ENHANCEMENT OF STABILITY AND BIOGAS PRODUCTION FROM ANAEROBIC DIGESTION OF FOOD WASTE AND ITS MIXTURE WITH RAW SLUDGE

Zulekhan Din Muhammad, Noor Yahida Yahya*, Azrina Abd Aziz

Faculty of Civil Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Malaysia

Received: 5 March 2024, Accepted: 8 April 2024, Published: 30 May 2024, Publisher: UTP Press, Creative Commons: CC BY 4.0

ABSTRACT

Anaerobic digestion (AD) is a widely used technology applied globally for managing food waste (FW). However, biogas production has an issue with low yield due to the inhibition of microbial activities, consequently resulting in AD instability. In this study, sludge is used as an additive during AD of (FW) to investigate the enhancement of AD's biogas production and stability. This work aims to critically analyse the sludge's ability to produce biogas with and without sludge in AD of (FW) at 26°C. AD batch tests were performed at the laboratory scale operating three sets of digestors (500 ml glass bottle with 350 ml operating volume). The first set of digestors operated without sludge for (7, 14, 21 and 28 days), whereas the second set of digestors had different amounts of sludge dosage (1 g, 2 g, 3 g, and 4 g) for 14 days. The last set operated with a fixed sludge dosage of 4 g for (7, 14, 21 and 28 days). It was observed that biogas production increased when sludge was added to the AD. Furthermore, the characterisation analysis of sludge identified the -OH, C-H, C-C and C-O functions by Fourier-transform infrared (FTIR) spectroscopy and the elemental composition of Si, Al, and O observed by scanning electron microscope equipped with energy-dispersive x-ray spectroscopy (SEM-EDX) which enhanced the biogas production and the stability of AD.

Keywords: *anaerobic digestion, biogas production, food waste, sludge*

INTRODUCTION

Climate change and global warming are significant threats to the future of humankind [1]. To protect the environment for future generations, society is now emphasising sustainable and green approaches to overcome these issues. Therefore, recent attention has shifted to environmentally friendly energy solutions [2]. Renewable energy sources that meet energy requirements have the potential to provide energy with zero emissions of greenhouse gases. Developing sustainable renewable energy systems will make it feasible to solve the most significant issues [3].

As an alternative to fossil fuels, biogas from biomass produced through anaerobic digestion (AD) offers renewable and sustainable energy [4]. Additionally, biogas technology is an eco-friendly method of managing organic waste and sludge, particularly in rural areas of developing countries [5]. It is crucial in many developing countries to provide the essential energy needed for electricity and heat [6]. Significant environmental advantages include reduced greenhouse gas emissions and recycling organic waste from households and industries [7]. Commonly, the feedstock for biogas includes livestock manure, cafeteria food waste, and sludge [8]. Sludge refers to the residual material generated as a byproduct of the wastewater treatment process, and sludge production is anticipated to rise globally [9]. Sludge is disposed of primarily through incineration, landfilling and agricultural usage. However, it is essential to note that each technique poses a significant environmental and human health risk [10].

Anaerobic digestion is generally considered an economical and environmentally friendly technology for treating various organic wastes, including sludge [11]. It is rich in organic matter, which can boost the overall organic content of the feedstock, making it more suitable for anaerobic digestion and potentially resulting in increased biogas production [12]. AD is a biological procedure carried out without oxygen that results in the stability and breakdown of organic matter [13]. A typical conversion process for organic waste to biogas consists of four steps [14]. The initial step is hydrolysis, in which exoenzymes produced by hydrolytic microorganisms break down the organic complex compounds and produce simple sugars, fatty acids, and amino acids [15]. The second step, acidogenesis produces alcohols, short-chain organic acids, and organic-nitrogen compounds. The third step of the process is acetogenesis, which involves using homo acetogenic bacteria to generate acetic acid from the reduction of hydrogen and carbon dioxide. The last step is the methanation process, which involves the conversion of carbon dioxide to methane by hydrogenotrophic methanogens [16]-[17].

