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REVIEW ARTICLE

Review: Biogas Production Utilizing Indigenous Bacteria from Liquid Tofu By-product and Organic Botanical Food Waste in Small and Medium Enterprises (SMEs)

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ABSTRACT

The increasing production of liquid tofu by-products and botanical food waste by SMEs highlights the need for sustainable waste management while providing significant potential for biogas generation. Liquid tofu by-products and organic botanical food waste have potential for biogas production, with a focus on the role of indigenous microbial in the process. This review aims to evaluate and synthesize current research regarding the utilization of liquid tofu by-products and botanical food waste for biogas generation, with particular emphasis on the role of indigenous microorganisms and the applicability of such systems in SMEs. This review was conducted by gathering information from articles retrieved from scientific databases using keywords such as biogas production, liquid tofu by-product, indigenous bacteria, etc. From the data collection process, the gathered information will be analyzed and synthesized to conclude. The reviewed studies indicate that co-digestion of liquid tofu by-products and botanical food waste can improve substrate balance, optimize the carbon-to-nitrogen ratio, and enhance methane production compared with single-substrate digestion. The findings suggest that small-scale biogas systems utilizing these waste streams could contribute to waste reduction, renewable energy production, and sustainable waste management in SMEs. In conclusion, combining liquid tofu by-products with botanical food waste can generate more biogas than the digestion of using vegetable waste alone.

KEYWORDS: *Biogas, Botanical food waste, Food waste, Indigenous bacteria, Tofu by-product*

Introduction

The continuous increase in human population is a major factor in the increase in food production. Current dietary trends such as vegan and vegetarianism are increasing food production, especially botanical food products. Botanical food is quite popular and sought after for health, economic, and lifestyle reasons (Alcorta et al., 2021). Indonesia is a country with a tropical climate that is very supportive of the growth of vegetables and fruits. Due to the increase in population and public demand for botanical products, there are many small and medium industries producing botanical products, especially vegetables and fruits. In addition to fiber, vitamins, and minerals, botanical products, especially soybeans, have a high protein content. In the daily diet, protein is needed for human growth and development (Rizzo and Baroni, 2018). One of the processed soybean products that is popular throughout the world, especially Asia, is tofu (Zinia et al., 2022). The tofu processing industry as one of the soybean-based food producers has also experienced an increase in production. However, with the existence of SMEs, various botanical organic wastes are also produced, such as vegetable and fruit scraps, as well as solid and liquid tofu waste.

Tofu waste is divided into two types, namely solid waste and liquid waste (Faisal et al., 2016). Solid tofu waste is the result of the filtering and clumping process and can be utilized as animal feed or other processed foods such as crackers. Liquid tofu waste is very much generated and is the result of the process of washing, boiling, pressing and molding tofu. Unsimilar to solid tofu waste, liquid tofu waste is unable to be processed as food nor animal feed and usually is thrown away. Liquid tofu waste when disposed of directly into the environment can produce a disturbing odor and cause environmental pollution because it contains BOD5, COD, and TSS (Kurniawan et al., 2024). These wastes have great energy potential, but are often not optimally utilized. In the context of SMEs, effective and efficient waste management is crucial, given the limited resources and technology that these companies have. Tofu liquid waste, which is rich in organic compounds, has great potential to be converted into alternative energy sources, particularly biogas, through anaerobic fermentation processes (Nurwujita et al., 2021). The use of indigenous (local) bacteria in the fermentation process of organic waste is an innovative and environmentally friendly solution. These bacteria are naturally present in the local environment, so they have the ability to adapt at local conditions and do not require high costs for acclimatization or processing (Sobhi et al., 2023). By utilizing tofu liquid waste and botanical food waste for biogas production, SMEs can reduce environmental impacts while creating a sustainable alternative energy source.

This study aims to explore the potential of using tofu liquid waste and botanical organic waste from SMEs as biogas feedstock with the help of indigenous bacteria. This innovation will not only help reduce waste and address pollution issues, but also support green economic growth among SMEs through renewable energy production.

Material and Method

Literature Research Strategy

This review was conducted through a comprehensive literature review of relevant scientific studies. Relevant scientific publications were collected from Google Scholar, ScienceDirect, Scopus, SpringerLink, and other peer-reviewed databases. The literature search was performed using combinations of the following keywords such as, biogas production, tofu wastewater, liquid tofu by-product, food waste, botanical waste, anaerobic digestion, methanogenic bacteria, indigenous microorganisms, and SMEs.

