INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

IJIE

Vol. 17 No. 1 (2025) 260-268
https://publisher.uthm.edu.my/ojs/index.php/ijie

Anaerobic Digestion of Food Waste Enhanced by Rubber Sludge Biochar

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DOI: https://doi.org/10.30880/ijie.2025.17.01.021

Article Info

Received: 15 August 2024
Accepted: 20 January 2025
Available online: 30 April 2025

Keywords

Food waste, anaerobic digestion, methane, renewable energy, biochar, rubber sludge

Abstract

Food waste (FW) is a huge global issue and predominantly occurs in highly urbanized and developed countries. Anaerobic digestion (AD) is recognized as one of the most sustainable, cost-effective and efficient means to cater to the problem. Despite that, AD process often suffers from system over-acidification, high lag time, high carbon dioxide content, low methane yield and prone to system failure. This study characterized the properties and evaluated the effects of rubber sludge-derived biochar addition on anaerobic digestion of food waste (ADFW) as well as explored the optimum conditions of ADFW to have an enhanced biogas production. Rubber sludge-derived biochar was fabricated under pyrolytic temperature of 500°C. ADFW pH range used for this research work were 4-8. Further, investigation focused on the biochar dosage of 5, 10, 15, 20 and 25 g with the duration of 7 to 35 days. The findings of this study indicate maximum biogas generated at pH 6 with 15 g BC/L FW of biochar dosage for 35 days.

1. Introduction

The growing food waste generation is often associated with rising living standards, urbanization, population increase, economic and industrial expansion. Its implications to humans and the environment have gained global attention. Landfilling as the easiest and cheapest option remains as the most common municipal solid waste (MSW) disposal method in Malaysia. Food waste in landfills accounts for nearly 44% of the total MSW, which is believed to be the fastest and largest growing waste type in terms of the volume that is generated [1]. The rapid growing volume of MSW results in many saturated landfills and the current operating landfills are reported to have their capacity nearly surpassed.

Apart from landfills scarcity, food waste has a more significant implication to the economy, society and environment. 95% of food waste disposed of in landfills will anaerobically be decomposed and certainly have the atmosphere impacted by greenhouse gases (GHG) emissions [1]. It is reported that decomposed food waste accounts for 8% of annual GHG emissions across the globe. Malaysia as a developing country is not exempt from experiencing the adverse effects of GHG emissions. Acknowledging the need to ensure environmental integrity, local government engagement in addressing food waste should be scaled up and enhanced food waste management system has always been a prominent concern.

AD is an economically feasible process where complex microbials convert organic compounds into simpler components under oxygen-free conditions [2]. The processes involved in ADFW are illustrated in Fig. 1. Biogas is produced as the product of AD through four processes including hydrolysis, acidogenesis, acetogenesis and methanogenesis in which the processes are driven by different groups of microorganisms [3]. Different groups and categories of bacteria are engaged in each stage.

