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Production of Biogas As An Alternative Green Energy with Organic Wastes As The Main Raw Materials

(*PRODUKSI BIOGAS SEBAGAI ENERGY HIJAU ALTERNATIF MENGGUNAKAN LIMBAH ORGANIK SEBAGAI BAHAN BAKU UTAMA)*

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ABSTRACT

This research focused on the utilization of four different organic wastes, namely snake fruit, orange, cabbage, and tomato wastes, for the production of biogas. The main objectives were twofold: (1) to investigate the characteristics and biodegradability of these wastes, and (2) to evaluate their potential for anaerobic methane production. The experiment was conducted using 250 L bioreactors, with the four wastes serving as the primary raw materials. A starter culture of cattle dung was added, and the mixture was incubated for eight weeks. Regular sampling and analysis were carried out to assess water content, biodegradability, specific rate of volatile material reduction, and gas yield. The results showed that the water content of the four waste systems remained relatively consistent throughout the experiment. Biodegradability analysis revealed that all of the wastes were biodegradable, with varying levels of degradation ranging from 23.10 ± 2.89% to 59.84 ± 4.17%. Snake fruit waste exhibited the highest resistance to degradation, while tomato waste was the most easily degradable. Kinetic analysis indicated specific rates of volatile material reduction (μ) of 0.006 ± 0.0006 per day for the most resistant waste and 0.0170 ± 0.0021 per day for the least resistant waste. The incorporation of these four waste types in the biogas production process had a positive effect on gas formation. Therefore, these organic wastes hold promise as valuable resources for biogas production, addressing both the issue of waste accumulation and the energy crisis in an environmentally beneficial manner.

Keywords: biogas; composting; methane; organic waste

ABSTRAK

Objek penelitian ini adalah pemanfaatan empat limbah organik yang berbeda, yaitu limbah buah salak, jeruk, kol, dan tomat, untuk produksi biogas. Tujuan utamanya ada dua: (1) untuk menyelidiki karakteristik dan biodegradabilitas limbah tersebut, dan (2) untuk mengevaluasi potensinya untuk produksi metana secara anaerobik. Percobaan dilakukan dengan menggunakan bioreaktor 250 L selama delaapan minggu, dengan empat limbah sebagai bahan baku utama dan kultur *starter* dari kotoran ternak. Pengambilan sampel dan analisis rutin dilakukan untuk menentukan kadar air, biodegradabilitas, laju spesifik pengurangan bahan volatil dan hasil gas. Hasil penelitian menunjukkan bahwa kandungan air dari keempat sistem limbah tersebut relatif konsisten selama percobaan. Analisis biodegradabilitas mengungkapkan bahwa semua limbah dapat terurai dengan tingkat degradasi yang bervariasi mulai dari 23,10 ± 2,89% hingga 59,84 ± 4,17%. Limbah buah salak adalah yang paling sulit terurai, sedangkan limbah tomat adalah yang paling mudah terurai. Analisis kinetik menunjukkan tingkat pengurangan spesifik bahan volatil (µ) adalah sebesar 0,006 ± 0,0006 per hari untuk limbah yang paling sulit terurai dan 0,0170 ± 0,0021 per hari untuk limbah yang paling mudah terurai. Penggabungan keempat jenis limbah ini dalam proses produksi biogas berdampak positif pada pembentukan gas. Oleh karena itu, limbah organik ini menjanjikan sebagai bahan baku untuk produksi biogas, sekaligus mengatasi masalah akumulasi limbah dan krisis energi dengan cara yang bermanfaat bagi lingkungan.

Kata-kata kunci: biogas; pengomposan; metana; limbah organik

INTRODUCTION

The generation of substantial amounts of organic waste from agricultural practices, cultural events, market activities and tourism-related operations has become a prevalent issue. Particularly in Bali, there has been a significant increase in the volume of organic waste over time. In the Nusa Penida district, a small region within Bali, it has been estimated that a daily quantity of 15.9 tonnes of wet organic waste is produced, corresponding to 6.36 tonnes of dry-weight organics, assuming a 60% water content (Widyarsana and Agustina, 2020). As these organic wastes are biodegradable, they hold potential as raw materials for composting. The composting process yields biogas, which can serve as a valuable alternative energy source.

