Integrated Biogas and Organic Fertilizer Production: A Review

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***Abstract*—The increasing demand for sustainable energy and environmentally responsible waste management has accelerated interest in integrated waste-to-energy systems. This review critically examines the production of biogas through anaerobic digestion of biodegradable waste, including human waste, cow dung, and kitchen waste, with a focus on co-digestion strategies and process optimization. The study evaluates key operational parameters such as temperature, pH, carbon-to-nitrogen ratio, and retention time, and their influence on methane yield and system stability. A comparative analysis of mono-digestion and co-digestion systems reveals that co-digestion enhances biogas production by improving nutrient balance and microbial activity. Furthermore, the review explores the potential of digestate as an organic fertilizer, highlighting its nutrient composition and role in improving soil fertility and crop productivity. Emerging technologies, including IoT-based monitoring and artificial intelligence for process optimization, are also discussed. The integration of biogas production with agricultural applications supports circular economy principles by converting waste into valuable energy and bio-inputs. Despite its advantages, challenges such as process inefficiencies, high initial investment, and lack of standardization remain. The paper identifies key research gaps and provides future directions for enhancing system performance and scalability. The findings indicate that integrated biogas systems offer a sustainable solution for renewable energy generation, waste management, and eco-friendly agriculture.**

ENVIRONMENTAL IMPACT STATEMENT

This review highlights the potential of integrated biogas systems as a sustainable solution for managing biodegradable waste while generating renewable energy. By analyzing co-digestion strategies and process optimization, the study demonstrates improved methane yield and system efficiency. The utilization of digestate as an organic fertilizer further supports soil health and reduces reliance on chemical inputs. The incorporation of IoT-based monitoring enhances process control and scalability. Overall, the study contributes to circular economy practices by converting waste into valuable energy and agricultural inputs, thereby reducing environmental pollution and promoting sustainable development.

***Index Terms*—Biogas, Anaerobic Digestion, Co-digestion, Digestate, Circular Economy, Organic Fertilizer, Waste-to-Energy**

I. Introduction

Rapid urbanization, industrialization, and population growth have significantly increased the generation of biodegradable waste, leading to serious environmental challenges such as greenhouse gas emissions, soil contamination, and water pollution. Conventional waste disposal methods such as landfilling and open dumping are unsustainable and result in the loss of valuable organic resources. In this context, anaerobic digestion (AD) has emerged as an efficient and environmentally sustainable technology for converting organic waste into renewable energy in the form of biogas.

Anaerobic digestion is a biological process in which microorganisms degrade organic matter in the absence of oxygen, producing methane-rich biogas and nutrient-rich digestate. This process contributes to waste stabilization, energy recovery, and nutrient recycling, making it a key component of sustainable waste management systems (Holm-Nielsen et al., 2009; Weiland, 2010). Furthermore, the integration of biogas production with agricultural applications aligns with circular economy principles, where waste materials are converted into valuable resources such as energy and fertilizers (Kothari et al., 2010; Achinas et al., 2017).

Despite these advantages, several critical research gaps still limit the widespread adoption and efficiency of integrated biogas systems. There is a lack of large-scale implementation studies under real field conditions, insufficient long-term data on the impact of digestate application on soil health, and limited development of advanced monitoring and control systems for process optimization. Additionally, the optimization of multi-feedstock co-digestion systems remains a challenge due to variability in substrate composition and operational conditions. Addressing these gaps is essential for improving the efficiency, reliability, and scalability of anaerobic digestion technologies.

II. FEEDSTOCK CHARACTERISTICS AND SUITABILITY

2.1 Types of Feedstocks

The selection of feedstock plays a crucial role in determining the efficiency of biogas production. Common feedstocks include agricultural residues, animal manure, food waste, and municipal organic waste. These materials vary in terms of organic composition, moisture content, and biodegradability, which directly influence methane yield.

Food waste is highly biodegradable due to its high content of carbohydrates, proteins, and lipids, making it an excellent substrate for biogas production. However, its rapid degradation can lead to acid accumulation and process instability. In contrast, lignocellulosic biomass such as agricultural residues requires pre-treatment to enhance biodegradability (Zhang et al., 2014).

2.2 Co-Digestion Advantages

Mono-digestion of a single substrate often leads to imbalances in nutrient composition, resulting in reduced microbial activity and process instability. Co-digestion, which involves the simultaneous digestion of multiple substrates, has been widely recognized as an effective strategy to overcome these limitations.

By combining carbon-rich and nitrogen-rich substrates, co-digestion improves the carbon-to-nitrogen (C/N) ratio and enhances microbial diversity. Studies have demonstrated that co-digestion significantly increases methane yield and process stability compared to mono-digestion (Mata-Alvarez et al., 2011; Ward et al., 2008). Additionally, co-digestion reduces the risk of inhibitory effects and improves overall system efficiency (Li et al., 2011; Zhang et al., 2011).

