Advancements in Biogas Production from Cow Dung: A Review of Present and Future Innovations

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Abstract. Indonesia is the fourth most populous country in the world, which is significant with energy consumption. Currently, Indonesia is heavily dependent on fossil fuels to its energy needs, but continued reliance on these fuels could lead to depletion. To overcome this problem, biogas is considered as an alternative energy source for cooking and electricity, especially from waste such as cow dung. This research provides an overview of biogas production from small cattle farms in Indonesia, with a focus on cow dung as a valuable resource. It covers factors that increase biogas production, multiple digesters, purification techniques, and integrates Internet of Things (IoT) technologies. Articles for this study were selected using the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) method from reputable journals indexed in Scopus and PubMed. Sustainable biogas from cattle farms offers energy generation using abundant cow dung. Optimizing production involves adjusting raw materials, temperature, pH, C/N ratio and HRT. Different types of digesters have unique advantages. Purification techniques such as water scrubbing, PSA, etc. increase methane production. Integrating IoT provides monitoring and optimization. Biogas production has enormous potential for renewable energy, requiring the use and application of efficient techniques, digester types, purification, and IoT integration for a greener future.

Keywords : Biogas, Cow Dung, Renewable Energy, Purification, Digester, Internet of Things

1 Introduction

Biogas is a renewable energy produced through the anaerobic digestion of organic materials, such as animal manure, agricultural residues, food waste, and sewage [1]. It primarily consists of methane and carbon dioxide, with small amounts of other gases. Biogas provides a sustainable energy source and can be used for cooking, heating, and electricity generation [2]. Cow dung, a byproduct of small-scale cattle farming, serves as a valuable resource with multiple applications. Cow dung can be processed in biodigesters to produce biogas, contributing to renewable energy production and reducing greenhouse gas emissions. Additionally, It can be used as an organic fertilizer to enhance soil fertility and improve crop productivity [3, 4]. The utilization of cow dung promotes sustainable waste management practices and harnesses its potential for agricultural and energy-related purposes. However, the implementation of biodigesters in rural areas faces challenges. Lack of awareness and education about biodigester technology, high installation costs, maintenance requirements, inconsistent feedstock availability, and limited infrastructure pose obstacles to widespread adoption. Cultural and social factors may also influence the acceptance and utilization of

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biodigesters within communities [5, 6]. Efforts are needed to raise awareness, provide financial support, offer training and technical assistance, and address infrastructure limitations. By addressing these challenges, the potential benefits of biodigesters and the utilization of cow dung can be maximized, contributing to sustainable waste management, energy production, and rural development [7–10]. This study focuses on the potential of biogas in Indonesia, highlighting the use of cow dung as a substrate and the advantages of biogas for energy and fertilizer. It also discusses future technologies aimed at increasing user adoption and improving the efficiency of biogas systems.

2 Methode

The systematic review and meta-analysis followed the PRISMA method, which is a widely recognized framework for conducting such studies. The selection of keywords was tailored to address the specific research question of this study, included both compound expressions ("cow dung biogas") and individual/synonymous words ("cow dung" or "cattle manure" as alternatives), ensuring a comprehensive search without excluding potential documents. The databases were searched using various combinations of terms, such as "biogas cow dung," "biogas cattle manure energy conversion," "co-digestion cattle manure," "biogas purification cattle manure," "biogas reactor cow dung," "biogas IoT," "biogas reactor cow manure," "digester cow dung," "gas characterization biogas cow," and "biogas cow dung emission," targeting the title, summary, and keywords of the documents. The sorting process involved selecting journals indexed as Q1, Q2, Q3, and Q4, published between 2013–2023 (10%) and 2018 – 2023 (90%).

3 Biogas

3.1 Small-Scale Cattle Farming

In Indonesia, there are currently around 16.6 million cattle, with 43% located in Java Island, 25% in the Eastern Islands, and the remaining 32% scattered across other islands. The majority of cattle production, approximately 90%, comes from smallholder farming systems, involving around 6.5 million farmers living in rural areas [24]. The remaining 10% is contributed by commercial farmers (less than 1% of the total) and large beef cattle companies, primarily targeting the Java island market. These smallholder farmers not only raise cattle for meat production for the urban market but also utilize them for manure to support crop growth and as valuable assets for their livelihoods [25].

