in the shift to a more resilient, accessible, and ecologically conscious future because of its capacity to convert environmental issues into long-term solutions. Organic waste from a variety of industries, including forestry, agriculture, and livestock, can be converted into biogas, a renewable gas. Generally speaking, this biofuel, which is used globally as an energy source for both industrial and home reasons, can be produced anywhere there is decomposing organic waste [57]. The two primary methods for producing this gas are thermochemical conversion, which changes biomass by applying high temperatures, and anaerobic digestion, which is the biological breakdown of organic matter without oxygen. The primary distinction between the two processes is the kind of biomass they use: thermochemical conversion is focused on using forest biomass, such as wood and other dry lignocellulosic waste, whereas anaerobic digestion is primarily used for agricultural and livestock waste, which is moist and readily biodegradable [58-60]. In contrast to the usage of fossil fuels like coal and oil [61-64], these alternative procedures are sustainable. It should be mentioned in this connection that the gas generated in thermochemical conversion may also be referred to as wood gas or pyrolysis gas, depending on national nomenclature. This is significant since biogas is only defined as an anaerobic digestion product in some legal systems. Additionally, several researchers have tried using the biogas technology. [65] investigated the developments in anaerobic digestion for effective biogas generation and suggested that using the technique to convert organic matter especially animal waste is an effective way to produce renewable biogas. Methane emissions from decaying trash are caught and transformed into a useful energy source by using an anaerobic digester. Temperature, pH, retention duration, and substrate composition are some of the variables that affect the efficiency of biogas generation [66-70].

The type and proportion of organic matter in animal waste significantly impact biogas yield and composition, with higher organic content generally leading to increased methane production [71-73]. The production of biogas from animal waste does not only offers an environmentally friendly alternative to fossil fuels but also addresses the pressing issue of organic waste management in agricultural settings. Additionally, [74] discussed the dual role of biogas in renewable energy production and waste management in agricultural systems which clearly placed emphasis on the development of innovative storage solutions to ensure the reliable supply and utilization of biogas produced, thereby enhancing its viability as a renewable energy source and also to contribute to the advancement of sustainable energy practices and to promote the adoption of biogas technology in agricultural communities. Using biogas for cooking and lighting decreases the pressure on the environment by minimizing the usage of biomass and the creation of greenhouse gases (as methane that is produced regularly from manure is now trapped and used). The chemical makeup of biogas and the physical properties that emerge from it are used to define it. Methane (CH_4) and inert carbonic gas (CO_2) make up the majority of its composition. Biogas and fertilizer-grade slurry are the end products of anaerobic digestion. About 55–60% methane, 25–45% carbon dioxide, 0.1% oxygen, 0.1% carbon monoxide, 1–10% hydrogen, 1-3% nitrogen, and trace amounts of hydrogen sulfide are all present in biogas. The vast majority of Nigerians living in rural regions rely on firewood for cooking and lighting as they lack access to gas or electricity.

Nigeria is extremely fortunate to have access to a wide range of energy resources, both traditional and unconventional. As of 2005, it was projected that there were 61,000,000 tons of reserves for animal waste alone, which is a potential source for the production of biogas, and 83,000,000 tons of reserves for crop residue annually [75]. According to estimates, Nigeria may produce more than 17 billion cubic meters of biogas a year, which would cover a significant amount of its energy requirements [76]. Disease and pollution issues have been brought about by the current agricultural waste disposal system. The removal and management of deforestation would be aided by the increased search for alternative energy sources, such as biogas produced from waste materials. The installation of biogas facilities would significantly reduce these issues and contribute to environmental preservation. It is impossible to overstate the significance of biogas as a substitute energy source. It is a more affordable, sustainable, and ecologically friendly energy source. Therefore, the purpose of this study is to use anaerobic digestion to produce and assess biogas from cow manure and food leftovers.

2. METHODOLOGY

This section covered the strategies and resources employed to get the intended result.

2.1 Materials

Pig manure, water, a 30-liter plastic digester, gas collection equipment, shovels, and hand gloves are among the supplies used.

2.2 Sample Collection

The leftover food was gathered from Mama D eateries in Oghara, which is situated in the Ethiope West local government region of Delta State, Nigeria, while the fresh pig manure was gathered from a nearby pig farm in Jesse. The pig manure was scooped up with a shovel and placed in a sanitized plastic container.