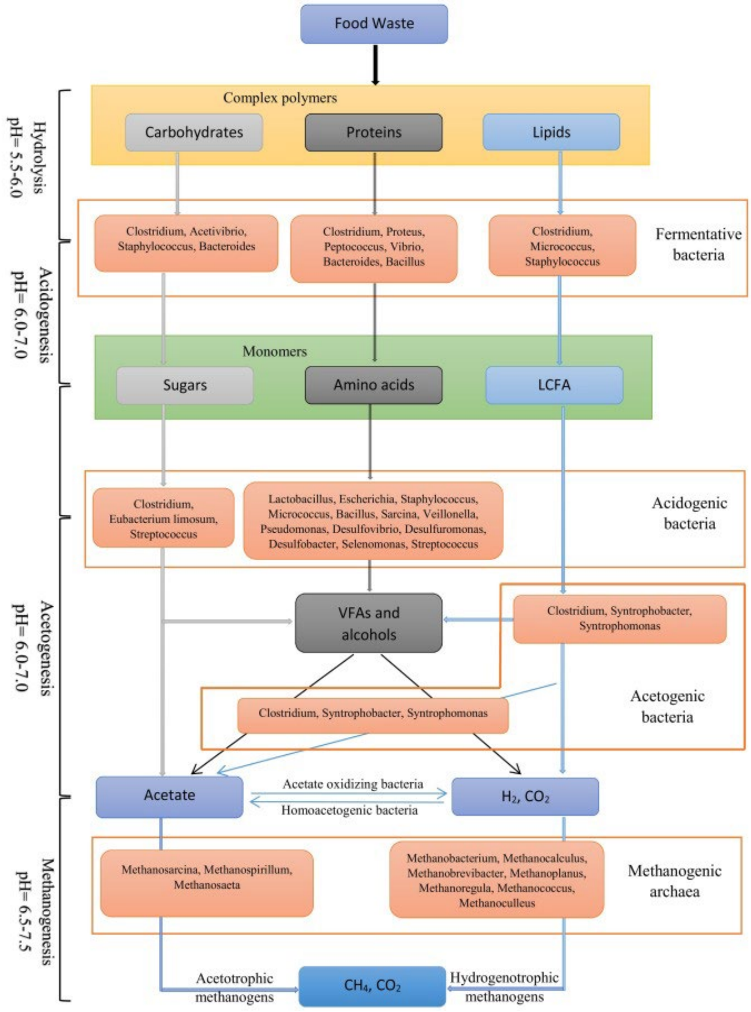

Fig. 1 *Anaerobic digestion process and archaea involved in each stage [4]*

Clostrodium, acetivibrio, bacillus and micrococcus are the bacteria involved in hydrolysis stage where these bacteria will break down complex polymers such as carbohydrates, protein and lipids into simpler soluble monomers, sugars, amino acids and long chain fatty acids. The monomers are then further decomposed into volatile fatty acids (VFAs), propionic acid, butyric acid, formic acid and lactic acid by acidogenic bacteria, streptococcus, lactobacillus and sarcina [4]. Acetogenesis is the stage where acetogenic bacteria transform VFAs into acetic acid and hydrogen. The last stage in AD is methanogenesis where methane and carbon dioxide are produced by anaerobic archaea named methanogens [4]. Methanogens produced methane through two major ways; i. Decomposition of acetic acid into hydrogen (H_2) and methane (CH_4); ii. H_2 as electron donor and CO_2 as electron receiver to produce CH_4 [5].

Indirect interspecies electron transfer (IIET) between microorganisms determines the efficiency of methane production. The stagnation of IIET will hinder VFAs decomposition, thus resulting in VFAs accumulation which consequently lead to methanogens intoxicant. Accumulation of undissociated acids exposed the AD system to over-acidification condition. Methanogens are known to be inactive or may be die under extremely acidic conditions resulting in low methane rate production [5]. Biochar as a conductive material enables it to be the mediator to facilitate direct interspecies electron transfer (DIET) [6]. DIET is gaining attention compared to IIET due to its high efficiency, energy saving and high electron transfer rate to accelerate the conversion process of VFAs to methane [5]. The electron transfer between geobacter and methanosarcina via DIET bypasses the need of hydrogen as interspecies electron carrier. In addition, biochar's acid buffering capacity will help to balance the pH value of AD and can enhance the activity of microorganisms.

Various type of biogas can be produced from food waste such as methane, hydrogen and hythane. The sky-high global dependency on fossil fuels for power generation can be reduced with biogas substitution. Fossil fuels, the world's most dominant energy sources contain carbon and hydrogen which can be burned for energy and the burning process of these natural sources eventually release a huge amount of carbon in the atmosphere. Statistics reported in 2022, Malaysia have an enormous increase in GHG emissions with 122% as compared to 2005 in the power industry alone. The conversion of food waste to those biogas products also can contribute to the

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achievement of SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production), as it provides significant advantages in the forms of energy-efficient and environmentally friendly technology.

Biogas derived is primarily composed of 50% - 70% methane, 30% - 50% carbon dioxide and 1% - 5% hydrogen content [7], [8]. However, there are also other contaminants presence with the biogas including hydrogen sulphide, ammonia, siloxanes, halogens and other volatile organic compounds [9]. Eric & Mtabazi [2] claims that the contaminant gases in biogas will result in AD stability disruption and eventually lower the substrate degradation rate. Despite the suitability of AD, there are few conditions that need to closely be taken care of. The undesirable circumstances will make anaerobic digestion of food waste (ADFW) process unstable, exhibits greater sensitivity to operational changes and inhibit methane derivation process.

The disruption of the ADFW process due to the presence of contaminant gases can be overcome by biochar supplements, a carbon-rich conductive solid material produced by the thermal decomposition (pyrolysis) of biomass with limited oxygen supply at relatively low temperatures (<700 °C) [4]. Over the past few years, biochar has gained popularity due to its prominent roles in toxins adsorption, ion exchange conductivity, and high micro-porosity [10]. Apart from that, alkaline property, abundant functional groups, good buffering capacity and electrical conductivity makes biochar a good supplement to promote methane derivation [10]–[12]. Biochar inclusion could improve the methane derivation, enhance ADFW stability as well as improving degradation of food waste [13], [14]. This research work was conducted to explore the impact of biochar inclusion in ADFW and to investigate the optimum condition of ADFW in generating methane gas.