The concentration of cattle farming activities in Indonesia can be attributed to favorable climate, agricultural traditions, and supportive infrastructure. This serves as a significant source of income for rural households, as cattle can be raised for milk, meat, and dairy products that are sold in local markets or processed into value-added goods. This contributes to the economic well-being and livelihoods of rural communities [26]. However, if not managed properly, cattle agricultural waste and dung can lead to environmental issues such as odors, water contamination, and the release of greenhouse gases like methane [27].

Cattle farming has been an integral part of rural communities for centuries, offering various advantages that contribute to food security, economic stability, and social well-being. It plays a crucial role in ensuring food security by providing a sustainable source of high-quality protein through milk, meat, and dairy products. This availability enhances dietary diversity and overall nutritional well-being in rural areas. Cows can also be used for breeding, ensuring a steady supply of calves for meat production, thus enhancing animal protein availability in the local food system [28]. Cattle farming brings economic benefits to rural communities by providing income through the sale of milk, meat, dairy products, leather, and manure. These income opportunities contribute to the growth of rural economies, stimulate local markets, and create employment opportunities within the community. Moreover, cows hold social significance and contribute to community cohesion by being deeply rooted in cultural traditions and social gatherings. They are seen as valuable assets and are often shared or exchanged during important social events, strengthening social bonds and fostering a sense of belonging among community members [29].

3.2 Cow Dung Source

As one of the most populous countries globally, Indonesia is witnessing rapid growth and has become the largest energy consumer among ASEAN nations. Projections indicate a continuing increase in energy demand, reaching up to 450×10^9 KWh by 2026 [30]. Similar to other Southeast Asian countries, the majority of household energy in Indonesia is used for cooking, lighting, cooling, heating, and appliances. The number of residential households has been steadily rising at a rate of 1.5% per year, with an average of around four people per household [31]. In 2010, the IEA reported that 80% of Indonesia's power generation relies on non-renewable and fossil-based resources. Oil, gas, and coal dominate the primary energy supply, with Indonesia becoming a net oil importer since 2004 due to insufficient local production. Hence, the adoption of sustainable and renewable energy technologies, including biogas from animal waste, has become crucial for Indonesia's energy sovereignty [32].

With a population exceeding 260 million people, Indonesia is a significant consumer of meat in the region. It is projected that animal product consumption will reach 5,277.7 metric tons by the end of 2022, equivalent to the amount of manure generated from animal waste [33]. Cow dung, which is abundant in Indonesia, can be utilized as a raw material for biogas production, offering a waste management solution while reducing environmental pollution and greenhouse gas emissions. Biogas production from cow dung provides a renewable energy source, primarily methane, which can be used for cooking, heating, and electricity generation. Implementing biogas systems at the village level improves living standards, energy access, and promotes economic activities in rural communities [34].

The anaerobic digestion of cow dung in biodigesters produces biogas, while the remaining material, called slurry or digestate, serves as a nutrient-rich fertilizer. The slurry, containing essential nutrients like nitrogen, phosphorus, potassium, and organic matter, enhances plant growth, crop yields, soil quality, and sustainable agriculture [35]. Proper management of slurry application, including nutrient monitoring and following guidelines, reduces reliance on synthetic fertilizers, minimizing environmental impacts. Utilizing cow dung slurry enables cost reduction, byproduct recycling, and sustainable farming practices. Analyzing nutrient content and adjusting application rates based on crop and soil requirements optimize the use of slurry as a valuable fertilizer resource [36].

3.3 Biogas Energy

Biogas can be used as a direct substitute for traditional cooking fuels such as wood, charcoal, or LPG (liquefied petroleum gas). It can power various cooking appliances such as stoves, burners, and ovens. The combustion of biogas produces a clean and efficient flame, making it a practical and environmentally friendly option for cooking [37]. When biogas is used for cooking, the heat energy from methane can replace the use of traditional fuels like firewood or charcoal, providing a cleaner and more efficient cooking alternative. Biogas can also be used to generate electricity through combustion in an engine or by using it as a fuel for a gas turbine or microturbine. Methane, as a key component of biogas, serves as an energy source with a high heat content [38]. The specific heat content of methane can vary slightly depending on the quality and composition of the biogas, but on average, methane has a heat content of approximately 1,000 BTUs per cubic foot or 35.3 MJ per cubic meter. The heat energy content of methane makes it a valuable fuel for various energy applications [39]. The quantity of methane generated in the anaerobic digestion (AD) process varies depending on the specific type of animal waste. For example, biogas derived from cow or chicken manure generally consists of approximately 50-70% methane [8]. When estimating the potential electricity generation from biogas produced by animal waste, it is common to assume methane generation rates of 60% for large ruminants, 45% for small ruminants, and 60% for poultry [40].