2.3 Preparation of Digestate

According to [57], ten kilograms (10 kg) of the food scraps were appropriately shred to lower particle sizes since they accelerated decomposition and, consequently, biogas output. As advised by [30], 10 kilograms of food waste and 5 kg of pig dung were combined, and water was then added as needed to maintain a moderate water content level and to create the ideal slurry for the production of biogas. As recommended by [12, 43], the water and waste were mixed in a 1:2 ratio in a plastic container to create a slurry before being put into the digester.

2.4 Charging of Digester

The goal of the experimental setup, as depicted in Fig. 1, was to increase the generation of biogas by co-digesting food scraps and pig manure. A mesophilic temperature range of 25 to 37 degrees Celsius was used to co-digest the mixed substrates. Because psychrophilic and thermophilic bacteria undertake slower anaerobic digestion than mesophilic bacteria, the mesophilic temperature range is recommended in this investigation [67]. Additionally, the low process temperature makes it challenging to sustain anaerobic digestion facilities under psychrophilic temperature conditions. Moreover, it is well known that thermophilic bacteria are extremely sensitive to disruptions, necessitating expensive process control and monitoring [67]. As more methanogenic bacteria are operating on the substrate, the ideal mesophilic temperature often results in shorter HRT (greater biogas production) [35, 53]. The batch reactor was a digester constructed from a 30-liter plastic bottle. A water collector and displacement bottle were attached to the digesters. The reactors and the displacement bottles were connected by rubber tubes. The reactors were manually supplied with 15 kg of substrates and water at a 1:2 ratio. The composition of the gases in the generated biogas was assessed.

2.5 Determination of Biogas Percentage Composition

A laboratory portable gas meter was used to determine the following compositions of the biogas generated from pig dung that was co-digested with leftover food: There are various gaseous components present, including methane, carbon dioxide, carbon monoxide, water vapor, and hydrogen sulphide.

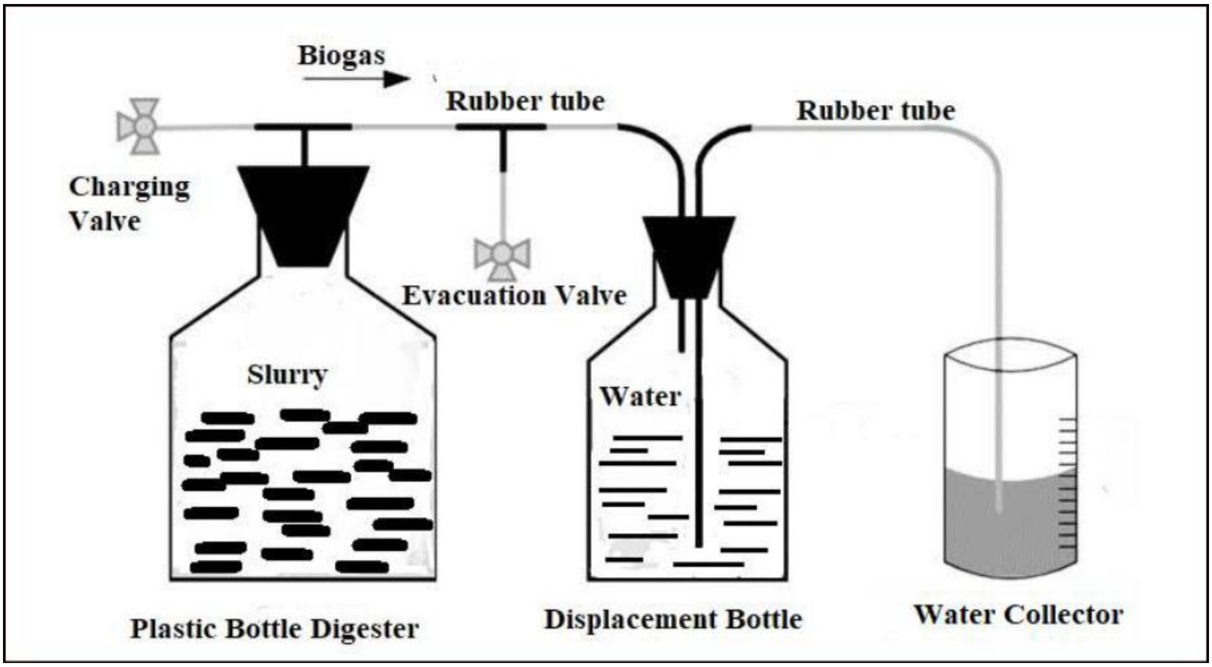

Fig. 2 Experimental setup [42]

3. RESULTS AND DISCUSSION

After 38 days of hydraulic retention, a cumulative biogas yield volume of 0.51 m3 was achieved. The results showed that the temperature variations were 36.01±2 °C and the pH range was 68.45±25 m. According to the temperature's effects on biogas yield, mesophilic temperatures of 36.018°C produced the highest biogas yield, which was consistent with study by [59]. According to reference [16], at greater mesophilic temperatures, the HRT is shortened and the rate of biogas evacuation is higher. Additionally, a mesophilic temperature range of 36 to 38 °C can produce the highest biogas yield. On the other hand, a lower mesophilic temperature may lengthen the HRT and result in a lower biogas output. Table 1 displays the findings of the compositional analysis of the biogas made from leftover food and pig manure.