2. Methodology

2.1 Fabrication of Rubber Sludge-Derived Biochar

The rubber sludge was collected from the effluent treatment tank of Kilang Getah Kg Awah - FGV Holdings Berhad, Temerloh, Pahang. The sludge was then dried in a tray dryer at 120°C for four hours and referred to as biosludge in the present research work. The raw sludge was then put into a muffle furnace and transformed into biochar. The furnace was set to increase the temperature from 20°C to 500°C, then keep the pyrolytic temperature at 500°C. The temperature was used by several studies to have the ability in producing biochar with favourable characteristics includes high surface area, high porosity and high pH value [6], [15], [16]. In a previous research work, the writer concluded 565°C are the optimal preparation temperature to promote methane derivation [12]. Biochar was cooled in a desiccator, ground finely, sieved and stored for future use.

2.2 Characterization of Rubber Sludge-Derived Biochar

The total carbon (C), hydrogen (H), and nitrogen (N) concentrations of biochar was determined using elemental analyzer (Vario MACRO Cube, Elementar, Germany) while biochar pH value was measured using a pH meter (S220-Kit, Mettler Toledo, Switzerland). The surface morphologies and element distributions of rubber sludge-derived biochar were observed by means of scanning electron microscope, SEM (TM3030 Plus, Hitachi, Japan) with Energy Dispersive X-Ray Spectroscopy, EDX analysis (Oxford Instruments, UK) analysis at 5 kV.

The surface functional group of biochar was investigated using fourier-transform infrared (FTIR) spectroscopy, (Spectrum 100, Perkin Elmer, USA). The samples for FTIR were mixed homogenously with dry potassium bromide (KBr) (0.01% w/w) in an agate mortar and a hydraulic press was used to produce composite pellets for analysis. FTIR spectra was analysed within the range of 400 to 4000 cm^{-1} [17].

2.3 Fabrication of Food Waste Substrate

Food waste from few cafeterias in Universiti Malaysia Pahang Al-Sultan Abdullah, Gambang was collected and used as feedstock in this study. The contaminants and foreign matter (bones, peels, plastic wastes and disposable tableware) was first removed and discriminated from the food waste. The feedstock was mixed with 500 ml of water and homogenized with a blender. The water was added to further aid the mixing process of the feedstock before it transformed into a uniform slurry state. Thereafter, the substrate was collected in plastic zip lock bags and stored in the refrigerator at 4°C until use to avoid biological degradation.

2.4 ADFW Digester

Glass bottles were used as AD process setup and consists of a digester, a water chamber and a water collector. Water displacement method as shown in Fig. 2 often used in laboratories for volumetric gas measurement due its simplicity and economic means. The digester contained slurry feedstock was connected to the water chamber (initially filled with water) by using a flexible plastic pipe. Anaerobic condition was achieved by flushing the headspace of the digester bottle with pure nitrogen for 2 minutes.

AD process took place in the digester and the produced biogas flow through the pipe into the water chamber. The biogas produced in the digester flowed into the water chamber resulting in the water to be displaced from the water chamber to the water collector. Thus, the volume of biogas produced from AD process measured by the amount of water in the water collector.