Anaerobic co-digestion (AcoD) has seen extensive application in enhancing biogas output from digesters [18]. AcoD involves the simultaneous AD of multiple substrates, presenting a promising approach to address the limitations of single-substrate digestion and enhance the sustainability of AD through heightened biogas production. AcoD offers notable advantages, including enhanced process stability, mitigation of inhibitory substances, improved

*Corresponding author.
E-mail address : nooryahida@umpsa.edu.my

nutrient balance, and decreased emission of greenhouse gases into the atmosphere [19].

Food waste is usually generated in kitchens, restaurants, agricultural fields, food processing plants, industry markets, etc. [6]. The average household in Malaysia consumes between 0.5 and 0.8 kg of food waste daily, making for around 63.1% of the daily solid waste components. Food waste primarily comprises proteins, lipids, carbohydrates, and fibers. It also has a high water content (>80%) and is readily biodegradable [20]-[21]. Recently, food waste has been explored as a potential feedstock for biogas production by anaerobic digestion [22]. However, the high organic matter content and high biodegradability result in the existence of inhibitory chemicals such as volatile fatty acids (VFAs), which would result in low methane yield and instability of the AD system. Consequently, this decreases biogas production and leads to AD system failure [23].

A recent study has shown that adding sludge as an additive to anaerobic digestion and optimising the operating parameters of AD could improve anaerobic digestion performance and biogas yield by alleviating the accumulation of VFAs and increasing the activity of hydrogenotrophic methanogens [24]. The specific impact of sludge on VFAs depends on the characteristics of microorganisms of sludge that may compete with the indigenous microbial community in the anaerobic digester. This competition can affect the balance of microbial populations and potentially limit VFA production [25]. Through an overview of the additive of sludge effects on anaerobic digestion performance and biogas yield, to provide a promising solution for achieving sustainable development, environment, and bioenergy.

METHODOLOGY

Characterisation of Sludge as an Additive

The characteristics of raw sludge were performed by using different measuring instruments. FTIR determine the different functional groups and bonds on the sludge's surface using infrared spectroscopy. In addition, when other properties such as surface area and porosity are increased, there is a chance of reduction in sludge functional groups [26].

The surface morphology of the additive will be characterised using scanning electron microscopy (SEM) and electron dispersive X-ray analysis (EDX). Scanning electron microscopy and energy dispersive X-ray (EDX) analyses was conducted to study the morphological structure and elemental distribution of sludge.

Fourier Transform Infrared Spectroscope (FTIR)

Fourier Transform Infrared Spectroscope (FTIR, Nicolet iS5, USA) was used to investigate the functional group of raw sludge. The spectra were collected between 4000 and 500 cm^{-1}. Data was collected at room temperature by using the Potassium Bromide (KBr) pellet technique.

Scanning Electron Microscope (SEM)

The surface of raw sludge was analysed using a scanning electron microscope at a 2 mm X magnification (SEM, HITACHI TM3030Plus, Japan). The elements in the raw sludge were determined using energy-dispersive X-ray analysis (EDX) in a scanning electron microscope (SEM).

Preparation of Food Waste

Raw food waste will be taken from restaurants near the campus of Universiti Malaysia Pahang, Gambang. The main constituents of the food waste will be rice, vegetables, and fruit residuals. The food waste will be prepared by grinding and mixing the waste into smaller-sized particles (2 mm) and then further filtered and dewatered. Contaminants such as bones, plastic waste, and disposable tableware will be discriminated against from food waste. Thereafter, food waste will be collected in plastic zip lock bags and stored in the refrigerator at 4°C until use to avoid biological degradation. The sludge is collected from a local industrial effluent treatment system (IETS) and used as an additive in the anaerobic digestion of food waste.