Table 1. Compositional analysis of the biogas produced from pig dung and food leftover

S/N	Substrates (kg)	pH (m)	Temp. (^{0}C)	Biogas Composition	Percentage Composition (%)
1	Pig Dung + Food Waste	6.85±2	36.01±2	Methane	69.25
2	Pig Dung + Food Waste	6.85±2	36.01±2	Carbon (IV) oxide	25.15
3	Pig Dung + Food Waste	6.85±2	36.01±2	Carbon (II) oxide	1.95
4	Pig Dung + Food Waste	6.85±2	36.01±2	Hydrogen sulphide	1.05
5	Pig Dung + Food Waste	6.85±2	36.01±2	Water vapour	2.35
6	Pig Dung + Food Waste	6.85±2	36.01±2	Other gases	0.25

The biogas generated from cow dung has a methane content of 69.25% (Table 1). This figure falls between 50 and 70 percent of what [13, 25, 33, 41] previously reported. Evaluating the energy efficiency of biogas is one of the main goals of its composition analysis. The calorific value and energy yield of biogas are determined by methane, the primary energy component. Designing effective biogas-powered devices, such as burners and generators, requires a higher methane concentration since it results in increased energy output. The biogas is valuable for energy generation in applications including heating, cooking, and electricity generation due to its methane content of 69.25. According to Table 1, the biogas generated included 1.05 percent hydrogen sulfide. Hydrogen sulfide is extremely corrosive and poisonous. It is detrimental to equipment and human health even at low doses. Gas cylinders and other infrastructure are harmed by its corrosive properties. H_2S must be removed by desulfurization procedures (e.g., using iron oxide filters or activated carbon) because of its toxicity and unpleasant odor. The gas is safer and better suited for producing energy once H_2S is eliminated. As shown in Table 1, the biogas's carbon monoxide level was 1.95 percent. Even at low concentrations, carbon monoxide is a poisonous gas that can be extremely harmful to one's health. Incomplete reduction or combustion processes during the biogas generation process are indicated by its presence in the gas sample. It has no effect on the biogas's energy value. The results of the compositional analysis of the biogas made from the substrates show that the carbon dioxide content was 27.15% (Table 1), which is less than the 30–40% range that [41] had previously reported. Given the quantity of carbon dioxide present, the biogas is likely a normal byproduct of anaerobic digestion. It must be eliminated or reduced in order to improve the purity of methane because it adds nothing to the gas's energy worth. It would be necessary to remove the carbon dioxide (CO2) from this gas sample using techniques like chemical absorption, pressure swing adsorption, or water washing in order to make it fit for high-efficiency use (such as in compressed natural gas [CNG] engines).

Furthermore, [44, 47, 70] states that the main components of biogas are carbon dioxide (25–50%) and methane (50–75%), with variable proportions of other gases such as hydrogen, hydrogen sulphide, and nitrogen (0–8%). The particular composition varies according to the anaerobic digestion process conditions and the supply of organic material (e.g., sewage, food waste, or manure). Water vapor, ammonia, and volatile organic molecules are examples of impurities, while hydrogen sulfide (H_2S) is a frequent trace impurity that is harmful and corrosive.

4. CONCLUSION

The production of biogas from organic agriculture and forestry waste is a strategic and multidimensional way to address the economic, social, and environmental issues of the twenty-first century. In addition to meeting the pressing need to slow down climate change, this strategy supports inclusive rural development, ecological regeneration, and the circular economy. Biogas is positioned in this context as a tangible instrument for reconsidering how humans interact with garbage and turning environmental liabilities into social and energy assets. More than just an energy alternative, incorporating this technology into public policies and sustainable development goals offers a genuine chance to create decentralized, resilient, and fair systems. Agroforestry leftovers are converted into biogas, which lowers greenhouse gas emissions, restores vital nutrients for farming, and directly boosts the local economy in rural areas. A number of Sustainable Development Goals, such as those pertaining to affordable and clean energy (SDG 7), climate action (SDG 13), responsible production and consumption (SDG 12), decent work and economic growth (SDG 8), and others, can also be greatly aided by its implementation. With methane making up the majority of the gas mixture, the study's analysis of the composition of biogas demonstrates the successful production of biogas from animal waste and validates the potential of animal waste as a sustainable feedstock for biogas generation. Biogas produced by anaerobic digestion is characterized by a high concentration of carbon dioxide and lower concentrations of hydrogen sulfide, carbon monoxide, and oxygen. Although methane is the main source of energy, the presence of contaminants such as CO_2 and H_2S suggests that additional purification is required to improve the biogas's quality and utility.