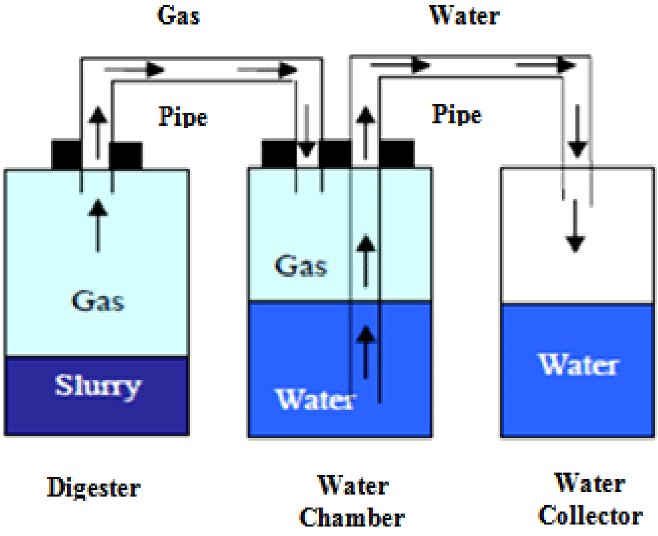


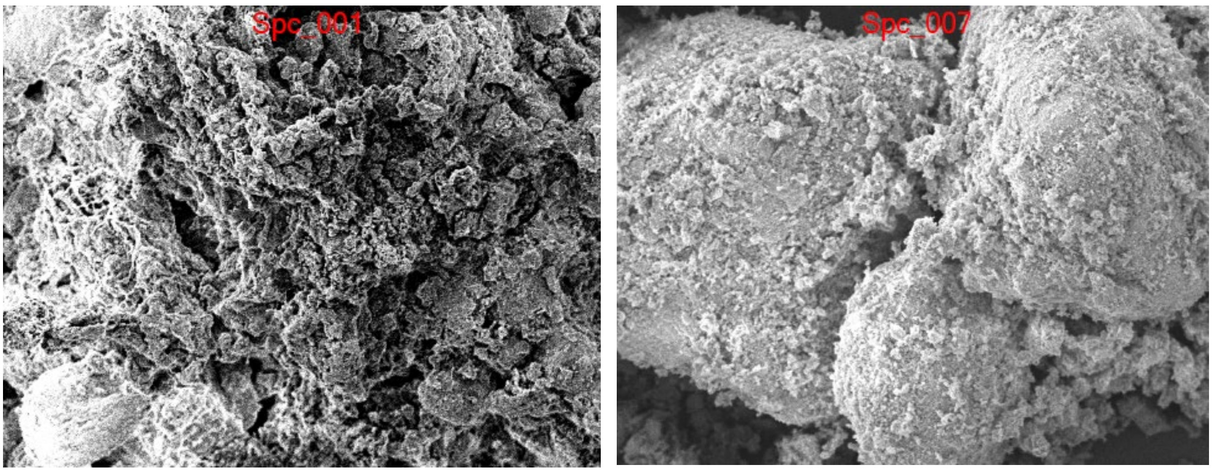
Fig. 2 *Water displacement method set up [24]*

3. Results and Discussions

3.1 Characterization of Biochar

3.1.1 SEM-EDX Analysis

Scanning electron micrographs, SEM in Fig. 3(a) illustrates the surface microstructure and morphology of rubber sludge before undergoing pyrolysis while Fig. 3(b) reveals the changes after pyrolysis process. Carbonized and high porosity biochar surface is believed to appear after pyrolysis process. Due to polymerization and dehydration, pyrolysis process increases the concentration of C while decreasing that of H and O [13]. Conversely, less micropores was observed on the biochar produced. Previous research shows by using temperature of 650°C, biochar produced have highly aromatic which is attributed to the degree of carbonization of organic matter and the formation of micropores [5]. Thus, the temperature used in this study is not sufficient to produce biochar with high micropores. The physicochemical properties of biochar including micropores and surface area can be enhanced with pyrolytic temperature higher than 500°C.



(a) (b)

Fig. 3 *Landing Voltage 5.0 kV, Magnification x 1000 (a)* Before pyrolysis; *(b)* After pyrolysis

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3.1.2 FTIR Analysis

FTIR analysis observed peaks in FTIR spectra to demonstrate specific functional groups present in the rubber sludge and biochar. Fig. 4 presents spectra that exhibits a broad -OH band stretching around 3200-3600 cm^{-1} for rubber sludge attributed to the content of -OH group. The remarkable wavelength difference between rubber sludge and biochar this phenomenon might be the occurrence of the dehydration reaction to generate H_2O and then precipitated. As exposed to high temperature, the surface of the biochar progressively developed a nearly flawless structure of micropores, mesopores, and macropores, and its specific surface area also increased giving the advantageous conditions for toxin adsorption, inhibition level of metabolites reduction (VFAs, ammoniacal agents, etc.) and heavy metals during AD [18]–[20]. More intriguingly, certain microorganisms can thrive in the deep pores of biochar and show tolerance to environmental fluctuations, which enhances the stability of AD and biogas production [21].

The band located at 3020 cm^{-1} associated with =C-H, which was produced from the dehydrogenation reaction and the cracking of alkane components. The absorption peaks ranged from 1700 to 1570 cm^{-1} was related to the C=O, which were formed via the reactions like dehydration. The abundance of the C=C at 1600 cm^{-1} indicates the increased temperature promoted the aromatization reactions. Aromatic C–O stretching was detected at 1038 cm^{-1} in biochar indicating the intensity of carbon content was higher as compared to raw sludge. This result was consistent with studies conducted by [13], [22], which found that biochar has a greater carbon content after pyrolysis.