Traditionally, developing countries have relied on incineration and landfilling methods for managing organic waste (Pariatamby *et al*., 2020). However, these methods have proven to create new environmental challenges, such as air and water pollution. In Bali, where land prices are considerably high, landfilling is no longer a feasible waste management option. Conversely, composting has emerged as an alternative approach, particularly in developing countries, due to its minimal environmental risks and the production of compost as a beneficial by-product (De Boni *et al*., 2022; Sayara *et al*., 2020). Composting also facilitates the generation of biogas, primarily methane, during the decomposition of organic waste (Sayara and Sánchez, 2021; Yasmin *et al*., 2022). Biogas, as a cost-effective alternative energy source, holds great potential, especially for rural or remote areas (Pilloni and Abu-,Hamed, 2021; Situmeang *et al*., 2022).

With the ongoing global energy crisis, there has been a growing interest in research focused on biogas production. In Indonesia, the government has implemented measures to reduce the use of subsidized fossil fuels, including kerosene, which has been replaced or limited by liquid petroleum gas (LPG). The availability of subsidized kerosene has ceased entirely within the past decade. Consequently, it is imperative to develop novel methods for alternative energy production. Biogas production has emerged as a reliable and attractive solution, utilizing anaerobic digestion of organic matter, such as manure, food waste, agricultural waste or sewage sludge, with active participation of microorganisms, including bacteria and archaea, within closed biogas fermenters (González *et al*., 2022; Leitão *et al*., 2022).

According to Kabaivanova *et al*. (2022), the process of anaerobic biogas production in fermenters involves four sequential stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis. During the hydrolysis stage, complex compounds like cellulose are broken down into simpler compounds, such as sugars, amino acids and fatty acids, through the action of microbial enzymes (Lin *et al*., 2021). The availability of these simpler compounds initiates the second stage known as acidogenesis, where acidogenic bacteria further degrade them into various organic acids, including propionic acid, acetic acid and butyric acid (Kabaivanova *et al*., 2022; Lin *et al.,* 2021). In the third stage, acetogenesis, acetogenic bacteria convert the products of acidogenesis into acetate, hydrogen and carbon dioxide (Singh *et al*., 2021). Finally, in the methanogenesis stage, methanogenic archaea facilitate the conversion of acetate, hydrogen and carbon dioxide into methane (González *et al.,* 2022; Leitão *et al*., 2022). The biogas generated during the four stages described previously can be utilized as an energy source, while the solid residue remaining in the digester can be utilized as organic fertilizer (Siciliano *et al*., 2019). Recycling organic waste through biogas and compost production has emerged as a cost-effective, dependable and sustainable approach to organic waste management, contributing to reduced greenhouse gas emissions (Wassenaar *et al*., 2016).

Based on the aforementioned background, a research project was undertaken with the aim of investigating the feasibility of utilizing organic wastes as a raw material for biogas production. The primary objectives of this study were twofold: (1) to examine the characteristics and biodegradability of organic wastes generated in Bali, and (2) to assess the potential of these wastes in methane production through anaerobic processes. By focusing on these objectives, the study aimed to contribute to the understanding of the organic waste management and renewable energy production in the context of sustainable resource utilization.

RESEARCH METHODS

Preparation of Materials for Fermentation

Four distinct types of organic wastes, namely snake fruit *(Salacca zalacca)*, cabbage *(Brassica oleracea var. capitata)*, orange (*Citrus* sp.) and tomato *(Solanum lycopersicum)* wastes, obtained from the local market, were specifically chosen for this research study. These waste materials were selected based on a preliminary evaluation, where they exhibited superior performance in terms of biogas production rates compared to other waste types. Prior to the inoculation stage, the organic wastes underwent a chopping process to increase the surface area-to-volume ratio. This was done to promote enhanced microbial adhesion and enzymatic degradation of the waste materials, thereby facilitating more efficient and rapid degradation.

Starter Preparation

The active starter for composting and biogas production was prepared by diluting cattle dung with water at a specific ratio of 5:6 (w/w), where five parts of cattle dung were mixed with six parts of water. This particular ratio was determined as the optimal proportion based on the findings reported by Rastogi *et al.* (2019). Consequently, this established ratio was consistently employed for all treatments throughout the duration of the research project.

Preparation of Composting Process

The separate bioreactors, each with a volume of 1.5 L, were filled with 160 g of chopped wastes. These bioreactors were then inoculated with active inoculums at a rate of 1100 mL, resulting in a working volume of 1260 mL, and incubated at ambient temperature for two months. Samples from all bioreactors were collected periodically and analyzed for water content, volatile substrate content and dry weight.

