

Biogas and Biofertilizer From Waste: A Review

Al-Amin Shafa Abdulkarim ¹, Jibril Mohammed ¹, Kabir Abogunde Abdulyekeen ¹,
Olumide Olu Olubajo ¹, Surajudeen Abdulsalam ¹

¹ *Abubakar Tafawa Balewa University*

Tafawa Balewa Way, P. M. B. 0248, Bauchi, 740272, Nigeria

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Corresponding Author:

Jibril Mohammed

jmohammed@atbu.edu.ng

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Abstract. Bio-resources, particularly non-fossil biogenic materials, offer sustainable energy production, waste management, and soil enrichment solutions. Biogas technology, leveraging anaerobic digestion (AD), transforms diverse organic wastes into methane, an eco-friendly energy source. This review highlights the potential of bio-fertilizer and biogas production from various waste types, including animal, plant, sewage sludge, and agricultural residues. Animal waste, mainly cow dung and poultry droppings, is an effective substrate for biogas production, with co-digestion methods enhancing yield and efficiency. It also revealed that blending poultry droppings with banana peels or cow manure with delignified spent coffee grounds optimizes the carbon-to-nitrogen ratio, improving biogas and bio-fertilizer yields. Plant waste, such as water hyacinth and *Ulva* sp. seaweed, also shows promise when co-digested with animal waste. The review further noted that adding biochar to plant waste significantly enhances biogas production and improves the nutritional value of spent slurry, making it suitable as a bio-fertilizer. Chemical pretreatments of agricultural residues like wheat straw further ensured increased biogas yield and improved the biomethane production kinetic. This review observed that sewage sludge from wastewater treatment plants significantly boosts biogas production, particularly when co-digested with food waste. Adjusting optimal mixing ratios and mechanical mixing techniques enhanced biogas yield and energy potential, while the resulting digestate meets regulatory standards for use as a soil conditioner. This review underscores the economic and environmental benefits of optimizing biogas and bio-fertilizer production, particularly in regions like Nigeria, where such practices can address challenges in electricity generation, fertilizer costs, and waste management.

Keywords: Anaerobic digestion; Biogas; Bio-fertilizer; Animal waste; Plant waste; Agricultural waste; Sewage sludge.

INTRODUCTION

Bio-resources are non-fossil biogenic resources obtained from biological origin or nature that humans can use for multiple purposes; they are also referred to as life-generated materials and processes that are naturally and sustainably renewable and biodegradable to produce food, substantial products, and/or energy carriers (such as hydrogen, fuels, biomass, i.e., biogas, etc.), authors [1, 2]. Due to high carbon contents, waste is significantly used as a potential source for the production of a wide range of high-value products like compost (source of nutrients to

plants), biofuels, biogas, bioethanol, organic acids, pigments, dyes, etc., through solid-state fermentation and digestion [2].

Biogas technology has recently garnered increased interest, notwithstanding its long-standing recognition. This technology utilizes anaerobic digestion to transform diverse organic wastes such as manure, municipal solid waste (MSW), sewage sludge, and agricultural slurry into methane, providing a versatile and renewable energy source [3]. Anaerobic digestion presents effective waste treatment and generates valuable methane due to the involvement of di-

verse microbial metabolisms authors [4, 5]. Biogas applications have expanded from heat and electricity production to encompass vehicle fuel and function akin to natural gas. Traditional disposal methods, such as landfills, composting, incineration, and agricultural utilization, confront limitations stemming from health and environmental considerations. Anaerobic digestion emerges as an eco-friendly and economically viable alternative by optimizing the generation and utilization of biogas, which can significantly reduce operational costs for wastewater treatment plants or even generate revenue through biogas sales. Also, a by-product of the AD yields digestate, rich in nutrients suitable for utilization as bio-fertilizer authors [3, 6].

Researchers have explored diverse strategies to enhance the efficiency of anaerobic digestion and reduce costs related to digested sludge disposal, including optimizing control parameters, co-digestion, pretreatment techniques, and biological hydrogen methanation [7]. The methane produced exhibits a high heating value, rendering it a prospective substitute for liquid and gaseous fuels. Anaerobic digestion encompasses a multifaceted sequence of biochemical reactions guided by microorganisms within a multi-phase process, facilitating the conversion of organic matter into methane and carbon dioxide under diverse operational conditions [6].