III. ANAEROBIC DIGESTION PROCESS

Anaerobic digestion consists of four main stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. During hydrolysis, complex organic compounds are broken down into simpler molecules. Acidogenesis converts these molecules into volatile fatty acids, while acetogenesis produces acetic acid, hydrogen, and carbon dioxide. Finally, methanogenesis converts these intermediates into methane and carbon dioxide.

The efficiency of the AD process is influenced by several operational parameters, including temperature, pH, retention time, and organic loading rate. Mesophilic conditions (30–35°C) are commonly used due to their stability, while thermophilic conditions offer higher reaction rates but require greater energy input.

However, the process is sensitive to inhibitory substances such as ammonia, heavy metals, and sulfides, which can negatively affect microbial activity and methane production (Chen et al., 2008). Proper control of these parameters is essential for maintaining system stability and maximizing biogas yield.

IV. CO-DIGESTION VS MONO-DIGESTION

A comparative analysis of mono-digestion and co-digestion systems reveals that co-digestion offers significant advantages in terms of methane yield, process stability, and nutrient balance. Mono-digestion systems often suffer from issues such as nutrient deficiency, accumulation of inhibitory compounds, and unstable microbial activity.

In contrast, co-digestion systems provide a balanced nutrient composition, which enhances microbial growth and improves digestion efficiency. Recent studies have shown that co-digestion can increase methane yield by improving substrate synergy and reducing process inhibition (Berhe et al., 2023; Paranjpe et al., 2023).

Furthermore, co-digestion enhances system resilience by stabilizing pH levels and preventing acid accumulation, thereby reducing the risk of process failure.

V. PROCESS OPTIMIZATION TECHNIQUES

Optimization of anaerobic digestion processes is essential for improving system efficiency and maximizing biogas production. Various strategies have been developed to enhance process performance, including pre-treatment techniques, addition of trace elements, and advanced reactor configurations.

Pre-treatment methods such as mechanical, thermal, and chemical treatments improve the biodegradability of substrates by breaking down complex structures. The addition of trace elements has also been shown to enhance microbial activity and methane production.

Advanced technologies such as artificial intelligence (AI) and machine learning are increasingly being used to optimize AD processes. These technologies enable real-time monitoring, predictive modelling, and improved process control, leading to enhanced system performance (Al-Zuhairi, 2026).

VI. DIGESTATE UTILIZATION AND SOIL IMPACT

Digestate, the residual product of anaerobic digestion, is a valuable organic fertilizer containing essential nutrients such as nitrogen, phosphorus, and potassium. It also contains beneficial microorganisms that improve soil health and plant growth.

Application of digestate has been shown to improve soil structure, increase water retention, and enhance nutrient availability. Studies have demonstrated that digestate can partially replace chemical fertilizers, thereby reduce environmental pollution and promote sustainable agriculture (Nkoa, 2014; Alburquerque et al., 2012).

However, concerns related to nutrient leaching, heavy metal accumulation, and pathogen presence need to be addressed to ensure safe application (Tambone et al., 2010).

VII. CIRCULAR ECONOMY AND SUSTAINABILITY

Integrated biogas systems play a crucial role in promoting circular economy principles by converting waste into valuable resources. These systems enable efficient waste management, energy recovery, and nutrient recycling, thereby reducing environmental impact.

Biogas production contributes to the reduction of greenhouse gas emissions by capturing methane that would otherwise be released into the atmosphere. Additionally, the use of digestate as fertilizer reduces dependence on chemical fertilizers, further enhancing sustainability (Angelidaki et al., 2011; Holm-Nielsen et al., 2009).

VIII. EMERGING TECHNOLOGIES

Recent advancements in technology have significantly improved the efficiency and scalability of anaerobic digestion systems. IoT-based monitoring systems enable real-time tracking of process parameters such as temperature, pH, and gas production.

Artificial intelligence and computational models are increasingly being used for process optimization and predictive analysis, enabling improved system performance and reliability (Al-Zuhairi, 2026).

IX. ECONOMIC ANALYSIS

The economic feasibility of biogas systems depends on factors such as feedstock availability, plant size, and operational efficiency. Biogas systems provide economic benefits through reduced fuel costs, energy savings, and income generation from organic fertilizers.

However, high initial investment costs and maintenance requirements remain significant challenges for large-scale implementation (Achinas et al., 2017).

X. CONCLUSION

Integrated biogas production and organic fertilizer generation systems provide a sustainable and efficient solution for managing biodegradable waste. Co-digestion enhances methane yield and system stability, while digestate utilization supports sustainable agriculture. Emerging technologies such as AI offer promising opportunities for optimizing system performance. Future research should focus on addressing existing challenges and improving scalability for large-scale implementation.

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