Set Up of Anaerobic Digestion of Food Waste

AD of food waste batch tests was performed at the laboratory scale operating three sets of digestors (500 ml glass bottle with 350 ml operating volume). The bottle was seeded with 250 ml of food waste and 100 ml of distilled water. The first set of digestors operated without sludge and contained four digesters at 26°C; initially, each digestor was fed with food waste, and the retention time for digesters was (7, 14, 21 and 28 days). The other set of reactors operated with sludge at 26°C, the four digesters operated sequentially and each digestor operated with different sludge dosages of (1, 2, 3 and 4 grams) to a constant food waste amount for 14 days. The last set of digestors operated with a fixed amount of

Figure 1 Set up of anaerobic digestion of food waste with and without sludge

Table 1 Operating conditions of anaerobic digestion without sludge

Digestors	Food waste (FW)	Retention time (T)	Operation condition
D1	250 ml	7 days	Mesophilic
D2	250 ml	14 days	Mesophilic
D3	250 ml	21 days	Mesophilic
D4	250 ml	28 days	Mesophilic

Table 2 Operating conditions of anaerobic digestion with different sludge dosage

Digestors	Food waste (FW)	Retention time (T)	Sludge dosage (D)	Operation condition
D1	250 ml	14 days	1 g	Mesophilic
D2	250 ml	14 days	2 g	Mesophilic
D3	250 ml	14 days	3 g	Mesophilic
D4	250 ml	14 days	4 g	Mesophilic

Table 3 Operating conditions of anaerobic digestion with fixed sludge

Digestors	Food waste (FW)	Retention time (T)	Sludge dosage (D)	Operation condition
D1	250 ml	7 days	4 g	Mesophilic
D2	250 ml	14 days	4 g	Mesophilic
D3	250 ml	21 days	4 g	Mesophilic
D4	250 ml	28 days	4 g	Mesophilic

sludge 4 g, and contained four digestors at 26°C, and the retention time for digestors was (7, 14, 21, and 28 days).

Measurement of Percentage of Biogas using Water Displacement Method

The performance of AD was observed by the total amount of biogas produced in the anaerobic digestion (AD) of food waste without sludge and food waste with sludge. The total biogas production was measured using the water displacement method. The volume of water displaced in the container equals the volume of the gas. One end of the silicone tube was connected to the digester, and the other end was connected to the inverted measuring cylinder, which contains water [27]. The amount of gas calculated equals the volume of water displaced. The biogas is allowed to collect in the inverted measuring cylinder by displacing water.

The rate of wet and dry biogas production can be calculated as follows:

$$\frac{\text{Rate of wet}}{\text{Dry biogas production}} = \frac{\text{Volume of wet biogas captured}}{\text{Time taken}} \quad (1)$$

Gases collected over water are saturated with water vapour. Therefore, $P_{total} = P_{biogas} + P_{water}$. The partial pressure of water in the mixture, P_{water} is the equilibrium vapour pressure of water at the specified temperature. The combined Boyle's and Charles's Laws were used to calculate the volume of dry biogas using the equation below:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \quad (2)$$

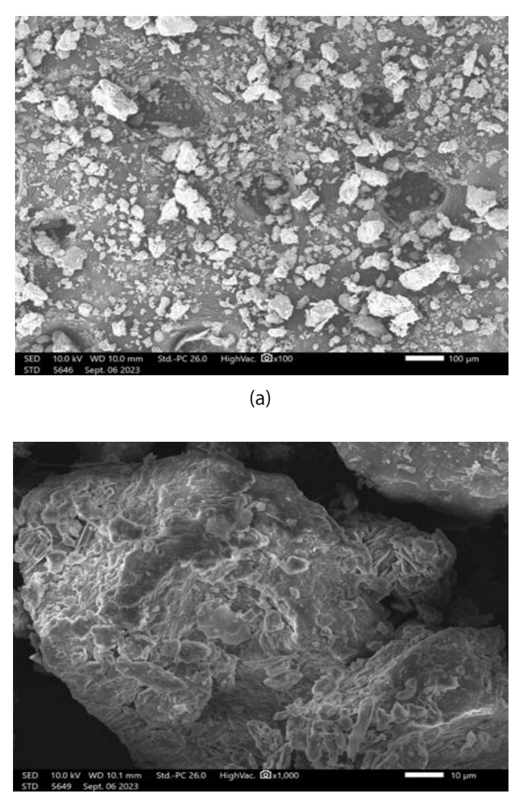
Lastly, the yield of biogas production was calculated using the following equation:

$$\text{Yield of biogas} = \frac{\text{Volume of wet biogas (ml)}}{\text{Mass of raw materials (g)}} \quad (3)$$

RESULTS AND DISCUSSION

Surface Morphology Analysis by Scanning Electron Microscopy (SEM-EDX)

SEM analysis was used to evaluate the change in the surface morphology of sludge. The SEM images of raw sludge are shown in Figure 2. Figure 2a and Figure 2b show the raw sludge at two magnification scales, 100 and 1000. The morphology of raw sludge shows a higher porosity and rough surface, which make it a favourable environment for microbial activity. Microorganisms involved in anaerobic digestion can colonise the surface and penetrate deep into the porous structure of the raw sludge, where they can metabolise organic matter and produce methane and other fermentation byproducts [26]. The corresponding EDX analysis results are shown in Table 1.9, where the results are presented in mass percentage of the samples. EDX of sludge indicates that C (7.21%), O (49.18%), Si (22.91%), Al (8.84%) and Fe (11.86%). These elements aid in the breakdown of organic matter and facilitate the conversion of food waste into biogas.



(a)

(b)

Figure 2 (a) SEM image of sludge at 100 magnification scale, (b) sludge at 1000 magnification scale

Table 4 EDX analysis of sludge

Sample	Elements	Mass (%)	Atomic (%)
Sludge	C	7.21	11.94
	O	49.18	61.11
	Al	8.84	6.51
	Si	22.91	16.22
	Fe	11.86	4.22

Additionally, they may help improve the nutrient balance of the substrate, promoting microbial activity and enhancing the overall efficiency of the anaerobic digestion process [28].

Functional Group Identification by Fourier Transform Infrared (FTIR)

FTIR analysis was used to investigate the function group on the surface of sludge. The KBR spectra of the sludge are presented in Figure 3. The two main peaks are at 3422 and 1636 cm^{-1}. The first peak is due to the -OH bond, while the second is characteristic of the C–C bond. Typical moieties in the sludge were also identified, such as the S=O stretching vibration that was detected at 1031 cm^{-1}. The detection of functional groups such as hydroxyl, carbon-carbon, and sulfone within raw sludge utilised as an additive in the anaerobic digestion of food waste signifies the intricate nature of the organic material. These functional groups denote diverse organic compounds that microbial metabolism can utilise during anaerobic digestion. The degradation of these compounds contributes to biogas production. This study concluded that the sludge was suitable for anaerobic treatment, as it contained ingredients for the growth of microorganisms [29].

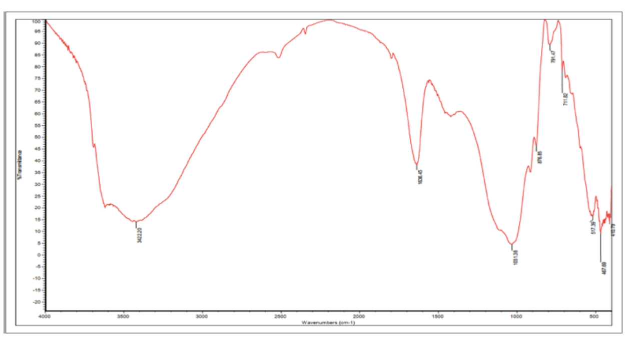


Figure 3 Fourier transform infrared analysis of sludge

Effect of the Amount of Sludge Dosage

The parametric effect of the amount of sludge dosage on AD was analysed in four different amounts of sludge dosage, which are 1 g, 2 g, 3 g, and 4 g. This operation was done under a fixed retention time of 14 days. In each anaerobic digester, 250 ml of food waste mixture was placed in a bottle (digester), then each digester was put at the same place that gets the most sunlight, and all digesters will be observed for 14 days. Figure 4 shows the results of the biogas yield at four different amounts of sludge dosage.