However, most of these studies have predominantly focused on two methods, co-digestion and pretreatment, while neglecting to assess the economic feasibility of the primary product (biogas) and the secondary product (bio-fertilizer) derived from substrates. Although extensive research on biogas and bio-fertilizer production from sewage sludge in wastewater treatment plants, a significant research gap still needs to be seen concerning the comprehensive economic evaluation of their impact on the surrounding community and the treatment facilities. Understanding the financial implications of these sustainable practices is crucial for decision-makers and stakeholders to adopt a more financially sustainable approach to wastewater treatment and resource recovery.

The *objective of this research* is to provide a comprehensive understanding of the economic feasibility and environmental impact of utilizing biogas and bio-fertilizer produced from various waste substrates, with a focus on optimizing anaerobic digestion processes through co-digestion,

pretreatment techniques, and control parameters to maximize methane yield and nutrient recovery, thereby providing sustainable and financially viable solutions for waste management and renewable energy generation in wastewater treatment facilities.

RESULTS AND DISCUSSION

Biogas production and bio-fertilizer from animal waste. Animal waste is a valuable and cost-effective substrate for biogas production through anaerobic digestion, providing dual benefits of sustainable energy generation and effective waste management. Improper handling and disposal of animal waste can pose environmental threats due to elevated levels of nitrogen, phosphorus, pathogens, antibiotics, heavy metals, and microorganisms. Utilizing anaerobic digestion technology mitigates these concerns while harnessing the nutrient-rich content, organic matter concentration, and buffering capacity of animal waste for biogas production. Manure from various animals is suitable, given its diverse nutrient composition. The characteristics of animal waste, influenced by management practices, diet, and digestive systems, vary, encompassing faeces, urine, bedding materials, cleaning water, and small branches. Critical parameters such as volatile solids (VS), total solids (TS), pH, and carbon-to-nitrogen ratio play a pivotal role in determining methane production potential [8]. Manures and slurries from animals like cows, buffaloes, horses, minks, and poultry have long been utilized for biogas production, offering good-quality CH₄ (50–60%) and producing digested slurry that can replace fertilizer and reduce odours and microbial pathogens. However, a limitation is their low dry matter content (<10%), resulting in low biogas production authors [8, 9].

A study investigated the effect of varying pH on biogas yield from cow dung using three tin digesters maintained at pH levels of 4.52 (acidic), 6.80 (neutral), and 8.52 (alkaline) [10]. The study operates under mesophilic conditions with a hydraulic retention time of 21 days; the researchers prepared the digesters with slurries of cow dung and water in a 1:7 ratio. Results indicated that the daily biogas yield was highest at pH 8.52, while pH 4.52 exhibited the lowest yield. Cumulative biogas yield over the study period showed alkaline pH yielding the highest at 2850 ml, followed by neutral and acidic pH at 2410 ml and 1300 ml, respectively. Biogas generation com-

menced at the earliest in alkaline pH and was delayed in acidic conditions, with a continuous increase observed throughout the study duration, peaking in the final week. Overall, the research highlights cow dung's potential for biogas production via anaerobic digestion, with pH playing a critical role, favouring higher yields in alkaline conditions. The study underscores the importance of proper organic waste management to promote biogas production for national energy needs and recommends further research into additional factors influencing biogas generation to identify optimum conditions. The authors [11] investigated the biogas production potential of a 2.15 m³ pilot plastic digester using cow dung as substrate – the digester, made from high-density polyethylene (HDPE) plastic, aimed to address previous leakage issues. A ventilation test confirmed the digester's integrity. Results showed a total biogas yield of 4.00 m³, with methane dominating at 54.50%. The study's success in achieving a leak-free digester highlights HDPE's benefits. Cow dung demonstrated potential as a substrate for biogas production. Recommendations include further exploration of substrate variations and continuous monitoring for optimal efficiency and sustainability in biogas production. Author [12] assessed biogas production from various substrates, with cow dung yielding 200 ml/100 g of substrate, showcasing its potential for energy generation.