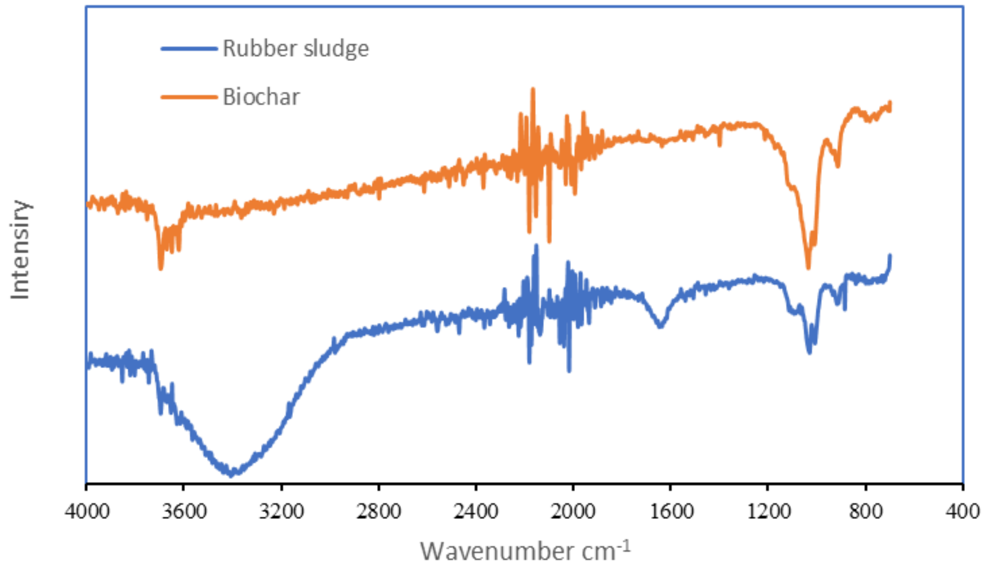

Fig. 4 *FTIR analysis of rubber sludge and biochar*

3.2 ADFW Analysis

3.2.1 Effects of Biochar Dosage on Biogas Yield

Biochar dosage in this experiment is defined as the mass of biochar per volume bulk sludge. 15 g BC/L FW was the condition that have maximum methane yield recorded. The result was supported by a research work conducted by Peng et al. [12] where 15.52 g BC/L FW was found to have the highest biogas yield. Meanwhile, the biochar amount ranging between 0-10 g BC/L FW was concluded as an unfavourable range. This can be seen through the results obtained where 5-10g of biochar added to AD produced relatively low amount of biogas. [23] suggest biochar amount ranging from 0 g BC/L FW – 13 g BC/L FW have a negative correlation with biogas yield. Excessive BC added into the digester may lead to the methane yield declination that can attribute to the nonselective adsorption of BC and will have a proportionate association with the cost [6]. Due to the above reason, many researchers have set 30g BC/L FW as the ceiling in conducting the experiments. Thus, the unexplored area of biochar dosage that exceed 30g BC/L FW remains uncertain.

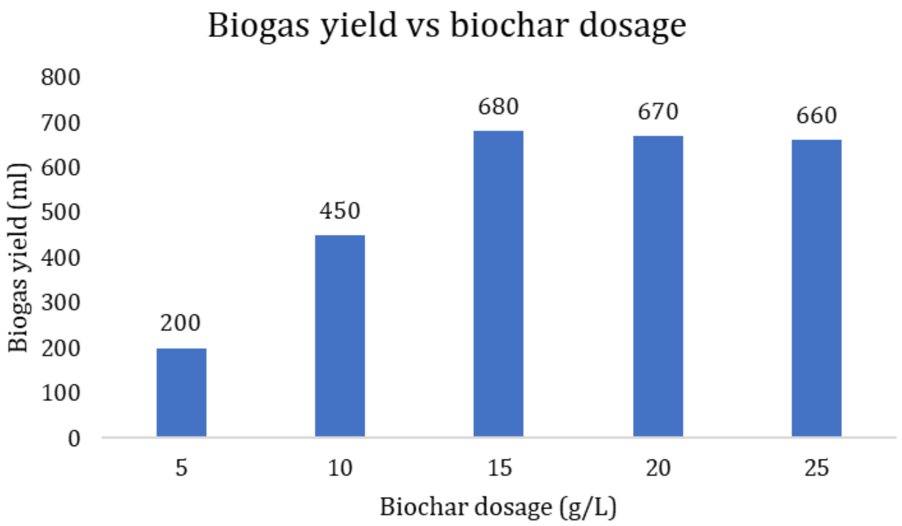

Fig. 5 *The effects of biochar dosage on biogas yield*

3.2.2 Effects of ADFW pH Value on Biogas Yield

Anaerobic archaea or methanogens are very sensitive to pH fluctuation and acidic condition and tend to be inactive if there is VFAs accumulation in the system. The growth rate of methanogens significantly decreased when the pH level falls below 6.0 [21]. The author also explains that pH values outside of the range of 6.5-8.2 would limit the activity of methane generation by the methanogens. On the other hand, other studies suggest that almost no microbial activity was observed when the pH is below 4.5. Fig. 6 shows the biogas production was highest when the pH level is 6. pH range between 6 and 7 are the most favourable to have an enhanced and efficient ADFW [23]. The findings of this research work illustrate the biogas produced is at the lowest with ADFW pH 4 and 5, which is not suitable for methane generation.