Currently, many developing countries have embraced anaerobic digestion (AD) as a sustainable waste-to-energy solution. Potential for biogas generation from animal waste could reach up to 4.6 million m^3 per year, resulting in the production of 8.27×10^9 KWh of electricity annually [41]. The growing demand for livestock products in Indonesia has led to a significant amount of biodegradable waste in the form of animal manure, which is suitable for biogas production. However, this potential remains largely untapped [42]. According to the Indonesia Energy Outlook and Statistics (IEOS) of 2006, feedstock, including cow, buffalo, and pig droppings, for biogas production is available across all 34 provinces, albeit in varying quantities and origins. The provinces with the highest potential for biogas energy from animal waste are East Java (125.9 megawatts), Central Java (63.0 MW), East Nusa Tenggara (56.7 MW), and North Sumatra (46.8 MW) [11]. These findings indicate promising prospects for biogas energy derived from animal waste in rural Indonesia [1, 9, 32].

4 Current Technology

4.1 Biogas Digesters

Farmers commonly employ two types of digesters on their farms: household and communal. The larger-scale communal digester is well-suited for farms with over 30 cattle and offers greater cost-effectiveness. On the other hand, smallholder farm households, typically owning two or three cows, prefer the smaller household digester [46]. These digester variants vary in size, ranging from 4 m^3 to 12 m^3, and come with lower investment and maintenance costs. Such small-scale digesters have numerous advantages, including the production of biogas and organic fertilizers, making them highly valuable for smallholder farmers [47]. Moreover, there are several commonly utilized digester types, namely the fixed dome digester, floating drum digester, and plastic biodigester. Floating drum and plastic biodigesters are suitable for small-scale biogas production, while fixed dome digesters are generally employed for larger biogas production [48].

Fixed Dome Digester have a varies volume depending on the specific application and amount of waste generated, ranging from a few cubic meters to several hundred cubic meters [45]. This digester type consists of a sealed chamber, which can be either underground or semi-underground, with a dome-shaped gas holder. The materials used for constructing the digester chamber include reinforced concrete, bricks, or prefabricated panels [49]. Biogas, produced within the chamber, ascends and displaces the gas holder. The gas holder is connected to a gas outlet for the purpose of collection and utilization [50]. These digesters find wide usage in small-scale and community-level contexts, especially in rural areas[41].

Floating Drum Digesters are digester systems that are either completely sealed, underground, or partially underground. They are constructed using materials such as concrete or masonry [38]. These digesters feature a gas holder, typically in the form of a dome-shaped or cylindrical container, which floats on the surface of the digester slurry [49]. The digester operates through anaerobic digestion, in which organic waste is introduced into the chamber.

Bacteria decompose the organic matter in the absence of oxygen, resulting in the production of biogas, primarily composed of methane (CH_4) and carbon dioxide (CO_2) [13]. When biogas is used, the gas holder rises, and when it is utilized, the gas holder descends. These digesters are extensively utilized in small-scale and household-level settings [11, 12]

A Plastic Bag Digester is a robust biogas digester that is constructed using materials such as high-density polyethylene (HDPE) or other durable substances. Its structure comprises a sealed container, available in various sizes for different applications, ranging from small-scale household systems to larger community or industrial setups [37]. It incorporates inlets for waste introduction, outlets for collecting biogas and processed slurry, and may also feature a gas storage system for storing the generated biogas [23, 24]. These adaptable biogas digesters are suitable for deployment in both rural and urban environments, including households, farms, schools, and small-scale industries [8]