Authors [13] investigate the potential of cow manure and delignified spent coffee grounds (DSCG) as substrates for biogas and biofertilizer production. Cow manure, with its varied components like hemicellulose, cellulose, lignin, nitrogen, phosphate, potassium, and calcium oxide, possesses a C/N ratio of about 20-25%, indicating its potential for biogas and biofertilizer production. To enhance its effectiveness, additional materials like organic waste are required to boost its C/N ratio. Blending these materials with cow manure improves nutrient balance, increasing biogas and biofertilizer yields. The study involved mixing cow manure with delignified spent coffee grounds (DSCG) and an EM-4 enhancer (6-12%) under a (C/N) ratio of 25 and pH range of 5-9. pH significantly influenced biogas production, particularly during the later stages of anaerobic digestion. The optimized conditions at pH 7 with a 9% enhancer addition resulted in enhanced biogas production, as indicated by a higher cumulative biogas yield (108 ml biogas/g COD) and improved production rate (4.02 ml bi-

ogas/g COD day) with a lag phase duration of 8 days. The modified Gompertz model exhibited strong predictability ($R^2 > 0.95$) across all data points, highlighting the efficacy of the digestion parameters.

The authors [14] study demonstrated that poultry droppings (PD) alone have the potential to generate biogas, albeit at a lower level, which is a Biogas yield of 329.74 ml/g VS compared to co-digestion, which has 347.0 ± 53.6 ml/g VS (1.05 times higher than mono-digestion), methane production from the 100:0 PD ratio was 193.9 ± 21.4 ml/gVS was notably inferior to co-digestion with banana peels, with 200.1 ± 18.6 ml/gVS (1.03 times higher than mono-digestion). The study delves into the potential of anaerobic co-digestion, combining poultry droppings (PD) with banana peels (BP) to maximize biogas production, optimizing the mixing ratio. Over an 83-day batch study conducted at 35°C, the research identified the 50:50 ratio of PD and BP, yielding the highest biogas and methane output. Key substrate characteristics such as pH, TS, VS, Ash content, TN, TAN, and C/N ratio were pivotal in the anaerobic co-digestion. Maintaining an optimal pH of around 7 for methanogenic microorganism growth and achieving a C/N ratio of 20 to 30 were critical for efficient biogas production. The study underscores the superiority of co-digestion over mono-digestion, highlighting the efficacy of incorporating banana peels to augment biogas production from poultry droppings. These findings underscore the significant enhancement in biogas and methane yields achievable through adding banana peels, reinforcing the importance of exploring co-digestion strategies to maximize biogas production efficiency. Further research avenues include investigating various pretreatment methods to boost biogas production and optimizing waste management strategies for both poultry droppings and banana peels.

The authors [15] conducted a study investigating the potential of poultry litter, comprising rice hulls, sawdust, and chicken manure, mixed with cow dung as a co-substrate for anaerobic digestion to produce biogas (methane). Four laboratory-scale reactors were employed, varying in proportions of poultry litter and cow dung. After 50 days at room temperature, the reactor with 25% cow dung and 75% poultry litter (R2) yielded optimal results, with a volatile solid reduction of 51.99%, a specific gas yield of 0.469 l/g, and a methane yield of 72.5%. The kinetic analysis con-

firmed first-order kinetics for anaerobic digestion. The study concluded that a specific blend of cow dung and poultry litter demonstrated high potential for biogas production, emphasizing the importance of substrate composition in maximizing biogas yield and efficiency. The authors [16] investigated the possibility of utilizing poultry waste for biogas production in Pakistan, offering a dual solution to renewable energy generation and waste management challenges. Poultry waste, abundant in organic compounds like carbohydrates, proteins, and lipids, undergoes anaerobic digestion to produce biogas, primarily methane, facilitated by various stages, including hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Co-digestion with other materials, such as rice husk, enhances biogas production efficiency, providing a cost-effective and environmentally friendly approach.

Additionally, anaerobic digestion yields valuable residual digestate biofertilizers, improving soil fertility. The study highlights the significant yield of biogas obtained. It emphasizes the necessity of addressing institutional, financial, technological, and societal barriers to drive the transition towards sustainable energy practices, ultimately contributing to a greener future.

The authors [14] investigated the potential of biogas production from Zungo pig manure, comprising three pig sizes, in the Atlantic department of Colombia. Gas analysis reveals a methane content exceeding 50%, confirming its flammability and energy potential. pH control is crucial due to its correlation with methane content, with an optimal pH range between 6 and 8. Gas chromatography shows methane composition above 50%, indicating combustion feasibility. However, controlled conditions were necessary for these results. pH influence on biogas composition is evident, with pH extremes yielding low methane content. Results suggest significant biogas production potential but highlight the need for pH control and further research on atmospheric variations, biogas calorific value, and other components' effects on energy efficiency.