As depicted in Figure 4, the biogas yield increased from 5.71 ml/g to 5.8 ml/g when the dosage of sludge escalated from 1 g to 2 g. The yield of biogas keeps increasing from 6.31 ml/g to 7.88 ml/g as the dosage of sludge increases from 3 g to 4 g. However, biogas yield sharply increases when the sludge dosage increases to 4 g. This was mainly because higher sludge addition could effectively alleviate VFA accumulation, resulting in higher levels of methanogenic activity [30]. Thus, the results show that biogas yield increased as the sludge dosage increased.

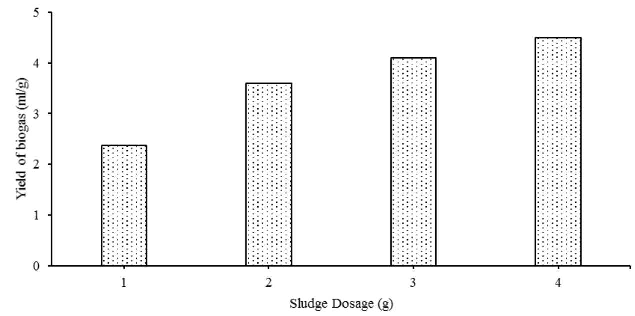


Figure 4 Yield of biogas by using different amounts of sludge dosage in AD

Effect of the Retention Time with Food Waste

Another significant factor affecting the biogas yield and the operating conditions of the AD was the retention time used in the anaerobic digesters to maximise the operating conditions of the AD. To assess this parameter, the biogas yield was observed in four different retention times without sludge, ranging from (7, 14, 21 and 28 days). This operation was done under a fixed feedstock dosage of 250 ml. Figure 5 shows the effect of retention time on biogas yield.

As depicted in Figure 5, biogas yield increased from 2.37 ml/g to 3.6 ml/g when the retention time increased from 7 to 14 days. Then, the yield of biogas again increased from 41 ml/g to 4.5 ml/g when the retention time increased from 21 to 28 days. The findings demonstrate that the highest biogas achieved was at the highest retention time with fixed feedstock of AD.

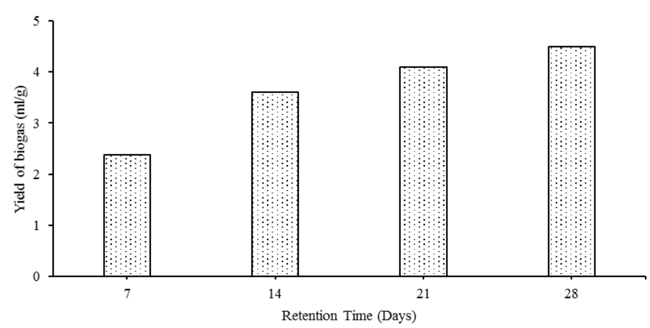


Figure 5 Yield of biogas by using different retention times of AD

Effect of the Retention Time with Sludge

Another important consideration influencing biogas production was the retention time employed within the digesters to optimise the operational parameters of the AD. Evaluating this factor, biogas production was monitored across four different retention times (7, 14, 21 and 28 days) without sludge. This operation was done under a fixed feedstock dosage of 250 ml and fixed sludge dosage of 4 g. Figure 6 shows the effect of the retention time on the yield of biogas.