Declaration of Conflicting Interests

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References

[1] E.U. Emifoniye, A.A. Erameh, E.K. Orhorhoro, P.E. Oyiboruona, A Machine Learning Approach for Pyrolysis of Plastic Waste: An Overview of Types, and Applications, International Journal of Scientific Research and Engineering Development, 8(3), 2025, pp 27-39

[2] A. Yoshida, China's ban of imported recyclable waste and its impact on the waste plastic recycling industry in China and Taiwan, Journal of Material Cycles and Waste Management, 24, 2022, pp 73-82. https://doi.org/10.1007/s10163 021-01297-2

[3] E.U. Emifoniye, A.A. Erameh, E.K. Orhorhoro, Investigation of proximate and ultimate analysis of household generated plastic waste for feasible design of a pyrolysis pilot plant. World Journal of Advanced Engineering Technology and Sciences, 15(01),2025, pp 2107-2118. https://doi.org/10.30574/wjaets.2025.15.1.0416

[4] E.K. Orhorhoro, A review of plastic waste management for a sustainable environment: Composition and approaches, European Journal of Sustainable Development Research, 9(3), 2025, em0314. https://doi.org/10.29333/ejosdr/16359

[5] E.K. Orhorhoro, E.U. Emifoniye, S.O. Okuma, Prediction of the Tensile Strength of an Experimental Design Reinforced Polyvinyl Chloride Composite using Response Surface Methodology, Jordan Journal of Mechanical and Industrial Engineering, 17 (3), 2023, 403-412

[6] A. Boarino, et al., Bio-physical pre-treatments in anaerobic digestion of organic fraction of municipal solid waste to optimize biogas production and digestate quality for agricultural use, Waste Manag., 189, 2024, 114–126, https://doi.org/10.1016/j.wasman.2024.08.023

[7] E.K. Orhorhoro, O. Oghoghorie, Review on Solid Waste Generation and Management in Sub-Saharan Africa: A Case Study of Nigeria, J. Appl. Sci. Environ. Manage., 23 (9), 2019, pp 1729-1737

[8] UN-Habitat. United Nations Human Settlements Programme 2023. International Zero Waste Day. 2023. Available online: https://onu-habitat.org/index.php/dia-internacional-de-cero-desechos (accessed on 26 March 2025).

[9] UNEP. Global Waste Management Outlook 2024: Beyond an Age of Waste—Turning Rubbish into a Resource; UNEP: Nairobi, Kenya, 2024; ISBN 978-92-807-4129-2.

[10] E.K. Orhorhoro, P.O. Ebunilo, E.G. Sadjere, Determination and Quantification of Household Solid Waste Generation for Planning Suitable Sustainable Waste Management in Nigeria, International Journal of Emerging Engineering Research and Technology, 5(8), 2017, 1-9

[11] European Commission. Transforming Organic Waste into Fertiliser for Emissions-Free Agriculture and Forestry. 2020. CORDIS. Available online: https://cordis.europa.eu/article/id/421818-transforming-organic-waste-into-fertiliser-for-emissions-free agriculture-and-forestry (accessed on 15 March 2025).

[12] E.K. Orhorhoro, J.O. Oyejide, Modelling of Biogas Yield from Anaerobic Co-digestion of Food Waste and Animal Manure using Artificial Neural Networks, Applications of Modelling and Simulation, 4, 2020, 81-88

[13] J.O. Oyejide, E.K. Orhorhoro, D. Atadious, Mathematical Modeling of Biogas Yield from Anaerobic Co-Digestion of Organic Waste and Pig Dung, International Journal of Engineering Science Invention, 7(5), 2018, 30-38

[14] P.O. Osunde, E.K. Orhorhoro, P.O.B. Ebunilo, Design of Three Stages Continuous Anaerobic Digestion (AD) Plant, American Journal of Engineering Research, 6(11), 2017, 11-321