The authors [17] examined the anaerobic co-digestion (AcoD) of pig manure and corn straw to enhance biogas and slurry production. The researchers identified optimal conditions, including a C/N ratio 25 for biogas production and 35 for biogas slurry performance. Elevated organic loading rate (OLR) and total solids (TS) content resulted in favorable outcomes. Microbial com-

munity analysis highlighted the significant role of Bacteroidetes and acetoclastic methanogenesis. Maintaining appropriate C/N ratios was crucial for stability, with AcoD effectively mitigating adverse effects such as volatile fatty acid (VFAs) accumulation observed in mono-digestion of corn straw. AcoD significantly increased biogas production and methane content while enhancing nutrient concentration in biogas slurry, particularly total potassium (TK). Optimal engineering parameters were determined through comprehensive investigation, emphasizing the importance of understanding microbial dynamics in optimizing AcoD systems for biogas and biofertilizer production.

Biogas and bio-fertilizers from plant waste. The authors [18] examined the influence of cow dung biochar addition on water hyacinth anaerobic digestion, focusing on biogas production and the potential utilization of spent slurry as a biofertilizer. The research reveals that supplementing with varying biochar doses (0.5%, 1%, and 1.5%) reduces the lag phase of biogas production. The 1% biochar setup exhibited the highest cumulative biogas production at 2721 ml, followed by 2388 ml (0.5% biochar), 1940 ml (1.5% biochar), and 1153 ml (control). Biochar addition, particularly at 1%, enhances maximum biogas production by 40.6% to 57.6% compared to the control. Spent slurry analysis indicates significant nutrient content, including total nitrogen (14.07-16.69 g/kg), phosphorous (15.76-17.8 g/kg), and potassium (21.56-24.12 g/kg), suggesting its suitability as biofertilizer. The carbon-to-nitrogen ratio and NH₄ content are within acceptable limits for bio-manure, indicating its potential for plant growth enhancement. Additionally, biochar supplementation improves biogas methane content in biogas (4.4% to 11%) and enhances spent slurry nutritional value. These findings highlight the potential of water hyacinth anaerobic digestion for sustainable biogas and biofertilizer production, underscoring the beneficial impact of biochar supplementation on the anaerobic digestion process. Further research is recommended to explore the long-term effects of biochar addition and its optimization for enhanced biogas and biofertilizer yields from water hyacinth biomass.

The authors [3] investigated the potential enhancement of biogas production via anaerobic digestion using blends of wastewater (WW) and microalgae (MA) as a co-substrate. Batch experiments conducted over 21 days under mesophilic

conditions reveal that co-digestion of WW and MA improves biogas yield compared to WW alone. The optimum mix ratio of WW to MA (3:2) yields the highest methane production of 44 ml CH₄/g COD, albeit lower than the theoretical yield of 350 ml CH₄/g COD. Reductions in total solids (TS), volatile solids (VS), and chemical oxygen demand (COD) are observed at the optimal mix ratio. The study also highlights the potential use of spent slurry as a biofertilizer due to its nutrient-rich composition. However, the study suggests that further research is needed to optimize biogas production rates, possibly by investigating additional substrates. The findings underscore the importance of anaerobic digestion in capturing methane emissions and offer valuable insights for future studies in this field.

The authors [19] reported a substantial enhancement in biogas production when *Ulva* sp. seaweed was co-digested with cow dung compared to mono-digestion. Specifically, the 3:1 mixture of *Ulva* sp. and cow dung yielded a biogas production of 574 ± 26 ml-g VS, representing a significant improvement over mono-digestion, which was reported at 356 ± 19 ml g⁻¹ VS. Furthermore, the methane content in the biogas from the co-digestion setup reached 72%, highlighting the efficacy of the combined substrate approach in methane generation. This notable increase in biogas yield and methane content underscores the synergistic effect of co-digestion, where the organic composition of *Ulva* sp. complements the nutrient profile of cow dung, resulting in enhanced biomethanation. These findings emphasize the potential of co-digestion strategies in chemical engineering processes to maximize biogas production from diverse organic substrates, contributing to the development of sustainable energy solutions.