Water Content Analysis

The gravimetric method was used in the analysis of water content. Samples that amounted to 10 g were placed in porcelain dishes of known mass, evaporated at 120^{o}C for 24 hours, placed in a desiccation chamber and weighed. This procedure was repeated three times until constant weight was obtained. The water content of the sample was calculated according to the following formula: $\%KA= [(M_{to}-M_{t1}) \text{ x } (M_{to})^{-1}] \text{ x } 100\%$. Where: %KA= Percentage of sample water content; M_{to}= Initial mass of the sample; M_{t1}= Mass of the sample after its water was evaporated.

Determination of Volatile Materials of Samples

The percentage of volatile materials in samples was determined by using the gravimetric method. The dry mass of samples previously obtained was heated at 600^{o}C for six hours in a furnace. The mass lost during this heating was the volatile materials of the sample. The rest was the mineral (carbon) content of the sample. The percentage of the volatile material in the sample was calculated according to the following formula: $\%VM= [(M_{to}-M_{t1}) \text{ x } (Mto)^{-1}] \text{ x } 100\%$. Where: %VM = Percentage of volatile material of the sample; Mto= Initial dry mass; M_{t1}= Mass of the sample after heated.

Calculation of Kinetic Parameter

The calculation of kinetic parameters was conducted according to the procedure specified by Lemus *et al.* (2004) and Solanki *et al.* (2018). The coefficient of the biodegradable rate was calculated based on the first-order biodegradation equation by calculating the volatile solid mass at day 0 and on day 7. The formula is as follows: $dC \text{ x } dt^{-1} = -\mu C$. Where: C= The biomass of volatile component of the waste in the bioreactor (g); t = Time (day); μ= Coefficient of the specific rate of organic material reduction in the bioreactors (per day) $\int_{C1}^{C2} \frac{dC}{C} = -\mu \int_{t1}^{t2} dt$ followed by integration as follows:

Calculation of this equation produces: ln C2-ln C1 = -μ(t2-t1. This equation can be written in another way, by assuming that t2–t1 as Δt, as follows: ln C2 x $C1^{-1}$ = μ.Δt,
where Δt is a half-life time (interval time needed to reduce the waste biomass into a half) When the Δt elapses, the biomass at t2 is half of the biomass at t1, or C2 = 0.5 C1. Substitution of C2 with 0.5 C2 will result in the following equation: ln 0.5 C1 x $C1^{-1}$ = -μ.Δt or ln 0.5 = -Δt.

The value of Δt was estimated from the curve of % volatile component of the waste vs time (Figure 1), by taking the value of C2 = 0.5 C1, along the curve. Based on this calculation, the value of μ was calculated using the following formula:

$$\ln 0.5 \times \Delta t^{-1} = -\mu\text{, or } -\mu = -0.693 \times \Delta t^{-1}\text{, then } \mu = 0.693 \times \Delta t^{-1}$$

Calculation of Biodegradability Level

The biodegradability level (β) is the amount of solid mass potentially biodegradable during the process of fermentation or the amount of initial solid mass at day 0 (t_0) convertible into gas and biomass at the end of the process (t_1). The unit of this parameter is % (w/w) (Lemus *et al*. 2004). The value of β is calculated according to the following formula: $\beta= [(M_{to}-M_{t1}) \times (M_{to})^{-1}] \times 100\%$

Where: β= Biodegradability of the samples; M_{to}= Mass of sample at the initial process; M_{t1}= Mass of the sample at the end of the process.

Gas Analysis

Gas produced during this process was periodically collected and analyzed at the Integrated Laboratory of Basic Sciences, Faculty of Mathematics and Sciences, Udayana University using a GC-MS instrumentation (GC-MS QP-2010 Ultra Shimadzu equipped with GC-MS post-run analysis and GC-MS real-time analysis software). The conditions of the GC-MS instrument were adjusted as specified in Solanki *et al*. (2018) with small modifications. The injection port temperature was maintained at 270°C and the column temperature was set from 50°C to 220°C and then increased to 270°C (10°C/minute), ending with a 10-minute constant temperature of 270°C. Helium UHP gas (ALPHAGAZ He Helium) was used as the carrier.

RESULTS AND DISCUSSION

The waste characteristics data, including water content and volatile solid substrate content, for the four samples are presented in Table 1 and Figure 1, respectively. These data served as the foundation for calculating the kinetic parameter (μ) and biodegradability level (β) of each sample.

As shown in Table 1, the water content of the samples slightly varied during the experiment. This tended to decrease slightly as the experiment progressed. During the incubation time, the metabolic activity of microbes in the bioreactors to degrade organic content produced heat (indicated by an increase in temperature reading, data not shown) that caused some water in the bioreactors to evaporate. During the experiment, no additional water was added, because the water content of the bioreactors was still in the range of optimum condition for biogas production, which falls between 85% and 95% of the total solids content of the feedstock (Kalandarov and Abdullayev, 2022). In biogas production, this range is optimum to trigger microbial activity in the organic waste biodegradation to produce methane. This range is often referred to as the mesophilic range (Alemayehu 2015; Angelidaki and Sanders, 2004).