[15] A.K. Ahmad, A.Yadav, D.K. Singh, A. Singh, comprehensive machine learning-coupled response surface methodology approach for predictive modeling and optimization of biogas potential in anaerobic Co-digestion of organic waste, Biomass Bioenergy 180 (November 2023) 106995, https://doi.org/10.1016/j.biombioe.2023.106995

[16] P.O. Ebunilo, E.K Orhorhoro, V. Oboh, P.U. Onochie, Effect of Temperature on Biogas Yields Using South-South Nigeria as a Case Study, Int J Technol Enhancements Emerg Eng Res., 4(3), 2016, 50-54

[17] M. Brahmi, B. Bruno, K.S. Dhayal, L. Esposito, A. Parziale, From manure to megawatts: navigating the sustainable innovation solution through biogas production from livestock waste for harnessing green energy for green economy, Heliyon, 10 (14), (2024), e34504. https://doi.org/10.1016/j.heliyon.2024.e34504

[18] S.I. Ukwaba, A.E. Ikpe, E.K. Orhorhoro, Adoption of a landfill system in Nigeria and the role of municipal solid waste segregation on its performance, Nigerian Rese. J. of Engr. and Environ. Sci., 3(1), 2018, pp 280-286

[19] C. Margreiter, M. Probst, M.E. Prem, A. Hofmann, A.O.Wagner, Gasification chars and activated carbon: systematic physico-chemical characterization and effect on biogas production. Heliyon, 10 (10), 2024, e31264, https://doi.org/10.1016/j.heliyon.2024.e31264

[20] E.K. Orhorhoro, A.E. Ikpe, S.I. Ukwaba, Effects of Landfill Gas Flow Trajectories at Three Distinct Temperature Phases on the Stress-Strain Displacement Properties of a Gas Extraction Pipe, J. Appl. Sci. Environ. Manage. 22 (11), 2018, 1737 1743

[21] J.A. Velásquez-Piñas, O.D. Calle-Roalcaba, L.R. Miramontes-Martínez, L.A. Alonso-Gómez, Economic and environmental assessment of biogas utilization technologies and perspectives of multicriteria analysis, ION J., 36, 2023, pp 29–47

[22] R.G. Cervi, M.S. Esperancini, O.D.C. Bueno, Economic Viability of using Biogas for Electrical Power Generation. Inf. Technol., 22, 2011, pp 3–14.

[23] FAO. Food Wastage Footprint Impacts on Natural Resources. Summary Report. 2023. Available online: https://www.fao.org/4/i3347e/i3347e.pdf (accessed on 15 March 2025).

[24] FAO. Global Food Losses and Waste. Extent, Causes and Prevention. 2011. Available online: http://www.fao.org/docrep/014/mb060e/mb060e00.pdf (accessed on 24 March 2025).

[25] E.K. Orhorhoro, J.O. Oyejide, Modelling of Biogas Yield from Anaerobic Co-digestion of Food Waste and Animal Manure using Artificial Neural Networks, Applications of Modelling and Simulation, 4, 2020, 81-88

[26] M. Assnakew Abebe, Characterisation peal of fruit and leaf of vegetable waste with cow dung for maximizing the biogas yield. Int. J. Energy Power Eng. 6 (2), 2017,13, https://doi.org/10.11648/j.ijepe.20170602.12

[27] A. Ahmad, A.K. Yadav, A. Singh, D.K. Singh, A comprehensive machine learning-coupled response surface methodology approach for predictive modeling and optimization of biogas potential in anaerobic Co-digestion of organic waste, Biomass Bioenergy, 180, 2023, 106995, https://doi.org/10.1016/j.biombioe.2023.106995

[28] O.O. Osita, U.G. Lawan, The optimum mesophilic temperature of batch process biogas production from animal-based wastes. Research Journal of Applied Sciences, Engineering and Technology 8(16), 2014, pp 1772-1776. http://dx.doi.org/10.19026/rjaset.8.1163

[29] M.A. Rahman, R. Shahazi, S.N.B. Nova, M.R. Uddin, M.S. Hossain, A. Yousuf, Biogas production from anaerobic co-digestion using kitchen waste and poultry manure as substrate—part 1: Substrate ratio and effect temperature. Biomass Conversion and Biorefinery, 13, 2021, 1-11. https://doi.org/10.1007/s13399-021-01604-9

[30] O.W. Orhorhoro, E.K. Orhorhoro, P.O. Ebunilo, Analysis of the Effect of Carbon/Nitrogen (C/N) Ratio on the Performance of Biogas Yields for Non-Uniform Multiple Feed Stock Availability and Composition in Nigeria. International journal of Innovative Science Engineering and Technology, 3(5), 2016, 119-126