Inclusion and Exclusion Criteria

The literature included in this review met the following criteria: (1) discussed biogas production through anaerobic digestion; (2) evaluated liquid tofu by-product, food waste, vegetable waste, fruit waste, or related organic substrates; (3) investigated microbial activity, methanogenic bacteria, indigenous microorganisms, or digestion performance; (4) were published in peer-reviewed journals between 2016 and 2026; (5) were available in full text and written in English or Indonesian.

The literature excluded in this review met the following criteria: (1) did not focus on biogas production; (2) lacked sufficient methodological information; (3) were conference abstracts without full papers; (4) focused exclusively on waste treatment without energy recovery.

Data Collection and Analysis

A total of 26 references published between 2016 and 2024 were selected and reviewed. The selected literature consisted of original research articles, review articles, and conference proceedings relevant to biogas production from tofu-processing by-products and botanical food waste. Information regarding substrate characteristics, microbial involvement, operating conditions, biogas production performance, digester design, and applicability in SMEs was extracted, compared, and qualitatively synthesized to identify current developments, challenges, and future research opportunities.

Results and Discussion

Among the reviewed substrates (Tabel 1.), tofu wastewater and tofu residue exhibited considerable potential for biogas production due to their high organic content. However, studies consistently reported that co-digestion with vegetable or food waste improved the C/N ratio and enhanced methane production compared with mono-digestion systems. Therefore, the combination of liquid tofu by-products and botanical food waste appears to be a promising strategy for sustainable biogas production in SMEs.

Table 1. Comparison of organic waste substrates for biogas production.

Substrate	Main Characteristics	Biogas/ Methane Potential	Advantages	Limitations
Tofu wastewater	High organic load, rich in proteins and dissolved nutrients, relatively low C/N ratio	High biogas potential under anaerobic digestion	Abundant by-products from tofu-processing SMEs; biodegradable	Excessive nitrogen may cause ammonia inhibition and process instability
Vegetable waste	Rich in carbohydrates, cellulose, and hemicellulose; moderate-to-high C/N ratio	Moderate methane production	Easily available and suitable as carbon sources	Rapid acidification may occur during digestion
Fruit waste	High moisture and fermentable sugar content	Moderate to high methane production	Rapid biodegradation and microbial utilization	Low pH may inhibit methanogenic activity
Tofu residue (okara)	High organic matter and residual protein content	High methane production, particularly after pretreatment	Valuable substrate for anaerobic digestion and co-digestion systems	Pretreatment may be required to maximize methane yield
Tofu residue + food waste + garden waste (co-digestion)	Improved nutrient balance and optimized C/N ratio	High methane yield than mono-digestion systems	Enhanced microbial activity and process stability	Requires monitoring of substrate mixing ratios
Mixed food waste	Variable composition containing carbohydrates, proteins, and lipids	Variable depending on feedstock composition and operating conditions	Large availability and high resource recovery potential	Inconsistent substrate quality and digestion performance

In addition to substrate characteristics, the design and operational performance of the digester are critical factors affecting biogas yield. Ridhuan (2016) utilized a fixed dome-type digester (Figure 1) for biogas production from liquid tofu by-product. The tool is made of plastic which makes it resistant to corrosion where the future is needed because in the process of making biogas will always be in contact with tofu waste liquid which is alkaline. The digester has a capacity of 90 liters.

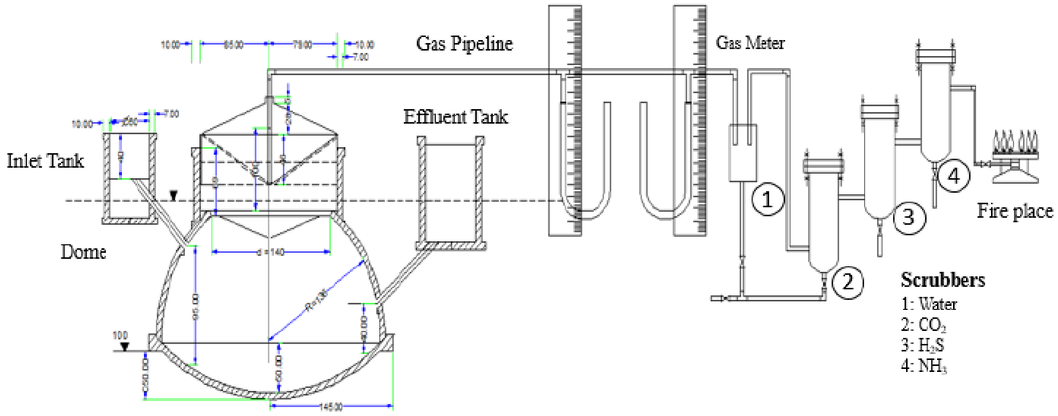

Figure 1. Common Design of Fixed Dome Digester (Uche et al., 2020).