According to Veluchamy and Kalamdhad (2017), the production rate of biogas will decrease if the feedstock contains too low a level of water. It is further stated by these authors that a decrease in moisture content from 70% to 50% significantly reduced

Table 1. The water content of the four wastes used in the experiment

No.	Waste types	Water content (% w/w)*		
		t_o	t_1	t_2
1	Snake fruits	90.81+1.78	85.40±1.35	87.70±3.38
2	Cabbage	95.24±19.44	91.16+1.78	85.50±1.71
3	Orange	97.62±1.43	90.81+1.78	84.17±0.90
4	Tomato	90.16±5.06	89.67+3.79	82.00±3.66

Note: *Values ± deviation standard in Table 1 are averages of 6 (six) replicates, (t stands for time).

the biogas production rate and overall methane yield. This indicates that the microbial activity to produce biogas in such limited water content will significantly decrease (Kouzi *et al*., 2020). A similar tendency will also occur when the feedstock becomes too diluted, and this will lead to a decrease in the efficiency and performance of the bioreactor (Meegoda *et al*., 2018). Therefore, maintaining the water content of the feedstock in the bioreactor is an important factor to affect the rate of biogas production.

As the microbe's metabolic activity was in progress, they used the volatile materials as the source of the substrate. This is indicated by the reduction of the volatile substrate content in all bioreactors as a function of time (Figure 1). In this analysis, the snake fruit wastes appeared to be the most recalcitrant components to be attacked by microbial enzymes when compared to the other three waste types. Although it was not analyzed in this research, some researchers reported that snake fruits contain a high level of tannins, approximately 34.58 mg GAE/g (Suica-Bunghez *et al*., 2016). Tannins also known as tannic acid is a common name for metabolic products in plants. Some tannins are relatively complex phenolic compounds. According to Adamczyk *et al*. (2017) tannins are toxic to microbes due to their ability to precipitate proteins. This was also supported by the findings of Nam and Hwang (2021) who reported that tannins inhibited the growth of Gram-positive and Gram-positive bacteria.

The mechanisms underlying the inhibitory effects of tannins on microbial growth are not yet fully elucidated. In addition to their ability to form complexes with proteins and biomolecules within microbial cells, resulting in protein precipitation, as reported by Hagerman (1987), several researchers have proposed that tannins can interfere with vital metabolic processes and disrupt cellular functions (Redondo *et al*., 2014). Furthermore, tannins have been observed to induce damage to the plasma membrane of microbial cells (Olchowik-Grabarek *et al*., 2022). Additionally, recent comprehensive reviews have highlighted the capacity of tannins to chelate essential ions necessary for microbial growth (Farha *et al*., 2020). However, further investigations are required to fully comprehend the intricate mechanisms through which tannins exert their inhibitory effects on microorganisms.

Based on the analysis of the biodegradability level (β) of the wastes and the specific rate of volatile material reduction (μ), snake fruit also showed consistent results as the most recalcitrant waste to be used as a substrate by microbes involved in the biogas production (Table 2).

The value of the biodegradability level (β) of a substrate indicates the recalcitrant level of this substrate to be attacked by microbial enzymes. The value of β is inversely related to the degree of recalcitrant of a substance. The data in Table 2 clearly shows that the tomato waste was degraded at the fastest rate (the respective values of biodegradability level and specific rate of volatile material reduction are 59.84 ± 4.17% and 0.0170 ± 0.0021 day^{-1}) when compared to others. This data indicates that these four types of organic wastes can be decomposed in

