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A Review on Biogas as a Renewable Energy Source from Organic Waste in Indonesia

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Abstract

Biogas derived from organic waste has gained increasing attention as a renewable energy option that simultaneously addresses energy security, waste management, and environmental sustainability. Indonesia possesses abundant organic waste resources, including livestock manure, agricultural residues, agro-industrial by-products, and municipal organic waste, yet their utilization for biogas production remains limited. This article reviews recent developments in biogas production from organic waste in Indonesia, with emphasis on anaerobic digestion technologies, feedstock characteristics, and biogas utilization pathways. Various digester configurations, pretreatment strategies, and operational parameters that influence biogas yield are discussed, along with applications ranging from household cooking and decentralized electricity generation to the use of biomethane as a transportation fuel. The review also highlights the agronomic potential of digestate as a biofertilizer within a circular economy framework. Despite its significant potential, biogas deployment in Indonesia faces technical, economic, and institutional challenges, including inconsistent feedstock supply, high initial investment costs, and limited policy integration. Strengthening technological adaptation, improving system integration, and enhancing policy support are therefore essential to promote large-scale and sustainable biogas development. Overall, organic waste-based biogas is positioned as a strategic component in Indonesia's transition toward a resilient and low-carbon energy system.

Introduction

Indonesia faces a dual challenge: rising energy demand and escalating environmental issues stemming from its persistent dependence on fossil fuels. Rapid population growth, industrial expansion, and accelerating urbanization have significantly increased national energy consumption, while coal, oil, and natural gas continue to dominate the country's energy mix. This dependency has led to a stable increase in greenhouse gas (GHG) emissions, making the energy sector one of the largest contributors to climate change impacts in Indonesia [1]. Separately, increasing volumes of solid and organic waste generated by households, agriculture, and industry have placed additional stress on environmental management systems [2], [3].

The environmental consequences of fossil fuel use are further compounded by emissions originating from unmanaged organic waste. Methane released from livestock manure, agricultural residues, and municipal solid waste contributes substantially to global warming due to its high global warming potential. Globally, biogas and biomethane are increasingly recognized as effective mitigation pathways because they capture methane emissions while producing low-carbon energy [6], [7]. In Indonesia, the waste sector alone accounts for a notable share of national GHG emissions, particularly in urban and peri-urban areas where waste treatment infrastructure remains limited [3], highlighting the urgent need for integrated waste-to-energy solutions.

Among renewable energy options, biogas offers a distinct advantage by directly using organic waste as feedstock. Livestock manure, agro-industrial by-products, and municipal organic waste are abundant and continuously generated throughout Indonesia. Through anaerobic digestion, these materials can be converted into methane-rich biogas, which can be used for cooking, electricity generation, heating, or upgraded into biomethane for use as a transportation fuel. International experience demonstrates that biogas systems can be effectively integrated into both rural and urban energy systems when supported by appropriate policies and technological frameworks [6], [7]. In Indonesia, however, development remains uneven due to technical and economic constraints [8].

Given Indonesia's strong agricultural base and large rural population, biogas has significant potential to support decentralized energy systems and improve rural livelihoods. Previous studies have emphasized that biogas adoption can enhance energy access, reduce household fuel expenditure, and promote circular economy practices by reusing digestate as organic fertilizer [4], [5], [8]. Nevertheless, despite extensive theoretical potential, practical utilization remains limited and split. Therefore, a comprehensive review of recent academic and practical studies is necessary to evaluate feedstock availability, technological pathways, utilization options, and sustainability implications of biogas development in Indonesia.