Biogas and bio-fertilizer production from agricultural waste. The author [20] researched the potential of utilizing biogas derived from the anaerobic fermentation of sugar cane vinasse, examining its applications and implications. It explores the feasibility of using vinasse biogas (VBG) for electricity production and describes its energy potential and cost-effectiveness. While vinasse is typically considered a harmful pollutant, the study highlights its potential as a valuable water source and nutrients when adequately treated. Despite the challenges associated with purification, the study suggests that vinasse management developments and trends offer promising opportunities. The research emphasizes the effective

utilization of VBG for producing biofuels and underscores the nutrient-rich nature of vinasse, making it an ideal fertilizer. By integrating VBG capabilities with conventional fuel utilization, the study proposes a paradigm shift towards a low-carbon society, aiming to enhance energy efficiency and reduce greenhouse gas emissions. Key outcomes include the availability of commercial technology for VBG production, its superior energy potential compared to other sources, and its consistent energy generation capabilities, outperforming intermittent renewable sources.

Additionally, the study highlights the positive impact of using vinasse as a biofertilizer on soil fertility, crop productivity, and pollution reduction. Experts urge policymakers to recognize these developments and implement standards supporting VBG technology's evolution, benefiting rural Indian society and the biofuel industry. Overall, the research underscores the potential of VBG as a sustainable energy source and biofertilizer, offering significant environmental and economic advantages.

The authors [21] explored the impact of three chemical pretreatment methods on biogas production from wheat straw during anaerobic digestion. Initially, the untreated wheat straw yielded 274 ml CH₄/g VS. Following pretreatment, the N-methyl morpholine N-oxide (NMMO) method increased biogas yield by 11%. In contrast, ethanol (organosolv method) and (NaOH) alkaline pretreatment increased it by 15%. These methods also improved the kinetics of biogas production. Alkaline pretreatment particularly stood out, increasing the specific rate constant (K₀) and maximum biogas production rate (R_m) by 155% and 118%, respectively. Overall, the results suggest that pretreatment enhances biogas yield and kinetics, with alkaline pretreatment showing the most significant improvement.

The authors [22] also investigated biogas production from wheat straw using acid-catalyzed steam pretreatment and enzymatic hydrolysis. The pretreatment process achieved a remarkable sugar yield of 95%, leading to a substantial improvement in methane yield by 57% compared to untreated straw, reaching 0.28 m³/kg added. Subsequent treatment of the straw hydrolysate in a UASB reactor, supplemented with nutrients, demonstrated a high methane production rate of 2.70 m³/m³.d at an OLR of 10.4 kg COD/m³.d, with a COD reduction of 94%. Moreover, the co-

digestion of straw and seaweed hydrolysates in a UASB reactor maintained stable anaerobic conditions, eliminating the need for additional nutrient supplementation and buffering agents. This approach showcased the economic viability of wheat straw biogas production, highlighting its potential competitiveness with other feedstocks.

Biogas Production from Sewage Sludge. The authors [23] examined the co-digestion of anaerobic thickened sewage sludge (ATSS) and rice straw (RS) under mesophilic conditions to improve biogas production while mitigating environmental impact. Lab-scale reactors were used to determine optimal conditions, with the 8% RS mixing ratio (MR) yielding the highest biogas volume, approximately 2.5 times that of digested thickened sludge (DTS) alone. Mechanical mixing (MM) in phase 2 increased biogas production by 2.8 times compared to DTS, with a 14% calorific value (CV) increase, indicating enhanced energy potential. Co-digestion at 8% MR with MM significantly enhanced cumulative biogas production, meeting regulatory standards for toxic parameters. Methane content remained within recommended ranges for all reactors, emphasizing co-digestion's efficacy in increasing methane volume while controlling composition. Co-digestion at 8% MR with intermittent MM offers a promising, sustainable approach for biogas production and environmental protection. Further research on scaling up and economic viability assessment is warranted to maximize its impact. The biogas yield for the optimal condition was approximately 2.5 times higher than that of DTS alone, with a 14% increase in CV, demonstrating the effectiveness of co-digestion in enhancing biogas production and energy potential.