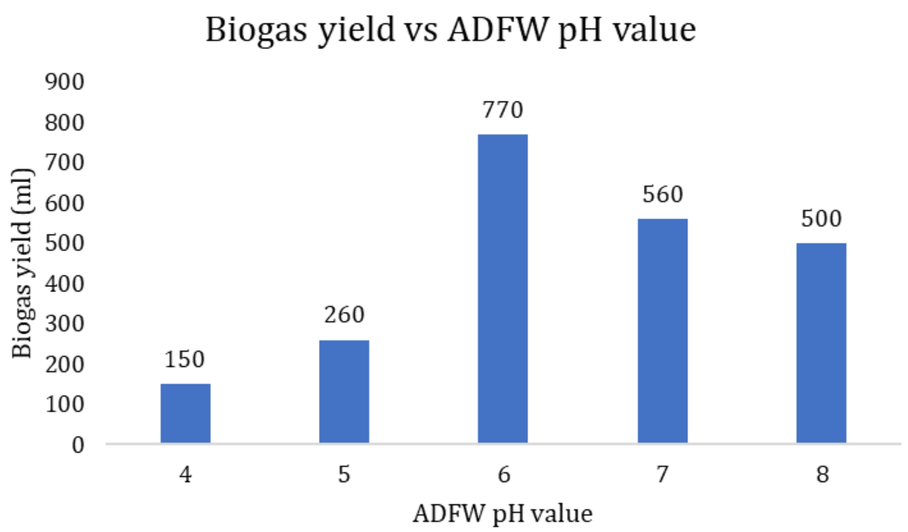

Fig. 6 *The effects of ADFW pH value on biogas yield*

3.2.3 Effects of Retention Time on Biogas Yield

The duration of organic matter's complete breakdown is known as the retention time, which it is one of the main key factors that need to be observed in anaerobic digesters. A retention period of 10–40 days is required to remediate organic waste at a mesophilic temperature [4]. The biogas yield increased with the increasing time with 1300 ml over the period of 35 days. The graph above illustrates the data from the studies using 15 g/L of biochar and shows a directly proportionate relationship between biogas yield and retention time.

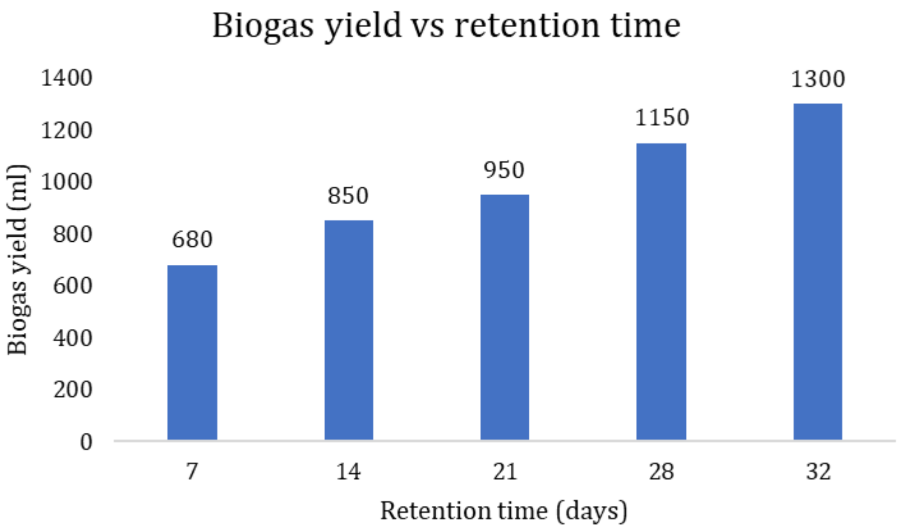

Fig. 7 *The effects of retention time on biogas yield*

4. Conclusion

AD is said to have multiple benefits in addressing current environmental issues. An enormous amount of food waste disposed of in landfills and the abundant rubber sludge can be significantly reduced. The supplementation of rubber sludge-derived biochar demonstrated a significant impact in enhancing the efficiency and effectiveness of AD process, but excessive amount added will have the system failed.

Since AD system alone are prone to failure and have longer lag time, biochar offers few capabilities in facilitating the system to enhance methane generation. Acid buffering capacity of biochar will reduce the possibility of the system's over-acidification due to VFAs accumulation. The growth rate of methanogens is at best with low VFAs. Biochar is also believed to be a suitable mediator in speeding up the rate of electron transfer by DIET over IIET to prevent VFA accumulation from taking place. Acidic ADFW condition will kill the microorganism and lead to decrease in methane gas yield. In conclusion, the suggested parameters to have optimum biogas yield is 15 g/L of biochar with 35 days of retention time at pH level 6.