[31] S. Oh, J. Lee, S.S. Lam, E.E. Kwon, J.M. Ha, D.C. Tsang, Y.S. Ok, W.H. Chen, Y.K. Park, Fast hydropyrolysis of biomass Conversion: A comparative review, Bioresour. Technol., 342, 2021, 126067

[32] L. Appels, J. Baeyens, J. Degrève, R. Dewil, Principles and potential of the anaerobic digestion of waste-activated sludge, Prog. Energy Combust. Sci., 34, 2008, 755–781

[33] E.K. Orhorhoro, O.W. Orhorhoro, E.A. Atumah, Performance Evaluation of Design AD System Biogas Purification Filter. International Journal of Mathematical, Engineering and Management Sciences, 3(1), 2018, pp 17–27, https://dx.doi.org/10.33889/IJMEMS.2018.3.1-003

[34] B. Charles, Optimising anaerobic digestion:Evaluating the Potential for Anaerobic Digestion to provide Energy and Soil amendmentUniversity of Reading, 25th March 2009; University of Southampton, Available online at https://www.google.com/search?q=Optimising+anaerobicdigestionCharles+BanksUniversity+of+SouthamptonEvaluating+the+Potential+for+Anaerobic+Digestion+to+provide+Energy+and+Soil+amendmentUniversity+of+Reading25th+March+2009&ie=utf-8&oe=utf-8, 2009 [Accessed 19th May, 2023]

[35] E.K. Orhorhoro, P.O. Ebunilo, R.I. Tamuno, I.A. Essienubong, The Study of Anaerobic Co-Digestion of Non-Uniform Multiple Feed Stock Availability and Composition in Nigeria, European Journal of Engineering Research and Science, 1(1), 2016, 39-42

[36] B. Demirel, P. Scherer, The roles of acetotrophic and hydrogenotrophic methanogens during anaerobic conversion of biomass to methane: A review. Rev., Environ. Sci. Biotechnol., 7, 2008, 173–190

[37] E.K. Orhorhoro, P.O. Ebunilo, E.G. Sadjere, Experimental Determination of Effect of Total Solid (TS) and Volatile Solid (VS) on Biogas Yield, American Journal of Modern Energy, 3(6), 2017, 131-135

[38] K. Singh, K.S. Ainala, S. Park, Metabolic engineering of Lactobacillus reuteri DSM 20,016 for improved 1,3-propanediol production from glycerol, Bioresour. Technol., 338, 2021, 125590

[39] I. Angelidaki, L. Treu, P. Tsapekos, G. Luo, S. Campanaro, H. Wenzel, P.G. Kougias, Biogas upgrading and utilization: Current status and perspectives, Biotechnol. Adv., 36, 2018, 452–466

[40] E.K. Orhorhoro, P.O. Ebunilo A.E. Ikpe, Effect of pH on Anaerobic Digestion (AD) of Organic Municipal Solid Waste in Benin City, Nigeria, Journal of the Nigerian Association of Mathematical Physics, 36(1), 2016, pp 369-374

[41] D.E. Oloaluwa, O.M. Ezugwu, E.K. Orhorhoro, Optimizing biogas production by anaerobic co digestion of poultry dropping and litter at mesophilic temperature and pH, Journal of Environmental Engineering and Energy, 2(1), 2025, 31-43. https://doi.org/10.22105/jeee.v2i1.38

[42] O. Oghoghorie, O. Erhinyodavwe, E.K. Orhorhoro, Anaerobic co-digestion of Cow Manure and Food Waste: An investigation of biogas yield from feedstock percentage variation, Discovery, 60, 2024, e24d1453

[43] E.K. Orhorhoro, O. Oghoghorie, Enhancing biogas yield through anaerobic co-digestion of animal manure and seaweed. Progress in Energy and Environment, 28, 2024, 1-22. https://doi.org/10.37934/progee.28.1.122

[44] P.O. Ebunilo, S.I. Ukwuaba, I.B. Owunna, E.G. Sadgere, E.K. Orhorhoro, Evaluation of Cow Dung and Talinum Triangulare as a Seeding Agent for the Production of Biogas from Domestic Wastes in Warri Metropolis, International Journal of Scientific & Engineering Research, 7(3), 2016, 633-641