The paper *Anaerobic Co-digestion of Municipal Wastewater Treatment Plant Sludge with Food Waste: A Study* investigated the effects of co-digestion of food manufacturing and processing wastes (FW) with sewage sludge (SS), specifically municipal wastewater treatment plant primary sludge and waste-activated sludge [24]. Bench-scale mesophilic anaerobic reactors were intermittently fed with varying ratios of SS and FW, operating at a hydraulic retention time of 20 days and an organic loading of 2.0 kg TS/m³·d. Results showed that the specific biogas production (SBP) increased by 25% to 50% with the addition of 1%-5% FW to SS, significantly higher than SBP from SS alone. While total solids (TS), volatile solids (VS), and total chemical oxygen demand (tCOD) removal slightly increased with co-

digestion, the biogas yield and methane content improved significantly, with no observed inhibitory effects. Metal screening of the digestate indicated compliance with guidelines for use as a soil conditioner. Batch biochemical methane potential tests determined an optimum ratio of up to 47-48% FW co-digested with SS. The study concludes that FW is a suitable co-substrate for anaerobic co-digestion with SS, significantly enhancing biogas yield and quality, with potential ratios of FW up to 47-48% without inhibition to the anaerobic digestion process. Overall, these findings underscore the promising potential of co-digestion to improve methane yield from SS.

The authors [25] extensively reviewed food waste anaerobic digestion (AD), emphasizing their high potential for biomethane production due to their rich organic matter content. Various influential parameters affecting biomethane production are discussed, including feedstock characteristics like nutrient composition, particle size, and inhibitory compounds, along with process parameters such as pH, temperature, retention time, and organic loading rate. Recent advancements aimed at enhancing AD of food wastes are categorized and analyzed, including optimization of operational parameters, use of additives, digestate recirculation, frequent feeding, and feedstock pretreatment methods. Despite the promising prospects of biogas production from food waste and municipal solid waste (MSW) management, operational challenges like undesired materials in MSW, acidification risks, and low process stability hinder widespread adoption. Optimizing operational parameters and employing additives, digestate recirculation, frequent feeding, and feedstock pretreatment are suggested to improve biogas production. However, further research is needed to develop more cost-effective processes that align with the biorefinery approach based on existing digesters. The review highlights the diverse range of substrates utilized for biogas production through anaerobic digestion, emphasizing their potential to address energy needs while mitigating waste management challenges. Mono-digestion of animal waste, mainly cow dung, elephant dung, and poultry droppings, stands out for its simplicity and high biogas yields [26]. However, co-digestion is more efficient, especially when combining substrates with complementary nutrient profiles, such as poultry droppings with banana peels or cow manure with delignified spent coffee grounds.

Moreover, the co-digestion of food waste with sewage sludge presents a promising solution for enhancing biogas yield from water treatment plant sludge. Optimal ratios of food waste supplementation have been shown to significantly increase methane production while simultaneously addressing waste management issues, highlighting the potential for synergistic effects in co-digestion systems.

CONCLUSIONS

This review paper provides a comprehensive understanding of the efficacy and potential of anaerobic digestion/co-digestion for producing biogas and bio-fertilizers. The various studies reviewed underscore the critical potential of anaerobic digestion in harnessing renewable resources for sustainable bio-fertilizer and biogas production. Animal waste (like cow dung and poultry droppings), plant residues (like water hyacinth), and agricultural by-products (like wheat straw and sugar cane vinasse) exhibit promising biogas yields with improved methane content when subjected to optimized conditions. Co-digestion, particularly blending complementary substrates, is a superior strategy, significantly enhancing biogas production efficiency and the resultant bio-fertilizer quality. Integrating pretreatment methods, such as enzymatic hydrolysis, alkaline, and acid-catalyzed, proved effective in improving biogas yields and process kinetics, with alkaline pretreatment showing remarkable improvements. Significant advancements could be made in sustainable waste management and renewable energy generation by leveraging pretreatment strategies and adopting optimized co-

digestion techniques, contributing to economic viability and environmental sustainability.

Future research should focus on conducting comprehensive economic assessments of biogas and biofertilizer production, considering factors such as capital investment, operational costs, revenue generation, and potential environmental benefits.

Encouraging the co-digestion of multiple waste streams, such as combining sewage sludge with animal manure or food waste, can optimize biogas production and improve process stability.

Efforts should be made to disseminate knowledge and best practices in anaerobic digestion technologies, particularly in regions with limited information and resources.

Governments and regulatory bodies should prioritize the development of supportive policies and regulations to incentivize investment in biogas and biofertilizer production infrastructure.

By addressing these recommendations, stakeholders can unlock the full potential of anaerobic digestion technologies in mitigating waste-related challenges, promoting renewable energy generation, and fostering agricultural sustainability.

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