Acknowledgement

The authors would like to thank Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA) for supporting the study through the Fundamental Research Grant (RDU230302) and Postgraduate Research Scheme 2023 (PGRS2303131).

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***Original draft, data curation****: Khadijah Muhammad;* ***Formal analysis****: Auni Nasuha Azmi;* ***Review and editing, Supervision, Conceptualization, Validation, Resources, Data curation:*** *Noor Yahida Yahya. All authors reviewed the results and approved the final version of the manuscript.*

References

[1] Vathana Bathmanathan, Jegatheesan Rajadurai & Ratnesvary Alahakone (2023) What a waste? An experience in a secondary school in Malaysia of a food waste management system (FWMS), *Heliyon, 9(10)*, https://doi.org/10.1016/j.heliyon.2023.e20327

[2] Eric Mutegoa & Mtabazi G. Sahini (2023) Approaches to mitigation of hydrogen sulfide during anaerobic digestion process–A review, *Heliyon*, https://doi.org/10.1016/j.heliyon.2023.e19768

[3] Kimaya A. Shukla, Abu Danish Aiman Abu Sofian, Ajit Singh, Wei Hsin Chen, Pau Loke Show & Yi Jing Chan (2024) Food waste management and sustainable waste to energy: Current efforts, anaerobic digestion, incinerator and hydrothermal carbonization with a focus in Malaysia, *Journal of Cleaner Production*, *448*, 141457, https://doi.org/10.1016/j.jclepro.2024.141457

[4] Sagor Kumar Pramanik, Suja, Fatihah Suja, Shahrom Md Zain & Biplob Kumar Pramanik (2019) The anaerobic digestion process of biogas production from food waste: Prospects and constraints, *Bioresource Technology Reports*, *8*, 100310, https://doi.org/10.1016/j.biteb.2019.100310

[5] Danyang Zhao, Binghua Yan, Chao Liu, Bin Yao, Lin Luo, Yang Yang, Lichao Liu, Fan Wu & Yaoyu Zhou (2021) Mitigation of acidogenic product inhibition and elevated mass transfer by biochar during anaerobic digestion of food waste, *Bioresource Technology, 338,* 125531, https://doi.org/10.1016/j.biortech.2021.125531

[6] Yuqi Chen, Yuzheng Wang, Hongyu Xie, Wenzhi Cao & Yanlong Zhang (2023) Varied promotion effects and mechanisms of biochar on anaerobic digestion (AD) under distinct food-to-microorganism (F/M) ratios and biochar dosages, *Waste Management*, *155,* 118-128, https://doi.org/10.1016/j.wasman.2022.10.030

[7] C. M. Ajay, Sooraj Mohan & P. Dinesha (2021) Decentralized energy from portable biogas digesters using domestic kitchen waste: A review, *Waste Management, 125,* 10-26, https://doi.org/10.1016/j.wasman.2021.02.031

[8] Max Rowan, Great C. Umenweke, Emmanuel I. Epelle, Inioluwa Christianah Afolabi, Patrick U. Okoye, Burcu Gunes & Jude A. Okolie (2022) Anaerobic co-digestion of food waste and agricultural residues: An overview of feedstock properties and the impact of biochar addition, *Digital Chemical Engineering, 4,* 100046, https://doi.org/10.1016/j.dche.2022.100046

[9] E. Mutegoa, N. M. Malima, A. Hilonga & K. N. Njau (2021) Effect of mixing ratios of natural inorganic additives in removing ammonia and sulfide in the liquid phase during anaerobic digestion of slaughterhouse waste, *Materials Today Chemistry, 20,* 100415, https://doi.org/10.1016/j.mtchem.2020.100415

[10] Tong-Hu Tsui, Le Zhang, Ee Yang Lim, Jonathan T. E. Lee & Yen Wang Tong (2021) Timing of biochar dosage for anaerobic digestion treating municipal leachate: Altered conversion pathways of volatile fatty acids, *Bioresource Technology*, *335,* 125283, https://doi.org/10.1016/j.biortech.2021.125283

[11] Irfan Saif, El-Sayed Salama, Muhammad Usman, Dae Sung Lee, Kamran Malik, Pu Liu & Xiangkai Li (2021) Improved digestibility and biogas production from lignocellulosic biomass: Biochar addition and microbial response, *Industrial Crops and Products*, *171,* 113851, https://doi.org/10.1016/j.indcrop.2021.113851

[12] Yun Peng, Lei Li, Qin Dong, Pingjin Yang, Hengyi Liu, Wenjie Ye, Di Wu & Xuya Peng (2023) Evaluation of digestate-derived biochar to alleviate ammonia inhibition during long-term anaerobic digestion of food waste, *Chemosphere*, *311,* 137150, https://doi.org/10.1016/j.chemosphere.2022.137150