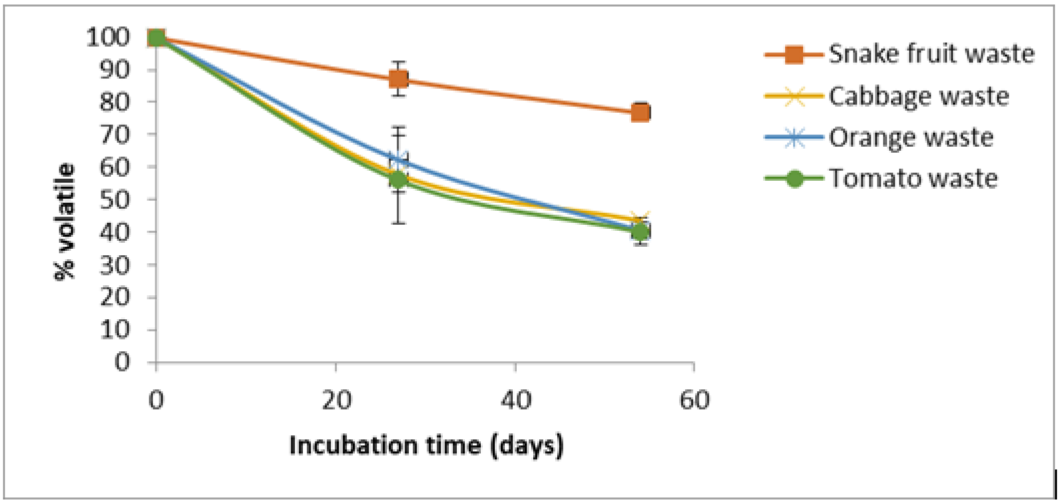

Figure 1. The degradation rate of the volatile components of the four waste types used in biogas production. Values in Figure 1 ± standard deviations are averages of five replicates.

Table 2. Biodegradability level (β) and specific rate of volatile material reduction (μ) of the four types of wastes.

No.	Waste types	Biodegradability level (%)	Specific rate volatile material reduction (day^{-1})
1.	Snake fruit waste	23.10 ± 2.89^a	0.006 ± 0.0006^a
2.	Cabbage waste	56.36 ± 5.19^b	0.016 ± 0.0016^b
3.	Orange waste	59.57 ± 2.50^b	0.0162 ± 0.0009^b
4.	Tomato waste	59.84 ± 4.17^b	0.0170 ± 0.0021^b

Note: Values in Table 2 ± standard deviations are averages of five replicates.
*Values in the same column followed by the same letter are not statistically significant at $p<0.05$, according to lst test following the analysis of variance (ANOVA).

an integrated process of biogas production (an effort to produce alternative energy to substitute the use of subsidized fossil fuels in Indonesia). Integration of such organic waste in biogas production will produce a significant amount of compost at the end of the process which can later be used to improve the topsoil texture or to reduce the use of inorganic fertilizers in the farming practices (Beck-Broichsitter *et al*., 2018). The use of compost as an organic fertilizer in farming practices also provides some level of protection for the crops from pathogen attack as the presence of antagonists in the compost (Lutz *et al*., 2020; Pane *et al*., 2022; Martin and Ramsubhag, 2015). Therefore, biogas production in combination with the decomposition of organic wastes will provide double advantages to the environment, because this integrated process will produce biogas (an alternative energy source) and simultaneously reduce the pollution level due to the organic waste accumulation.

In this experiment, the biogas production in bioreactors began on day seven after inoculation with active starters at various levels of volumes (Figure 2). During the 54 days of observation with periodic sample collections, bioreactors with orange fruit waste feedstock produced the highest level of gas when compared to others. Similar volumes of gas were also observed in bioreactors with tomato or cabbage wastes over the 54 days of incubation time (statistically not significant at $p<0.05$, Figure 2). Although the snake fruit waste showed the lowest level of biodegradability (β) in the previous observation (Table 2), it could also be used as a source of nutrients by indigenous microbes and stimulated the production of a significant volume of gas (Figure 2). Decomposition of organic matters in a closed system (Batch culture system), the four