Feedstock Availability and Biogas Potential in Indonesia

Indonesia possesses abundant organic resources that can serve as feedstock for biogas production, mainly due to the scale of its agricultural, livestock, and agro-industrial activities. Livestock manure is recognized as the most stable and widely utilized feedstock for anaerobic digestion, particularly from cattle, poultry, goats, and pigs. Its continuous availability and favorable carbon-to-nitrogen ratio make it highly suitable for sustained biogas production. Previous studies indicate that manure-based biogas systems offer reliable methane yields and relatively simple operational requirements, making them particularly appropriate for rural and peri-urban applications [10], [13]. In Indonesia, livestock manure is estimated to contribute a significant share of the national theoretical biogas potential, although only a small fraction has been practically exploited [8], [15].

Beyond livestock manure, agricultural residues, and agro-industrial by-products represent substantial yet underutilized feedstocks. Indonesia produces large quantities of rice straw, corn residues, sugarcane bagasse, and palm oil mill effluent, all of which contain high organic content, making them suitable for biogas production. However, lignocellulosic residues often require pretreatment to improve biodegradability and methane yield [11]. International studies demonstrate that physical, chemical, or biological pretreatment can significantly enhance biogas productivity, though these processes may increase system complexity and cost [9], [10]. Consequently, pretreatment strategies must be carefully selected to strike a balance between efficiency and economic feasibility.

Anaerobic co-digestion has emerged as an effective approach to overcome the limitations of single-feedstock systems. By combining livestock manure with agricultural residues or food waste, co-digestion improves nutrient balance, enhances microbial activity, and increases the stability of methane production [12]. Studies on food waste and organic municipal waste further confirm that co-digestion not only boosts biogas yield but also reduces operational risks such as acidification and process inhibition [14]. These findings are particularly relevant for Indonesia, where mixed organic waste streams are commonly available but rarely integrated into unified biogas systems.

Municipal organic waste represents another significant feedstock source, especially in densely populated urban and peri-urban areas. Organic fractions from households, traditional markets, and food service activities dominate the composition of municipal solid waste in Indonesia. When disposed of in landfills, this waste contributes to uncontrolled methane emissions and environmental degradation. Waste-to-energy strategies based on anaerobic digestion provide an effective pathway to convert this organic fraction into useful biogas while reducing dependence on landfills [6], [14]. However, successful implementation depends heavily on waste segregation at source, efficient collection systems, and public participation.

Overall, Indonesia's theoretical biogas potential is considerable when livestock manure, agricultural residues, and municipal organic waste are considered collectively. Studies suggest that similar biomass-rich countries could meet a meaningful share of decentralized energy demand through the deployment of biogas and biomethane [9], [16]. In the Indonesian context, the gap between technical potential and actual utilization remains influenced by feedstock logistics, technology readiness, economic viability, and institutional support [8], [15]. Strengthening feedstock mapping, promoting co-digestion strategies, and integrating biogas development into national and regional energy planning are, therefore, essential steps toward maximizing biogas's contribution to Indonesia's renewable energy portfolio.

Anaerobic Digestion Technologies and System Configurations

Anaerobic digestion (AD) is the fundamental technological process underlying biogas production, which involves the biochemical conversion of organic matter into a methane-rich gas under oxygen-free conditions. The process consists of four sequential stages, including hydrolysis, acidogenesis, acetogenesis, and methanogenesis, each mediated by distinct microbial communities. The stability and efficiency of biogas production depend strongly on maintaining appropriate environmental conditions, including temperature, pH, hydraulic retention time, and organic loading rate [17], [18]. Disruptions in any of these parameters may lead to process imbalance, reduced methane yield, or system failure.

Based on operating temperature, AD systems are commonly classified into psychrophilic (<25 °C), mesophilic (30–40 °C), and thermophilic (50–60 °C) regimes. Mesophilic digestion is the most widely applied configuration in Indonesia due to its relatively low energy requirement and stable operation under tropical climatic conditions [19]. Although thermophilic systems offer higher reaction rates and pathogen reduction, their sensitivity to temperature fluctuations and higher operational costs limit their applicability, particularly in small-scale and rural installations [20]. Consequently, mesophilic digesters remain the dominant choice for household and community-based biogas systems.