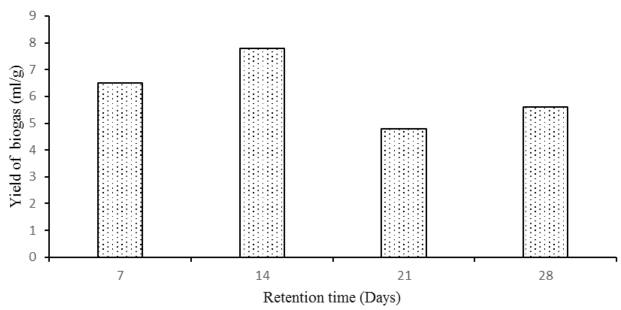


Figure 6 Yield of biogas by using different retention times of AD with sludge

CONCLUSION

The main objective of this study is to generate biogas through anaerobic digestion (AD) of food waste supplemented with sludge as an additive. This study is carried out to identify the potential of sludge as a future additive for biogas production and to enhance AD efficiency. To achieve the primary goal of this study, the objectives were established, which include the study of characterisation analysis of sludge as an additive in AD of food waste and analysis of the effect of sludge as an additive on the performance of AD by studying the optimum operating conditions of AD such as the effect of sludge dosage and effect of the retention time. The rough surface observed through SEM analysis suggests the presence of diverse microstructures within the sludge, which is a favourable environment for microbial activity. At the same time, the elemental composition identified by EDX, including Si, Al, Fe, C, and O, highlights its potential as a valuable additive for anaerobic digestion. Additionally, the FTIR results reveal functional groups such as -OH, C–C, and S=O. These functional groups represent various organic compounds that microbes can utilise in anaerobic digestion. These findings collectively indicate that incorporating sludge as an additive in the anaerobic digestion of food waste holds promise for enhancing biogas production. The total biogas is highly improved by adding sludge compared to without sludge. Anaerobic digestion of food waste with additives showed higher production of biogas in 14 days as compared to without additives. The yield of biogas obtained from sludge and without sludge AD is 7.8 ml/g and 4.5 ml/g, respectively. Therefore, the sludge helps in the degradation of organic content in FW prior to AD and enhances the biogas production

ACKNOWLEDGEMENT

The authors would like to thank the Faculty of Civil Engineering Technology for providing the experimental facilities and to all technicians at Environmental Engineering Laboratory. This study was supported by the Distinguished Research Grant (RDU230302). The authors express gratitude for the grant.

REFERENCES

[1] Q. Wang, C. Xia, K. Alagumalai, T.T. Nhi Le, Y. Yuan, T. Khademi, M. Berkani, and H Lu, "Biogas generation from biomass as a cleaner alternative towards a circular bioeconomy: Artificial intelligence, challenges, and future insights," *Fuel*, vol. 333, p. 126456, 2023.

[2] S.R. Chia, S. Nomanbhay, M.Y. Ong, A.H. Shamsuddin, K.W. Chew, and P.L. Show, "Renewable diesel as fossil fuel substitution in Malaysia: A review," *Fuel*, vol. 314, p. 123137, 2022.

[3] S. Bouckaert, A.F. Pales, C. McGlade, U. Remme, and B. Wanner, "Net zero by 2050: A roadmap for the global energy sector," IEA, 2021.

[4] A. Kasinath, S. Fudala-Ksiazek, M. Szopinska, H. Bylinski, W. Artichowicz, A. Remiszewska-Skwarek, and A. Luczkiewicz, "Biomass in biogas production: Pretreatment and codigestion," *Renewable and Sustainable Energy Reviews*, vol. 150, p. 111509, 2021.

[5] N. Tiwari, B. Garua, M. Bansal, and J. G. Sharma, "Biorefinery and waste management by co-digestion of sewage sludge with organic wastes," in *Development in Waste Water Treatment Research and Processes*, Elsevier, 2022, pp. 365–386.

[6] L. Wang, X. Ni, Y. Li, J. Li, and S. Cheng, "Framework proposal for estimating tourist food waste and its carbon footprint in China: Sampling from four main tourist destinations," *Resources, Conservation and Recycling*, vol. 197, p. 107107, 2023.