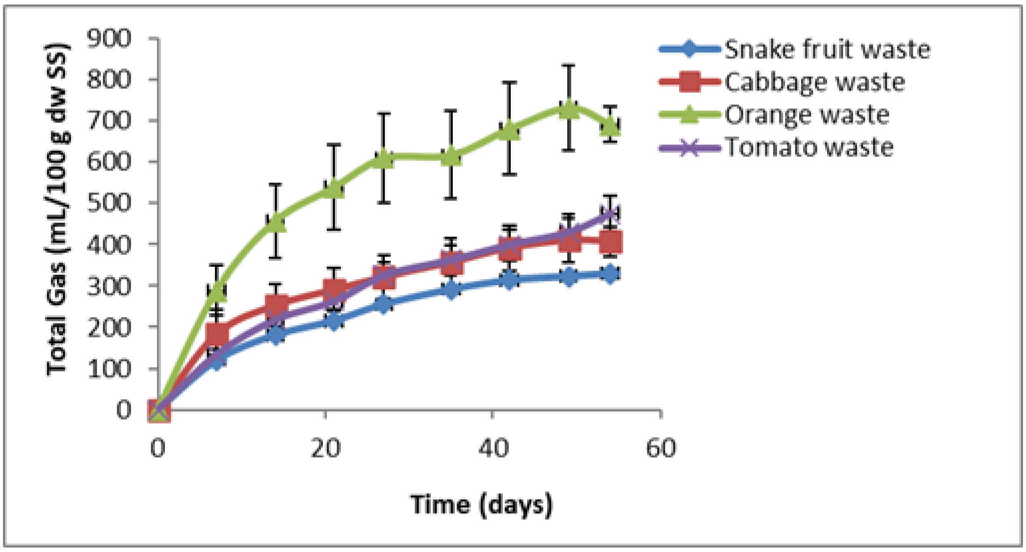

Figure 2. Total methane (mL/100 g dw solid substrate) produced by the bioreactors was periodically sampled at 7 days intervals. Values ± deviation standard in the figure are averages of triplicates.

stages (previously described in the introduction section) of biogas production as comprehensively reviewed by Tshemese *et al*. (2023) takes place. Initially, the raw waste materials with high levels of cellulose were degraded into simpler structures, such as oligo or monosaccharides (Lin *et al*., 2021). In the subsequent stage, acidic compounds were produced in the acidogenesis stage. Some compounds commonly produced during this stage include propionic acid, acetic acid and butyric acid by acidogenic bacteria (Wainaina *et al*., 2019). Acetogenesis and methanogenesis stages will then follow where the acidic compounds produced in the second stage were converted into acetate and gases, such as hydrogen and CO_2 (Singh *et al*., 2021). With the presence of methanogenic archaea in the bioreactors, the conversion of these three products into methane occurs (Wainaina *et al*., 2019). By comprehensively understanding the microbial community dynamics and functional profiling during the different stages of anaerobic digestion described above, biogas production and sustainable waste management practices can then be optimized.

CONCLUSION

It can be concluded from this experiment that the four types of organic wastes were biodegradable with various degrees of biodegradability (varied from 23.10 ± 2.89 to 59.84 ± 4.17%). Incorporation of such waste materials in biogas production, therefore, had great potential as it gave positive effects on the formation of biogas. This can then be used as an alternative method to solve two problems (accumulation of organic wastes and energy crisis) simultaneously.

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REFERENCES

Adamczyk B, Simon J, Kitunen V, Adamczyk S, Smolander A. 2017. Tannins and Their Complex Interaction with Different Organic Nitrogen Compounds and Enzymes: Old Paradigms versus Recent Advances. *Chemistry Open* 6: 610–614. https://doi.org/10.1002/open.201700113

Alemayehu YA. 2015. Enhancement and Optimization Mechanisms of Biogas Production for Rural Household Energy in Developing Countries: A review. *International Journal of Renewable Energy Development*- 4: 189–196. https://doi.org/10.14710/ijred.4.3.189-196

Angelidaki I, Sanders W. 2004. Assessment of The Anaerobic Biodegradability of Macropollutants. *Rev Environ Sci Biotechnol* 3: 117–129. https://doi.org/10.1007/s11157-004-2502-3

Beck-Broichsitter S, Fleige H, Horn R. 2018. Compost Quality and Its Function as A Soil Conditioner of Recultivation Layers – A Critical Review. *International Agrophysics* 32: 11–18. https://doi.org/10.1515/intag-2016-0093

De Boni A, Melucci FM, Acciani C, Roma R. 2022. Community Composting: A Multidisciplinary Evaluation of An Inclusive, Participative, and Eco-friendly Approach to Biowaste Management. *Cleaner Environmental Systems* 6: 100092. https://doi.org/10.1016/j.cesys.2022.100092

Farha AK, Yang Q-Q, Kim G, Li H-B, Zhu F, Liu H-Y, Gan R-Y, Corke H. 2020. Tannins as An Alternative to Antibiotics. *Food Bioscience* 38: 100751. https://doi.org/10.1016/j.fbio.2020.100751

González R, Peña DC, Gómez X. 2022. Anaerobic Co-Digestion of Wastes: Reviewing Current Status and Approaches for Enhancing Biogas Production. *Applied Sciences* 12: 8884. https://doi.org/10.3390/app12178884

Hagerman AE. 1987. Radial Diffusion Method for Determining Tannin in Plant Extracts. *J Chem Ecol* 13: 437–449. https://doi.org/10.1007/BF01880091

Kabaivanova L, Hubenov V, Dimitrova L, Simeonov I, Wang H, Petrova P. 2022. Archaeal and Bacterial Content in a Two-Stage Anaerobic System for Efficient Energy Production from Agricultural Wastes. *Molecules* 27: 1512. https://doi.org/10.3390/molecules27051512