Based on the research conducted by Ridhuan (2016), it showed that the longer the fermentation process, the amount of biogas produced would be higher. To produce the best quality biogas, the temperature used in the reactor is 27-23 °C and the ideal pH to use is 6.8 to 8. After fermentation for 8 days, the volume of gas obtained is 82.04 liters at a pressure of 0.91 kg/cm^2 (Table 1). The effective time for fermentation is 8-25 days because on the 26th day there was a decrease in the production of biogas (Figure 2).

Table 2. The effect of temperature and pressure in biogas production (Ridhuan, 2016).

Number	Room Temp. (°C)	Reactor Temp. (°C)	Reactor Pressure (kg/cm²)	Biogas Volume (liter)
1	27	27	0.00	-
2	28	28	0.06	1.85
3	28	28	0.06	1.74
4	29	29	0.12	4.36
5	29	29	0.19	11.52
6	30	29	0.26	20.37
7	30	30	0.31	32.78
8	30	30	0.48	44.10
9	31	30	0.57	58.27
10	31	31	0.69	82.04

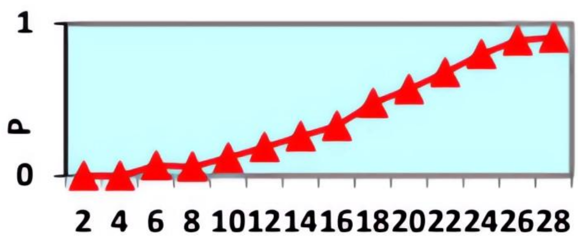

Figure 2. Comparison between biogas volume and temperature against number of days (Ridhuan, 2016).

To adapt the device to the tofu wastewater generation capacity and the storage capacity of SMEs, a biogas generator or digester made of a gallon covered by a lid and connected by a pipe made of a mixture of plastic and rubber to a measuring cup filled with water is used (Figure 3). This digester implements the liquid displacement method (Song et al., 2023). The volume of biogas produced is measured by the amount of water displaced or the height of water rising in the measuring cup when biogas is generated and flowed into the water. As biogas is generated from the digester, gas flows through a pipe into the measuring cup containing water, causing bubbles to form and displacing the water upwards. This method is commonly used to measure gas volume in simple systems like this because it is easy to implement and accurate enough for small-scale gas measurement. If 90 liters of wastewater can produce 82.04 liters of biogas, it can be estimated that 2.2 liters of tofu wastewater will produce as much as 2 liters of biogas of which it is possible to produce and can be produced by SMEs.

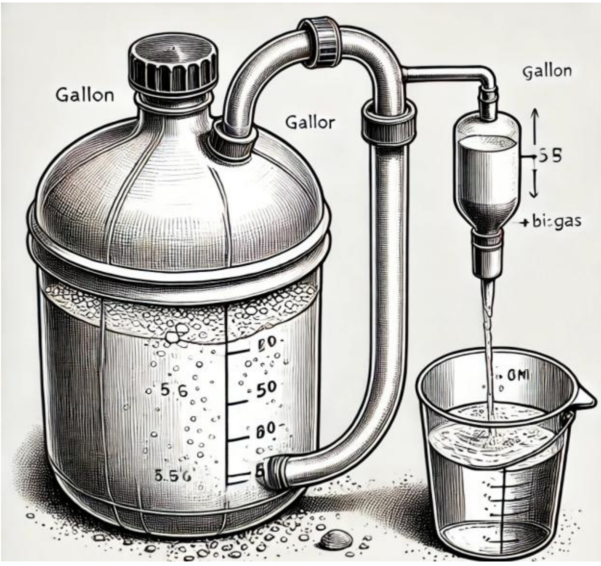

Figure 2. Illustration of modified gallon based digester suiting SMEs usage.

Biogas is a product of anaerobic degradation of organic matter by anaerobic bacteria (Arifan et al., 2021). The main components of biogas are methane (CH_4) which constitutes 54-80% of the volume of biogas and carbon dioxide (CO_2) which constitutes 20-45% of the volume of biogas. There are other minor components such as H_2, N_2, and H_2S. Basically, biogas technology utilizes the process of digestion by methanogenic bacteria that work in an unoxygenated environment and produce products, namely methane gas, which reaches 60% of the total gas of biogas reactor results (Ridhuan, 2016). The biogas produced can be used as an alternative to LPG gas to meet household needs, and as a large-scale electrical energy generator (Jameel *et al.*, 2024). This innovation not only could reduce environmental pollution by utilizing wastes as biogas, it also is an alternative to the use of LPG (Liquefied Petroleum Gas) which is a fossil-based fuel that is also harmful to the environment (Waris et al., 2021; Permatasari et al., 2021). This research contributes to the food industry and the environmental field by providing innovations, solutions, and methods in processing food waste into biogas as a form of overcoming the impact of food waste on the environment.