[7] F. Hanum, L.C. Yuan, H. Kamahara, H. Abdul Aziz, Y. Atsuta, T. Yamada, and H. Daimon, "Treatment of sewage sludge using anaerobic digestion in Malaysia: Current state and challenges," *Frontiers in Energy Research*, vol. 7, p. 19, 2019.

[8] R. Dalke, D. Demro, Y. Khalid, H. Wu, and M. Urgun-Demirtas, "Current status of anaerobic digestion of food waste in the United States," *Renewable and Sustainable Energy Reviews*, vol. 151, p. 111554, 2021.

[9] B. Adibimanesh, S. Polesek-Karczewska, F. Bagherzadeh, P. Szczuko, and T. Shafighfard, "Energy consumption optimisation in wastewater treatment plants: machine learning for monitoring incineration of sewage sludge," *Sustainable Energy Technologies and Assessments*, vol. 56, p. 103040, 2023.

[10] M. Domini, A. Abbà, and G. Bertanza, "Analysis of the variation of costs for sewage sludge transport, recovery and disposal in Northern Italy: a recent survey (2015–2021)," *Water Science and Technology*, vol. 85, no. 4, pp. 1167–1175, 2022.

[11] M. Tooraj, H. Hooshyar, P. Kimya, A. Sheida, S. Maryam, M. Dariush, and A. Borhan, "Future of Sludge Managemen", In: E. Jacob-Lopes ., L. Queiroz Zepka, and M. Costa Deprá (eds). *Sludge Management Systems—The Gutter-to-Good Approaches*, IntechOpen; London, UK, 2023.

[12] F. Gao, X. Ma, Y. Tan, B. Zhang, Y. Yang, H. Nie, and Z. Xu, "The Effect of Organic Matter from Sewage Sludge as an Interfacial Layer on the Surface of Nano-Al and Fluoride," *Molecules*, vol. 28, no. 18, p. 6494, 2023.

[13] A. Tawfik, M. Eraky, A.I. Osman, P. Ai, Z. Zhou, F. Meng, and D.W. Rooney, "Bioenergy production from chicken manure: a review," *Environmental Chemistry Letters*, pp. 1–21, 2023.

[14] A. Viancelli, T.M. Schneider, T. Demczuk, A.P.G. Delmoral, B. Petry, M.M. Collato, and W. Michelon, "Unlocking the value of biomass: Exploring microbial strategies for biogas and volatile fatty acids generation," *Bioresource Technology Reports*, p. 101552, 2023.

[15] A. Mohamed Ali, M.Z. Alam, F. Mohamed Abdoul-latif, M.S. Jami, I.G. Bouh,I.A. Bello, and T. Ainane, "Production of Biogas from Food Waste Using the Anaerobic Digestion Process with Biofilm-Based Pretreatment," *Processes*, vol. 11, no. 3, p. 655, 2023.

[16] A. Viancelli, T.M. Schneider, T. Demczuk, A.P.G. Delmoral, B. Petry, M.M. Collato, and W. Michelon, "Unlocking the value of biomass: Exploring microbial strategies for biogas and volatile fatty acids generation," *Bioresource Technology Reports*, vol. 23, p. 101552, Sep. 2023, doi: 10.1016/j.biteb.2023.101552.

[17] E. Torres, L.A. Rodriguez-Ortiz, D. Zalazar, M. Echegaray, R. Rodriguez, H. Zhang, and G. Mazza, "4-E (environmental, economic, energetic and exergetic) analysis of slow pyrolysis of lignocellulosic waste," *Renewable Energy*, vol. 162, pp. 296–307, 2020.

[18] C.K. Saha, R. Nandi, S. Akter, S. Hossain, K.B. Kabir, K. Kirtania, M.T. Islam, L. Guidugli, M.T. Reza, and M.M. Alam, "Technical prospects and challenges of anaerobic co-digestion in Bangladesh: A review," *Renewable and Sustainable Energy Reviews*, vol. 197, p. 114412, Jun. 2024, doi: 10.1016/j.rser.2024.114412.