Kalandarov PI, Abdullayev KK. 2022. Features of The Technology of Anaerobic Processing of Biotails using Humidity Control Devices. *IOP Conf Ser: Earth Environ Sci* 1043: 012011. https://doi.org/10.1088/1755-1315/1043/1/012011

Kouzi AI, Puranen M, Kontro MH. 2020. Evaluation of The Factors Limiting Biogas Production in Full-Scale Processes and Increasing The Biogas Production Efficiency. *Environ Sci Pollut Res* 27: 28155–28168. https://doi.org/10.1007/s11356-020-09035-1

Leitão A, Moni D, Maria C. 2022. Anaerobic Co-Digestion of Food Waste with Sewage Sludge from Wastewater Treatment Plant of Sequele, Luanda-Angola. *Environmental Challenges* 9: 100635. https://doi.org/10.1016/j.envc.2022.100635

Lemus GR, Lau AK, Branion RMR, Lo KV. 2004. Bench-Scale Study of The Biodegradation of Grease Trap Sludge with Yard Trimmings or Synthetic Food Waste via Composting. *Journal of Environmental Engineering and Science* 3: 485–494. https://doi.org/10.1139/s04-020

Lin C-Y, Chai WS, Lay C-H, Chen C-C, Lee C-Y, Show PL. 2021. Optimization of Hydrolysis-Acidogenesis Phase of Swine Manure for Biogas Production Using Two-Stage Anaerobic Fermentation. *Processes* 9: 1324. https://doi.org/10.3390/pr9081324

Loan LTT, Takahashi Y, Nomura H, Yabe M. 2019. Modeling Home Composting Behavior Toward Sustainable Municipal Organic Waste Management at The Source in Developing Countries. *Resources, Conservation and Recycling* 140: 65–71. https://doi.org/10.1016/j.resconrec.2018.08.016

Lutz S, Thuerig B, Oberhaensli T, Mayerhofer J, Fuchs JG, Widmer F, Freimoser FM, Ahrens CH. 2020. Harnessing the Microbiomes of Suppressive Composts for Plant Protection: From Metagenomes to Beneficial Microorganisms and Reliable Diagnostics. *Front Microbiol* 11: 1810. https://doi.org/10.3389/fmicb.2020.01810

Meegoda J, Li B, Patel K, Wang L. 2018. A Review of the Processes, Parameters, and Optimization of Anaerobic Digestion. *International Journal of Environmental Research and Public Health*, 15: 2224. https://doi.org/10.3390/ijerph15102224

Nam YJ, Hwang YS. 2021. Antibacterial and Antioxidant Effect of Ethanol Extracts of *Terminalia chebula* on *Streptococcus mutans*. *Clin Exp Dent Res* 7: 987–994. https://doi.org/10.1002/cre2.467

Olchowik-Grabarek E, Sękowski S, Kwiatek A, Płaczkiewicz J, Abdulladjanova N, Shlyonsky V, Swiecicka I, Zamaraeva M. 2022. The Structural Changes in The Membranes of *Staphylococcus aureus* Caused by Hydrolysable Tannins Witness Their Antibacterial Activity. *Membranes* 12: 1124. https://doi.org/10.3390/membranes12111124

Pane C, Spaccini R, Caputo M, De Falco E, Zaccardelli M. 2022. Multi-Parameter Characterization of Disease-Suppressive Bio-composts from Aromatic Plant Residues Evaluated for Garden Cress (*Lepidium sativum* L.) *Cultivation Horticulturae* 8: 632. https://doi.org/10.3390/horticulturae8070632

Pariatamby A, Bhatti MS, Hamid FS. 2020. Waste Management in Developing Countries: An Overview, in: Pariatamby A, Shahul-Hamid F, Bhatti MS. (Eds.). *Advances in Environmental Engineering and Green Technologies*. IGI Global, Pp. 494–519. https://doi.org/10.4018/978-1-7998-0198-6.ch020

Pilloni M, Abu-Hamed T. 2021. Small-Size Biogas Technology Applications for Rural Areas in the Context of Developing Countries, in: Sikora, A. (Ed.). *Anaerobic Digestion in Built Environments.* IntechOpen. https://doi.org/10.5772/intechopen.96857

Rastogi M, Nandal M, Nain L. 2019. Additive Effect of Cow Dung Slurry and Cellulolytic Bacterial Inoculation on Humic Fractions during Composting of Municipal Solid Waste. *Int J Recycl Org Waste Agricult* 8: 325–332. https://doi.org/10.1007/s40093-019-0277-3