4.2 Co-Digestion

Anaerobic digestion is a biological process that occurs in the absence of oxygen and involves specific bacteria [21]. It converts organic matter into methane and carbon dioxide through a series of four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis [22]. The utilization of high-quality feedstock is crucial for producing high-quality digestate. However, certain feedstocks present challenges for mono digestion due to unfavorable C/N ratios or high lipid content [33]. In such cases, co-digestion, which involves combining different substrates, is recommended to address imbalances and enhance volumetric methane productivity [44]. Co-digestion helps overcome issues like rapid acidification and poor carbon-to-nitrogen (C/N) ratios, thereby improving biogas production [15]. Compared to other organic waste, cattle manure biodegrades at a slower rate, primarily due to the presence of hay materials. To enhance biodegradability and volatile solids (VS) in the anaerobic reactor, incorporating co-digestion of cattle waste with additional feedstocks such as wheat straw, rice straw, or food waste is beneficial [43, 44]. Providing sufficient and efficient nutrient supply to microorganisms in the digester is critical for achieving maximum methane yield [8]. Manures contain a wide range of nutrients, and the addition of other organic wastes can significantly enhance methane yield, with improvements ranging from 40% to 100% [19].

4.3 Biogas Parameters

To optimize the production of biogas, it is crucial to ensure a well-balanced mixture of cow dung and water while maintaining an appropriate carbon-to-nitrogen ratio. Enhancing the composition of the feedstock and increasing biogas generation can be achieved by incorporating other organic materials rich in carbon, such as food waste or crop residues [25]. Scaling up the quantity of cow dung or organic waste added to the biodigester can lead to higher biogas production. However, it is essential to maintain a proper balance to avoid overloading or inhibiting the anaerobic digestion process.

The digester temperature significantly impacts biogas production. Anaerobic fermentation occurs within various temperature ranges: psychrophilic (<30°C), mesophilic (30 to 40°C), and thermophilic (50 to 60°C). The optimal temperatures for anaerobic organisms are mesophilic and thermophilic. The fermentation period duration depends on the temperature [27]. Methanogenic bacteria, responsible for biogas formation, are highly sensitive to temperature fluctuations, with an optimal range of 33 to 38°C. Biogas production is hindered at lower temperatures and harmed at excessively high temperatures, risking the death of specific bacteria strains. Preventing sudden temperature increases is crucial to maintaining bio-methane production. Insulation or heating systems are recommended for temperature control, particularly in colder climates [38].

The pH level is a critical factor that significantly impacts microbial growth during anaerobic fermentation. Maintaining the pH of the digester within the desired range of 6.8 to 7.2 is vital, and this can be achieved by controlling the optimal loading rate of the feedstock [19].The production of carbon dioxide and volatile fatty acids during the anaerobic process affects the pH of the digester contents. pH values below 6.0 to 6.5 hinder the activity of methane bacteria. To prevent a decrease in pH, chemicals such as sodium bicarbonate, sodium hydroxide, sodium carbonate, and sodium sulfide are commonly introduced to the organic substrate to provide buffering capacity [27, 28]

The carbon-to-nitrogen ratio (C/N ratio) is crucial for determining the suitability of cow dung for composting or anaerobic digestion. Maintaining an optimal C/N ratio within the range of 20 to 35 is essential for efficient decomposition and nutrient release [12]. Microbes require a C/N ratio of 20 to 30:1, with easily degradable carbon, to support their activities. Cattle manure typically has a low C/N ratio of 11 to 14, meeting the nutrient requirements for anaerobic bacteria.

TS, also known as Total Solid, refers to the proportion of biomass utilized during the AD process. It is influenced by the presence of moisture and water. When the TS value is low, it indicates a higher water content and humidity, and vice versa [9]. Water plays a crucial role in the decomposition of organic matter as it acts as a solvent and facilitates the movement and diffusion of microorganisms. The optimal TS value is typically around 9-10% or with a humidity range of 80-90% [41, 42].

The hydraulic retention time (HRT) is the duration the influent liquid phase remains in the digester. The required retention time varies based on technologies, process temperature, and waste composition. In mesophilic digesters, the typical retention time for treated wastes ranges from 10 to 40 days [5].If the retention time is too short, bacteria are washed out faster than they can reproduce, significantly reducing fermentation. A longer retention time allows for more complete substrate degradation, but reaction rates decrease.