[19] A. Paranjpe, S. Saxena, and P. Jain, "A Review on Performance Improvement of Anaerobic Digestion Using Co-Digestion of Food Waste and Sewage Sludge," *Journal of Environmental Management*, vol. 338, p. 117733, Jul. 2023, doi: 10.1016/j.jenvman.2023.117733.

[20] A. Nayak and B. Bhushan, "An overview of the recent trends on the waste valorisation techniques for food wastes," *Journal of Environmental Management*, vol. 233, pp. 352–370, 2019.

[21] T. G. Ambaye, E. R. Rene, A.-S. Nizami, C. Dupont, M. Vaccari, and E. D. van Hullebusch, "Beneficial role of biochar addition on the anaerobic digestion of food waste: a systematic and critical review of the operational parameters and mechanisms," *Journal of Environmental Management*, vol. 290, p. 112537, 2021.

[22] Y. Xu, Y. Lu, L. Zheng, Z. Wang, and X. Dai, "20.Perspective on enhancing the anaerobic digestion of waste activated sludge," *Journal of Hazardous Materials*, vol. 389, p. 121847, 2020.

[23] T. G. Ambaye, E. R. Rene, A.-S. Nizami, C. Dupont, M. Vaccari, and E. D. Van Hullebusch, "Beneficial role of biochar addition on the anaerobic digestion of food waste: A systematic and critical review of the operational parameters and mechanisms," *Journal of Environmental Management*, vol. 290, p. 112537, Jul. 2021, doi: 10.1016/j.jenvman.2021.112537.

[24] A. Kumar and S. Samadder, "Performance evaluation of anaerobic digestion technology for energy recovery from organic fraction of municipal solid waste: A review," *Energy*, vol. 197, p. 117253, 2020.

[25] Z. Zhu, K. J. Keesman, U. Yogev, and A. Gross, "24. Onsite anaerobic treatment of tomato plant waste as a renewable source of energy and biofertiliser under desert conditions," *Bioresource Technology Reports*, vol. 20, p. 101274, Dec. 2022, doi: 10.1016/j.biteb.2022.101274.

[26] L. Leng, Q. Xiong, L. Yang, H. Li, Y. Zhou, W. Zhang, S. Jiang, H. Li, and H. Huang, "An overview on engineering the surface area and porosity of biochar (ftir)," *Science of The Total Environment*, vol. 763, p. 144204, Apr. 2021, doi: 10.1016/j.scitotenv.2020.144204.

[27] N. Wid and N. Raudin, "Recovery of biogas from food waste using treated and untreated anaerobic digestion (water displacment method)," in *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 1205, no. 1, Jun. 2023, p. 012004, doi: 10.1088/1755-1315/1205/1/012004.

[28] C. Wang, X. Zhang, W. Wang, J. Sun, Y. Mao, X. Zhao, and Z. Song, "A stepwise microwave synergistic pyrolysis approach to produce sludge-based biochars: Feasibility study simulated by laboratory experiments," *Fuel*, vol. 272, p. 117628, Jul. 2020, doi: 10.1016/j.fuel.2020.117628.

[29] Z. Sun, L. Feng, Y. Li, Y. Han, H. Zhou, and J. Pan, "The role of electrochemical properties of biochar to promote methane production in anaerobic digestion," *Journal of Cleaner Production*, vol. 362, p. 132296, Aug. 2022, doi: 10.1016/j.jclepro.2022.132296.

[30] D. Johnravindar, J. W. C. Wong, D. Chakraborty, G. Bodedla, and G. Kaur, "Food waste and sewage sludge co-digestion amended with different biochars: VFA kinetics, methane yield and digestate quality assessment," *Journal of Environmental Management*, vol. 290, p. 112457, Jul. 2021, doi: 10.1016/j.jenvman.2021.112457.