The results of the mixture of botanical waste together with methanogenic bacteria, water, and 100 ml of molasses with a dose that has been adjusted to the methodology are able to produce organic carbon, and nitrogen. However, it also resulted in a decrease in Phosphorus and an increase in Potassium. This shows that there is activity of microorganisms that decompose organic materials. The addition of Effective

Microorganism (EM4) as much as 350 ml shows the most optimal results with the presence of microbial activity that decomposes organic matter. The use of Effective Microorganism (EM4) in the right amount in a sufficient fermentation period, with a mixture of botanical waste grammation that is not too much able to improve and affect the quality of the final product in the form of biogas (Adi et al., 2023). The ability of microbes to decompose organic matter produced from organic food waste is basic in the biogas production process. However, there is still a need for external control so as to obtain optimal conditions for maximum biogas production (Wang et al., 2022). The addition of 350 ml of methanogen bacteria and 100 ml of molasses aims to obtain biogas with optimal quality, and increase efficiency in efforts to sustain waste treatment. Basically, the mixture of organic food waste itself is capable of producing Effective Microorganism (EM4), but requires a special synthesis and fermentation process in the production process (Nasution & Rizka, 2022). Microbial decomposition plays a fundamental role in biogas production, but there are some external control factors such as pH and temperature that remain crucial to achieving optimal biogas yields (Purboyo & Fahruddin, 2024).

The results of the digester process from tofu liquid waste with botanical waste are effectively able to produce biogas. Preparation of liquid tofu by-product and botanical waste which is then combined through the digester stage in pH, temperature, and anaerobic conditions is a combination of organic waste that produces biogas. Combining liquid tofu by-products with botanical waste produces biogas with an ideal C/N ratio of 20:1 - 30:1. In general, liquid tofu by-products has a relatively low C/N ratio, where the nitrogen ratio is higher (Song *et al.*, 2021). While botanical waste has a high C/N ratio, with a higher carbon ratio (Adi et al., 2023). The combination of these two organic wastes can produce biogas with a balanced C/N ratio. Balanced C/N ratio is able to create optimal conditions for microbes to multiply in the biogas production process. The combination of these two organic wastes is also able to increase methane production which is the main component in biogas production (Choe et al., 2021).

One of the challenges that may be faced in producing biogas with a combination of liquid tofu by-products and botanical waste is the strict control of external conditions in terms of pH and temperature. In addition, variability in the quality of the waste composition can affect the fermentation process. Solutions that can be provided are consistency in providing supervision during the biogas production process, and the addition of Effective Microorganism (EM4) which optimizes the fermentation process and digester. However, the combination of these two organic wastes can be an effective strategy in producing biogas on an SMEs scale and a solution in minimizing environmental impacts.

Conclusion

In conclusion, tofu liquid waste and botanical wastes have the potential to produce biogas in large enough quantities to be utilized in daily cooking activities. However, there is a need for optimal control in the digester and fermentation process. The addition of Effective Microorganism (EM4) is able to optimize and overcome problems in the variable quality of organic waste used in the biogas production process. In the end, overall, biogas production by utilizing tofu car waste with botanical waste produces an effective waste treatment process into biogas and can be applied on an SMEs scale. Liquid tofu by-products can generate more biogas when combined with vegetable waste than when using vegetables alone. This research contributes to both the food industry and the environmental field by providing innovations, solutions, and methods for processing food waste into biogas as a form of overcoming the impact of food waste on the environment.

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Declaration of Generative AI

During the preparation of this work, the authors used literature search engines (Google Scholar, asta.ai, Google Gemini) to identify relevant scientific articles and writing assistance tools (Grammarly) to improve grammar and language clarity. Generative AI tools were used solely to assist in language refinement and idea organization. The authors critically reviewed, edited, and verified all content and takes full responsibility for the accuracy and integrity of the final manuscript.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Karyn Gracia Hartono was responsible for conceptualization, literature review, manuscript writing, and editing. Karla Katina Salim Nohkarsan contributed to manuscript writing, methodology design, and critical editing of the manuscript. Caroline Noel Amaris Purnomo also contributed to manuscript writing, and methodology design, formatting, and provided additional insight into the literature.

Ethical Statement

This study was conducted as a literature review and did not involve human participants or animal subjects. Therefore, ethical approval was not required. All information presented in this paper was gathered and collected from previously published works, and no primary data was collected. The authors affirm that this study complies with established ethical principles regarding the appropriate use of data and responsible publication practices.

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