5 Future Technology

5.1 Biogas Purification

It is important to consider that the heat energy content of methane in biogas can be influenced by the presence of other gases, including carbon dioxide (CO_2) that is the second most abundant gas in biogas, typically accounts for 40% to 50% of the volume [33]. The percentage of CO_2 in biogas is inversely proportional to the percentage of methane, meaning that as the methane content increases, the carbon dioxide content decreases, and vice versa. Higher concentrations of these gases in biogas can slightly reduce the heat energy content of methane. Biogas may also contain trace amounts of other gases such as hydrogen sulfide (H_2S), carbon monoxide (CO), and ammonia (NH_3). H_2S is a colorless, flammable, and toxic gas with a foul odor. Its corrosive nature poses a considerable risk to cogeneration engines, necessitating its removal from biogas. Inhaling H_2S can lead to reactions with enzymes in the bloodstream, inhibiting cellular respiration and resulting in pulmonary paralysis, sudden collapse, and fatality. Additionally, CO can be harmful to humans because it binds to hemoglobin in the blood, displaces oxygen and reduces the blood's ability to transport oxygen throughout the body and contributing to GHG emissions that cause global warming [36, 37].

To mitigate the impacts of impurities gases in biogas, various purification and conditioning processes can be employed, such as gas scrubbing, desulfurization, and dehydration. There is some technical use to purifying biogas such as water scrubbing, PSA, membran technology, chemival adsorption, and cryogenic [14]. The water scrubbing is a absorption of CO_2 with principle separates gas components based on their solubility in a liquid scrubbing solution. Water is commonly used as an absorbent in large-scale biogas scrubbing due to its lower sensitivity to impurities and CO_2 solubility being higher than that of CH_4. HS can be removed with CO_2, but it is advisable to separate H_2S first to prevent operational issues caused by its corrosiveness and foul odor [30, 41]. Optimized full-scale plants have achieved high biomethane content with minimal methane losses and comparable energy consumption to water scrubbing [20].

Pressure Swing Adsorption (PSA) is a widely used gas separation and purification technique that employs adsorbents like zeolites or activated carbon to selectively remove specific components from a pressurized gas mixture [10]. Various adsorbent materials, such as Molecular Sieves, Silicon Gel, Metal-Organic Frameworks (MOFs), Activated Alumina, and Carbon Molecular Sieves, are used in PSA based on specific separation requirements and contaminant [48]. Different adsorbents have unique adsorption capacities, selectivity, and regenerative properties. Methane recovery rates of 96-98% with 2-4% methane losses have been reported [13].

Membrane technology selectively purifies biogas by separating impurities using permeable membranes. The choice of membrane (polymeric or ceramic) depends on the targeted impurities [14]. These membranes allow methane to pass while limiting unwanted components. The advantages like targeted impurity removal, compact design, lower energy requirements, and scalability [15]. However, considerations include membrane fouling, temperature/pressure conditions, maintenance, and cost-effectiveness.

Cryogenic separation utilizes temperature differences to separate gases by cooling gas mixtures at high pressure [17]. This enables the separation of CO_2 from biogas, as well as other gases like N_2, O_2, and siloxanes through condensation and distillation. It offers advantages in treating landfill gas, achieving 98% pure CO_2 production, high-purity methane with minimal losses (<1%), and direct use in vehicles or injection into the gas grid [18]. However, the energy consumption is high due to compressing raw biogas at 200 bar, accounting for 5-10% of the biomethane produced [29].

Chemical absorption, similar to water/glycol scrubbing, transfers substances between biogas and liquid through chemical reactions. It utilizes CO_2 reactive absorbents like alkanol amines (e.g., MEA, DMEA) and alkali aqueous solutions (e.g., KOH, K_2CO_3, NaOH, $Fe(OH)_3$, $FeCl_2$) [15]. Despite high CO_2 removal efficiency, this method has relatively high energy consumption (regeneration heat) and potential issues like salt precipitation, foaming, and amine and chemical poisoning by O_2 [12, 13]

5.2 Implementation IoT for Biogas monitoring

To enhance biogas production and increase its usage is essential through maintaince of digester which includes tasks such as cleaning, sediment and scum removal, and maintaining proper sealing is to ensure its sustainability and continuous biogas production [18]. Proper storage and efficient utilization of biogas are crucial to prevent wastage and maximize its benefits. The future of biodigester technology for rural communities involves integrating user-friendly and accessible technologies to simplify usage and maximize benefits. Potential advancements include mobile applications and remote monitoring, plug-and-play biodigester systems, modular and scalable designs, streamlined feedstock preparation, integrated energy systems, innovative biogas appliances, and community training and support [12]. Mobile applications provide real-time data and troubleshooting assistance, while plug-and-play systems simplify installation and operation. Modular designs allow for gradual expansion, and simplified feedstock preparation enhances efficiency. Integration with other renewable energy systems offers hybrid energy solutions, and specialized biogas appliances cater to rural community needs [21]. Community training and support programs empower users and promote sustainable practices. These innovations aim to make biodigesters more accessible, user-friendly, and beneficial for rural communities [13, 14].