[45] H.M.A. Shahzad, F. Almomani, A. Shahzad, K.A. Mahmoud, K. Rasool, Challenges and opportunities in biogas conversion to microbial protein: a pathway for sustainable resource recovery from organic waste, Process Saf. Environ. Prot., 185, 2024, pp 644–659. https://doi.org/10.1016/j.psep.2024.03.055

[46] P. Mekwichai, P. Chutivisut, N. Tuntiwiwattanapun, Enhancing biogas production from palm oil mill effluent through the synergistic application of surfactants and iron supplements. Heliyon 10 (8), 2024, e29617, https://doi.org/10.1016/j.heliyon.2024.e29617

[47] P.O. Ebunilo, E.K. Orhorhoro, O.A. Adegbayi, Investigation of the purification of biogas from domestic wastes using local materials in Nigeria, International Journal of Scientific & Engineering Research, 7(2), 2016, 505-515

[48] A.T. Hoang, J.L. Goldfarb, A.M. Foley, E. Lichtfouse, M. Kumar, L. Xiao, S. F. Ahmed, Z. Said, R. Luque, V. G. Bui,

Production of biochar from crop residues and its application for AD, Bioresource Technology 363, 2022, 127970. https://doi:10.1016/j.biortech.2022.127970

[49] E.K. Orhorhoro, P.B. Ebunilo, E.G. Sadjere, Effect of Organic Loading Rate (OLR) on biogas yield using a single and three-stages continuous anaerobic digestion reactors, International Journal of Engineering Research in Africa, 39, 2017, pp 147-155. https://doi:10.4028/www.scientific.net/JERA.39.147

[50] R. Franqueto, J.D., da Silva, and M. Konig, Effect of temperature variation on co-digestion of animal waste and agricultural residue for biogas production, BioEnergy Research 13 (2), 2020, pp 630–42. https://doi:10.1007/s12155-019-10049-y.

[51] G. Ma, P. Ndegwa, J.H. Harrison, Y. Chen. Methane yields during anaerobic co-digestion of animal manurewith other feedstocks: A meta-analysis, Science of The Total Environment, 728, 2020,138224. https://doi.org/10.1016/j.scitotenv.2020.138224

[52] L. Meng, K. Jin, R. Yi, M. Chen, J. Peng, Y. Pan, Enhancement of bioenergy recovery from agricultural wastes through recycling of cellulosic alcoholic fermentation vinasse for anaerobic co-digestion, Bioresource Technology, 311, 2020, 123511. https://doi.org/10.1016/j.biortech.2020.123511

[53] E.K., Orhorhoro, E.E. Lindsay, J.O. Oyejide, Analysis and Evaluation of a Three-Stage Anaerobic Digestion Plant for Management of Biodegradable Municipal Solid Waste, International Journal of Engineering Research in Africa, 60, 2022, 75-87. https://doi:10.4028/p-a24obb

[54] C.B. Arenas, W. Meredith, C.E. Snape, X. Gómez, J.F. González, JE.J. Martínez. Effect of char addition on anaerobic digestion of animal by-products: Evaluating biogas production and process performance, Environmental Science and Pollution Research, 27, 2020, 24387–24399. https://doi.org/10.1007/s11356-020-08828-8

[55] E.K. Orhorhoro, P.O. Ebunilo, E.G. Sadjere, Development of a Predictive Model for Biogas Yield Using Artificial Neural Networks (ANNs) Approach, American Journal of Energy and Power Engineering, 4(6), 2017, 71-77

[56] M. Rapa, R.N. Darie-Niţ, G. Coman, Valorization of fruit and vegetable waste into sustainable and value-added materials, Waste 2 (3), 2024, pp 258–278. https://doi.org/10.3390/waste2030015

[57] E.K. Orhorhoro, P.O.B. Ebunilo, E.G. Sadjere, Design of Bio-Waste Grinding Machine for Anaerobic Digestion (AD) System. European Journal of Advances in Engineering and Technology, 4 (7), 2017, pp 560-568

[58] N. Rasit, W.A.W.A. Karim Ghani, M.H.C. Harun, S. Hamzah, R. Seswoya, M.N.I. Siddique, Feeding frequency efficacy on biogas yield of oily substrate anaerobic digestion in continuous stir tank reactor, Water Sci. Technol. 89 (10), 2796–2811, https://doi.org/10.2166/wst.2024.153

[59] E.K. Orhorhoro, A.A. Erameh, Performance evaluation of the effect of temperature and pH on biogas yields from anaerobic co-digestion of food waste and pig dung. Proceedings of Igbinedion University First Annual Research Day and Conference (5th August, 2019). Theme: Greening Academia/Industry Research Synergy: To Promote Sustainable Development Goals in Nigeria. Nigerian Journal of Engineering Science Research, 50-59, 2019, 2021