From a design perspective, anaerobic digesters can be categorized into fixed-dome, floating-drum, plug-flow, and continuously stirred tank reactor (CSTR) types. Fixed-dome digesters are widely used in Indonesia for their simple construction, low maintenance requirements, and long operational lifespan [21]. Floating-drum systems provide more stable gas pressure but are less popular due to higher construction and maintenance costs. For larger-scale applications, such as agro-industrial waste treatment, CSTR and plug-flow reactors are preferred owing to their ability to handle higher organic loading rates and mixed feedstocks [22].

Recent technological developments emphasize process optimization and system integration to enhance biogas productivity. Strategies such as co-digestion, improved mixing, controlled feeding, and digestate recirculation have been shown to improve methane yields and operational stability [12], [17]. In addition, biogas upgrading technologies, including water scrubbing, pressure swing adsorption, and membrane separation, enable the production of biomethane with higher methane content suitable for grid injection or vehicle fuel applications [23]. Although upgrading technologies remain limited in Indonesia, their integration presents a significant opportunity to expand biogas utilization beyond traditional household and electricity-generation applications.

Overall, the selection of anaerobic digestion technology and system configuration must consider feedstock characteristics, scale of operation, economic feasibility, and local technical capacity. Studies consistently highlight that inappropriate technology selection is a major cause of biogas system underperformance in developing countries [18], [21]. Therefore, context-specific system design, combined with operator training and technical support, is essential to ensure reliable and sustainable biogas production in Indonesia.

Biogas Utilization Pathways and Energy Applications

Biogas can be utilized through multiple pathways, depending on its quality, production scale, and the end-user's requirements. The most common application, particularly in developing countries, is direct combustion for cooking and heating. In rural Indonesia, household-scale biogas digesters are primarily used to replace liquefied petroleum gas (LPG), kerosene, and firewood for cooking purposes. This application provides immediate socio-economic benefits by reducing household energy expenditure and improving indoor air quality through lower particulate and carbon monoxide emissions compared to traditional biomass fuels [24], [25].

Beyond household use, biogas plays an increasingly important role in decentralized electricity generation. Biogas-fueled internal combustion engines and microturbines can supply electricity to rural communities, agro-industrial facilities, and small enterprises that lack reliable access to the national grid. Several studies report that biogas-based power generation systems are technically feasible and economically competitive when integrated with livestock farms, palm oil mills, and food-processing industries [26], [27]. In Indonesia, such systems offer particular advantages for remote and island regions where grid extension is costly and logistically challenging.

Another important utilization pathway is the upgrading of raw biogas into biomethane by removing carbon dioxide, hydrogen sulfide, and moisture. Biomethane has a higher methane concentration and can be used as a substitute for natural gas in transportation, industrial heating, or gas grid injection. International experience shows that biomethane-based fuels, such as bio-compressed natural gas (bio-CNG), significantly reduce greenhouse gas emissions and air pollutants compared to conventional fossil fuels [28], [29]. Although biomethane utilization in Indonesia remains limited, its development presents a strategic opportunity to decarbonize the transportation sector and enhance energy diversification.

In addition to its energy applications, the by-product of anaerobic digestion—digestate—represents a valuable resource that supports sustainable agriculture. Digestate contains essential nutrients, including nitrogen, phosphorus, and potassium, making it suitable for use as an organic fertilizer or soil conditioner. Studies indicate that digestate application improves soil structure, enhances nutrient retention, and reduces reliance on synthetic fertilizers, thereby contributing to circular economy principles [30], [31]. The combined utilization of biogas for energy and digestate for agriculture strengthens the overall sustainability and economic viability of biogas systems.