The stability of anaerobic digestion (AD) plays a crucial role in methane production, relying on a delicate equilibrium [15, 16]. Addressing these challenges is crucial as process instability can impact the economic feasibility of biogas plants. Therefore, monitoring and controlling the AD process are vital for comprehending its functional behavior and achieving efficient biogas production [26].

Internet of Things (IoT) refers to an interconnected environment created by internet-connected devices. It focuses on tasks such as data transmission, reception, and processing [27]. The primary objective of IoT is to enhance our daily routines and improve task performance by offering advantages such as traceability, adaptability, and real-time monitoring [19, 20]. Understanding the IoT space requires defining the IoT architecture and the three-layer architectures (sensor, middleware, and application layer) are the most common in IoT environments. The use of IoT-based wireless monitoring for biogas processes shows promise in improving real-time monitoring and control [32]. Implemented IoT in a pilot biogas plant using pH, temperature, and oxidation-reduction potential electrodes connected to a programmable logic controller. This allowed for real-time, offsite monitoring and rapid response to ensure reactor stability and biogas quality, ultimately improving biogas production efficiency by up to 80% [33]. The application of cow dung biogas is depicted in Figure 1, illustrating its utilization.

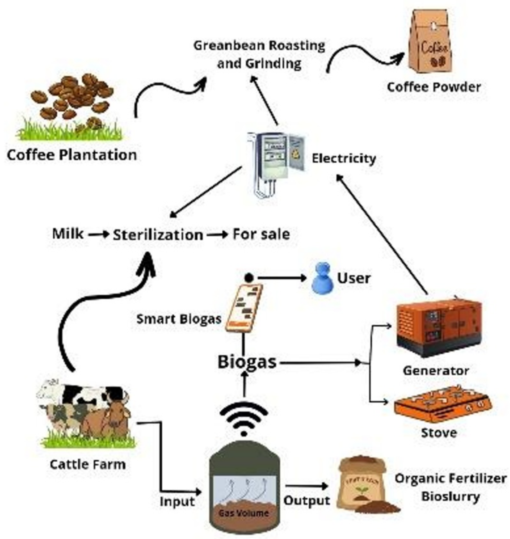

Fig. 1. Iot-enabled innovations in biogas production from cow dung

Conclusion

In Indonesia, smallholder farming systems raise the majority (90%) of the country's 16.6 million cattle, while commercial farmers and large beef cattle companies account for the remaining 10%. It contributes to food security, economic stability, and social well-being, but inadequate management can cause concerns such as odor, water pollution, and greenhouse gas emissions. Biogas derived from cow dung is a versatile and eco-friendly alternative for cooking and various energy applications. Careful management of biogas composition, including methane, carbon dioxide, hydrogen sulfide, carbon monoxide, and ammonia, is crucial for heat energy content, emissions, and proper functioning. Farmers use two types of digesters to biogas production, communal and household, with each offering benefits such as biogas and organic fertilizer production. High-quality feedstock and co-digestion with substrates like wheat straw, rice straw, or food waste improve methane yield. Optimizing biogas production requires a balanced mixture of cow dung, water, and carbon-rich organic materials. Various purification methods like water scrubbing, PSA, membrane technology, chemical adsorption, and cryogenic separation are employed, but energy consumption and maintenance need careful consideration. Proper maintenance and utilization of biogas are important for rural communities, including the addition of organic waste streams to biodigesters through co-digestion. The future of biodigester based on IoT technology involves integrating user-friendly innovations, such as mobile applications, remote monitoring, and plug-and-play systems, to enhance stability, efficiency, and real-time monitoring in biogas production.

Acknowledgement

This work was financially supported by Directorate of Research, Technology and Community Service provided by the Directorate General of Higher Education 2023, Indonesia

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