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

[61] E.J. Igbagbon, E.K. Orhorhoro, O. Erhinyodavwe, Design Analysis of a Miniature Steam Boiler for the Generation of Steam, J. Sci. Tech. Resear., 6(3), 2024, 87-98

[62] PO. Ebunilo, E.K. Orhorhoro, C.M. Chukwudi, A.I. Essienubong, Performance Evaluation of Biomass Briquette from Elephant and Spear grass in Benin City, Edo State, Nigeria, European Journal of Engineering and Technology Research, 1 (1), 2016, 15-17

[63] K.E. Madu, U. Nosegbe, E.K. Orhorhoro, J.E. Igbagbon, Performance Evaluation of a Photovoltaic System for Household in Asaba, Nigeria, African Journal of Environmental Sciences & Renewable Energy, 19(1), 2025, 42-60. https://doi.org/10.62154/ajesre.2025.019.01012

[64] E.J. Igbagbon, E.K. Orhorhoro, T.E. Erokare, Performance Evaluation of a Developed Miniature Steam Boiler Using Different Samples of Wood Waste as Fuel for Steam Generation, J. Advan. Indust. Techn. Appli., 5(1), 2024, 26-36. https://doi.org/10.30880/jaita.2024.05.01.004

[65] A. Pandey, B. Kumar, S. Singh, M. Gupta, Study on optimization of hydrogen sulfide removal using limestone in anaerobic digester effluent biogas. Energy Sources, Part A: Recovery, utilization, and environmental

effects, 42(20), 2020, pp 2411–2420

[66] J. Yin, X. Xie, X. Jiang, Z. Liu, Effects of thermal pretreatment on anaerobic digestion performance and microbial community structure of waste activated sludge, Bioresource Technology, 325, 2021, 124666

[67] P.O. Ebunilo, E.K. Orhorhoro, V. Oboh, P.U. Onochie, Effect of Temperature on Biogas Yields Using South-South Nigeria as a Case Study, Int J Technol Enhancements Emerg Eng Res., 4(3), 2016, 50-54

[68] P.O. Osunde, E.K. Orhorhoro, P.O.B. Ebunilo, Design of Three Stages Continuous Anaerobic Digestion (AD) Plant. American Journal of Engineering Research, 6(11), 2017, pp 11-321

[69] W. Wongarmat, S. Sittijunda, T. Imai, A. Reungsang, Co-digestion of filter cake, biogas effluent, and anaerobic sludge for hydrogen and methane production: optimizing energy recovery through two-stage anaerobic digestion, Carbon Resour. Convers., 2024, 100248, https://doi.org/10.1016/j.crcon.2024.100248

[70] E.K. Orhorhoro, P.O. Ebunilo, E.G. Sadjere, Development of a Predictive Model for Biogas Yield Using Artificial Neural Networks (ANNs) Approach, American Journal of Energy and Power Engineering, 4(6), 2017, 71-77

[71] A.K. Yadav, T. Abbasi, S.A. Abbasi, Biogas from animal dung: a critical review on process, enhancement, and limitations, Biomass Conversion and Biorefinery, 10, 2020, pp 605-623

[72] P.K. Karthikeyan, H.C.H. Bandulasena, T. Radu, A comparative analysis of pre-treatment technologies for enhanced biogas production from anaerobic digestion of lignocellulosic waste, Ind. Crops Prod., 215, 2024, 118591, https://doi.org/10.1016/j.indcrop.2024.118591

[73] A. Yoshida, China's ban of imported recyclable waste and its impact on the waste plastic recycling industry in China and Taiwan. Journal of Material Cycles and Waste Management, 24, 2022, pp 73-82. https://doi.org/10.1007/s10163 021-01297-2

[74] M.Z. Hossain, M.F.R. Zainudin, M.S. Rahaman, Biogas production from animal wastes: technology, challenges, and prospects, Journal of Material Cycles and Waste Management, 21, 2019, pp 601-613

[75] M.M. Agba, E.F. Ushie, I. Abam, M.S. Agba, J. Okoro, Developing the biofuel industry for effective rural transportation, European Journal of Scientific Research, 40, 2010, 44-449

[76] C.C. Eze, O.M. Chukwuma, C.O. Onwosi, J.N. Igbokwe, Assessment of biogas production potential from organic waste in Nigeria, International Journal of Renewable Energy Research, 10(2), 2020, pp 1109–1121