Overall, the versatility of biogas utilization pathways enables its integration across multiple sectors, including households, agriculture, industry, and transportation. However, the selection of appropriate utilization routes depends on factors such as biogas volume, gas quality, infrastructure availability, and economic considerations. Previous reviews emphasize that integrated planning of production and utilization systems is essential to maximize the efficiency and long-term impact of biogas deployment, particularly in developing countries such as Indonesia [26], [29]. Table 1 consolidates findings from recent literature by linking feedstock availability, anaerobic digestion technology, and utilization pathways, thereby illustrating the current state and potential of biogas development in Indonesia.

Table 1. Summary of biogas feedstock, technology, and utilization pathways

Feedstock Source	**AD Technology**	**Main Application**	**Key Insights**	**Ref.**
Livestock manure	Fixed-dome, mesophilic	Cooking, electricity	Stable yield, rural suitability	[8], [13], [21]
Manure + residues	Co-digestion	Electricity	Improved stability & methane yield	[10], [12]
Crop residues	Pretreated AD	Power & heat	Higher yield, higher cost	[9], [11]
POME	CSTR	Industrial power	High organic loading	[15], [26]
Municipal organic waste	AD with segregation	Electricity	Methane mitigation	[6], [14]
Digestate	Post-treatment	Fertilizer	Soil improvement	[30], [31]

Challenges and Policy Implications for Biogas Development in Indonesia

Despite its significant potential, biogas development in Indonesia remains constrained by several technical, economic, and institutional challenges. One of the primary barriers is the inconsistency in feedstock supply and quality, particularly for systems relying on agricultural residues and municipal organic waste. Poor waste segregation practices, limited collection infrastructure, and seasonal variability in biomass availability often lead to unstable biogas production and underperforming digesters [8], [15]. These issues highlight the need for improved feedstock management and standardized operational guidelines.

Economic constraints also play a critical role in limiting biogas deployment. Although biogas systems offer long-term cost savings, the initial investment cost for digester construction, gas engines, and upgrading technologies remains relatively high for smallholders and rural communities. Limited access to financing, subsidies, and technical assistance further exacerbates this challenge [6], [15]. As a result, many biogas projects heavily depend on external funding or donor-driven programs, raising concerns about their long-term sustainability once project support ends.

From an institutional perspective, fragmented policy frameworks and limited coordination among stakeholders hinder the adoption of large-scale biogas. While Indonesia has introduced renewable energy targets and waste-to-energy initiatives, biogas development is often treated as a small-scale or auxiliary solution rather than an integral component of national energy planning. Previous studies emphasize that stronger policy integration, clearer regulatory frameworks, and targeted incentives—such as feed-in tariffs for biogas-based electricity or support for biomethane upgrading—are essential to accelerate deployment [6], [8], [28].

Addressing these challenges requires a comprehensive and coordinated approach. Strengthening institutional capacity, enhancing public awareness, and fostering collaboration between government agencies, academia, and local communities are crucial steps toward sustainable biogas development. When supported by appropriate policies and technological innovation, biogas can transition from a niche rural technology to a strategic pillar of Indonesia's renewable energy and waste management systems.

Conclusion

Biogas represents a highly promising renewable energy option for Indonesia, offering integrated solutions to energy security, organic waste management, and greenhouse gas emission reduction. Drawing on abundant feedstocks such as livestock manure, agricultural residues, and municipal organic waste, biogas systems convert environmental liabilities into valuable energy and agricultural inputs. The review demonstrates that anaerobic digestion technologies and diverse utilization pathways—including cooking, electricity generation, biomethane production, and digestate reuse—are technically feasible and environmentally beneficial in the Indonesian context.

However, the gap between theoretical potential and actual implementation remains substantial. Technical limitations, economic barriers, and fragmented policy support continue to restrict its large-scale application. This review highlights that context-specific technology selection, improved feedstock management, and integrated policy frameworks are critical to overcoming these constraints. With strengthened institutional support, targeted incentives, and continued research and development, biogas can play a significant role in Indonesia's transition toward a more sustainable, decentralized, and resilient renewable energy system.

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