Redondo LM, Chacana PA, Dominguez JE, Miyakawa MEF. 2014. Perspectives in The Use of Tannins as Alternative to Antimicrobial Growth Promoter Factors in Poultry. *Front Microbiol* 5. https://doi.org/10.3389/fmicb.2014.00118

Sayara T, Basheer-Salimia R, Hawamde F, Sánchez A. 2020. Recycling of Organic

Wastes through Composting: Process Performance and Compost Application in Agriculture. *Agronomy* 10: 1838. https://doi.org/10.3390/agronomy10111838

Sayara T, Sánchez A. 2021. Gaseous Emissions from the Composting Process: Controlling Parameters and Strategies of Mitigation. *Processes* 9: 1844. https://doi.org/10.3390/pr9101844

Siciliano A, Limonti C, Curcio GM, Calabrò V. 2019. Biogas Generation through Anaerobic Digestion of Compost Leachate in Semi-Continuous Completely Stirred Tank Reactors. *Processes* 7: 635. https://doi.org/10.3390/pr7090635

Singh A, Moestedt J, Berg A., Schnürer A. 2021. Microbiological Surveillance of Biogas Plants: Targeting Acetogenic Community. *Front Microbiol* 12: 700256. https://doi.org/10.3389/fmicb.2021.700256

Situmeang R, Mazancová J, Roubík H. 2022. Technological, Economic, Social and Environmental Barriers to Adoption of Small-Scale Biogas Plants: Case of Indonesia. *Energies* 15: 5105. https://doi.org/10.3390/en15145105

Solanki S, Singh A, Sood H. 2018. GC Analysis of Invitro Developed Shoots of Stevia Rebaudiana Through Rapid Tissue Culture. *Social Science Research Network Journal*. https://doi.org/10.2139/ssrn.3298672

St. Martin CCG, Ramsubhag A. 2015. Potential of Compost for Suppressing Plant Diseases., in: Sangeetha Ganesan SG, Kurucheve Vadivel KV, Jayaraj Jayaraman JJ (Eds.). *Sustainable Crop Disease Management Using Natural Products*. CABI, UK. Pp. 345–388. https://doi.org/10.1079/9781780643236.0345

Suica-Bunghez IR, Teodorescu S, Dulama ID, Voinea OC, Imionescu S, Ion RM. 2016. Antioxidant Activity and Phytochemical Compounds of Snake Fruit *(Salacca zalacca)*. *IOP Conf Ser: Mater Sci Eng* 133: 012051. https://doi.org/10.1088/1757-899X/133/1/012051

Tshemese Z, Deenadayalu N, Linganiso LZ, Chetty M. 2023. An Overview of Biogas Production from Anaerobic Digestion and the Possibility of Using Sugarcane Wastewater and Municipal Solid Waste in a South African Context. *Applied System Innovation* 6: 13. https://doi.org/10.3390/asi6010013

Veluchamy C, Kalamdhad AS. 2017. A Mass Diffusion Model on The Effect of Moisture Content for Solid-State Anaerobic Digestion. *Journal of Cleaner Production* 162: 371–379. https://doi.org/10.1016/j.jclepro.2017.06.099

Wainaina S, Lukitawesa, Awasthi MK, Taherzadeh MJ. 2019. Bioengineering of Anaerobic Digestion for Volatile Fatty Acids, Hydrogen or Methane Production: A Critical Review. *Bioengineered* 10: 437–458. https://doi.org/10.1080/21655979.2019.1673937

Wassenaar T, Dumoulin F, Farinet J-L, Paillat J-M, Thuriès L, Tillard E, Vayssières J., Vigne M. 2016. Agricultural Organic Waste Recycling to Reduce Greenhouse Gas Emissions, in: Torquebiau E. (Ed.). *Climate Change and Agriculture Worldwide*. Dordrecht. Springer Netherlands. Pp.167–181. https://doi.org/10.1007/978-94-017-7462-8_13

Widyarsana IMW, Agustina E. 2020. Waste Management Study In The Archipelago Tourism Area (Case Study: Nusa Penida District, Bali Province, Indonesia). *E3S Web Conf* 148: 05002. https://doi.org/10.1051/e3sconf/202014805002

Yasmin N, Jamuda M, Panda AK, Samal K, Nayak JK. 2022. Emission of Greenhouse Gases (GHGs) during Composting and Vermicomposting: Measurement, Mitigation, and Perspectives. *Energy Nexus* 7: 100092. https://doi.org/10.1016/j.nexus.2022.100092