[13] Teklit Grebregiorgis Ambaye, Eldon R. Rene, Abdul-Sattar Nizami, Capucine Dupont, Mentore Vaccari & Eric D. van Hullebusch (2021) 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*, *290,* 112537, https://doi.org/10.1016/j.jenvman.2021.112537

[14] Yongshen Shi, Manli Liu, Jingyi Li, Yilin Yao, Jingchun Tang & Qigui Niu (2022) The dosage-effect of biochar on anaerobic digestion under the suppression of oily sludge: Performance variation, microbial community succession and potential detoxification mechanisms, *Journal of Hazardous Materials*, *421,* 126819, https://doi.org/10.1016/j.jhazmat.2021.126819

[15] Abhinav Choudhury & Stephanie Lansing (2020) Biochar addition with Fe impregnation to reduce H2S production from anaerobic digestion, *Bioresource technology*, *306,* 123121, https://doi.org/10.1016/j.biortech.2020.123121

[16] Qin Jiang, Yongdong Chen, Shangke Yu, Ruilin Zhu, Cheng Zhong, Huijing Zhou, Li Gu & Qiang He (2020) Effects of citrus peel biochar on anaerobic co-digestion of food waste and sewage sludge and its direct interspecies electron transfer pathway study, *Chemical Engineering Journal, 398,* 125643 https://doi.org/10.1016/j.cej.2020.125643

[17] Uttara Mahapatra, Abhijit Chatterjee, Chandan Das & Ajay Kumar Manna (2021) Adsorptive removal of hexavalent chromium and methylene blue from simulated solution by activated carbon synthesized from natural rubber industry biosludge, *Environmental Technology & Innovation, 22,* 101427, https://doi.org/10.1016/j.eti.2021.101427

[18] Anwarzeb Khan, Sardar Khan, Ming Lei, Mehboob Alam, Muhammad Amjad Khan & Amjal Khan (2020) Biochar characteristics, applications and importance in health risk reduction through metal immobilization, *Environmental Technology & Innovation, 20,* 101121, https://doi.org/10.1016/j.eti.2020.101121

[19] Mohammad Javad Bardi, Jackline M. Mutunga, Hiram Ndiritu & Konrad Koch (2023) Effect of pyrolysis temperature on the physiochemical properties of biochar and its potential use in anaerobic digestion: A critical review, *Environmental Technology & Innovation,* 103349, https://doi.org/10.1016/j.eti.2023.103349

[20] Zi-Fan Wu, Zhao-Kai Wang, Jia-Bing Li, Yu-Hong Qiu, Zu-Liang Chen, Gary Owens & Zhi-Man Yang (2024) Effects of biochars derived from different feedstocks and pyrolysis temperatures on the anaerobic digestion of kitchen waste, *Renewable Energy, 230,* 120833, https://doi.org/10.1016/j.renene.2024.120833

[21] Zhang-Wei He, Ai-Hua Li, Cong-Cong Tang, Ai-Juan Zhou, Wenzong Liu, Yong-Xiang Ren, Zhihua Li & Aijie Wang (2023) Biochar regulates anaerobic digestion: Insights to the roles of pore size, *Chemical Engineering Journal,* 148219, https://doi.org/10.1016/j.cej.2023.148219

[22] Jun Cao, Yutong Jiang, Xiao Tan, Lei Li, Songshan Cao, Jiayao Dou, Runqi Chen, Xiaoyun Hu, Zhiheng Qiu, Ming Li, Ziyin Chen & Hualun Zhu (2024) Sludge-based biochar preparation: pyrolysis and co-pyrolysis methods, improvements, and environmental applications, *Fuel, 373,* 132265, https://doi.org/10.1016/j.fuel.2024.132265

[23] Yi Zhang, Yijing Feng, Zhonghao Ren, Runguo Zuo, Tianhui Zhang, Yeqing Li, Yajing Wang, Zhiyang Liu, Ziyan Sun, Yongming Han, Lu Feng, Mortaza Aghbashlo, Meisam Tabatabaei & Junting Pan (2023) Tree-based machine learning model for visualizing complex relationships between biochar properties and anaerobic digestion, *Bioresource Technology, 374,* 128746, https://doi.org/10.1016/j.biortech.2023.128746

[24] Muhammad Rashed Al Mamun & Shuichi Torii (2015) Production of Biomethane from Cafeteria, Vegetable and Fruit Wastes by Anaerobic Co digestion Process, *Journal of Clean Energy Technologies*, *3(5)*, https://doi.org/10.7763/jocet.2015.V3.216