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Original Article

Enhancing biogas yield through anaerobic co-digestion of animal manure and seaweed

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Abstract

By 2050, it is predicted that there will be 9.8 billion people on the planet. The world's population is expanding, which creates an immediate energy demand, the majority of which is now provided by fossil fuels. Researchers are becoming more interested in seaweeds because they offer a sustainable and viable feedstock for the manufacture of biofuels. They are a good alternative energy source to fossil fuels because of their readily fermentable composition, high availability, and good degradation potential. The current work focuses on the co-digestion of animal manures with Sargassum spp., namely goat, pig, cow, and chicken manures. The study was conducted under mesophilic temperature conditions, i.e., ±37°C, at a hydraulic retention time (HRT) of 25 days. The findings were presented in terms of daily, cumulative, and total biogas production. From the biogas yield results obtained, it is apparent that the co-digestion of goat, pig, cow, and chicken manures with Sargassum spp. produced an improved biogas yield, unlike the substrates of sole digestion. Besides, the maximum total cumulative biogas yield of 3.51 m^3 was obtained with co-digestion of chicken manure and Sargassum spp., while the least total cumulative biogas yield of 2.68 m^3 was achieved with co-digestion of goat manure and Sargassum spp. Also, an optimum biogas yield was achieved with a mesophilic temperature of 37°C and the lowest biogas yield with a mesophilic temperature of 31°C.

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1 Introduction

Anaerobic digestion (AD) is a generally accepted method used to treat biodegradable organic wastes (BOWs), and wastewater [1,2]. The AD of biodegradable organic waste is considered feasible for recovering renewable energy and nutrients [3,4]. However, solely digesting of substrates in ADs can lead to unsteadiness due to the production of volatile fatty acids (VFAs), and ammonia which have repressive effects on methanogenic forming bacteria, thus biogas yield [5]. Co-digestion of different BOW substrates are considered a positive method to overcome limitations associated with the sole digestion of BOWs. Anaerobic co-digestion upsurges methane production due to the positive interactions in the acclimatization medium [6]. When dealing with animal manure, it is generally acknowledged that the methane produced by these organic materials is not high enough to make digestion profitable. The formation of nitrogen-containing substances may cause inhibition leading to poor performance. Consequently, adding a co-feedstock capable of balancing the Carbon/Nitrogen (C/N) ratio and trace element content will meaningfully increase methane yield [7-9] and energy valorization. Besides, a high or low C/N ratio affect biogas production. Organic wastes differ in C/N ratio, for example; C/N ratio for cow manure is 19.9, goat manure is 25, chicken manure is 10, pig manure is 20, sheep manure is 19 and for *Sargassum spp.*is 14.8 [10-14]. For optimum biogas yields, adjusting C/N ratio is desirable and this can be achieved by co-digestion of wastes of high C/N ratio with those of lower C/N ratio [14]. Animal manure contains large contents of organic substances, nitrogen, phosphorus, and pathogens, and hence has been classified as a main source of environmental pollution. For instance, animal manure donates 55% of chemical oxygen demand (COD), 22% of total nitrogen (TN), and 32% of total phosphorus (TP) to water contamination in China [15]. Ammonia is free throughout the degradation of proteins, reaching a peak concentration in the reactor that may constrain methanogens. This is responsible for the application of co-digestion in animal farms [16,17]. The buffering structure generated by the presence of these substances generates an environment where pH is kept at levels higher than 6.4 m, ensuring suitable acid–base environments for methanogens bacteria to operate [18,19].

Nevertheless, according to [20], co-digestion of pig and chicken dung with rice straw alleviated $NH4^+$–N toxicity and hence upsurge methane production by 10.57%. Also, [21] reported the mixture of cornstalks and wheat straw with cattle manure to enhance a balanced carbon/nitrogen ratio for optimum methane production and digester stability. The improvement attained in their study was credited to the high content of cellulosic carbon and the low presence of microbial inhibitors such as $NH4^+$–N and sodium ions in crop straw. Similarly, several researchers have investigated the co-digestion of animal dung with other lignocellulosic wastes to improve methane yield, such as spent mushroom substrate, durian shell, micro-algae, wastepaper, and vinasse [22-25]. Biogas production from animal remains was investigated by [26], and their findings revealed a methane yield of 0.47 m^3 CH_4/kgvs from biochemical methane potential (BMP) tests. Also, [27] observed in their research that co-digestion of swine manures with animal remains resulted in a doubling of biogas yield. Given the regulatory requirements for category material, [28] projected the optimization of the hydrothermal pretreatment of animal remains for improving biogas generation. Ammonium ions generated during protein degradation impede anaerobic action at concentrations close to 4.0 g/L [29]. However, numerous issues are pertinent in the response of the microflora to ammonium. Adaptation is crucial for enduring high levels of this cation in the digester liquor, along with pH and temperature. Co-digestion of feedstocks, with dissimilar C/N ratios, is an appropriate approach for improving degradation performance [30] and circumventing poisonous ammonia concentrations. Hence, the use of seaweeds as co-substrates are appropriate choice that has been appraised under small laboratory conditions in many cases [31]. The use of seaweeds in the production of bioenergy is an idea that has grown in recent years. Since 1980, an overall estimated 1686 scientific documents have been revealed. Also, since 2010, 97% of the scientific documents have been published as depicted in Fig. 1.

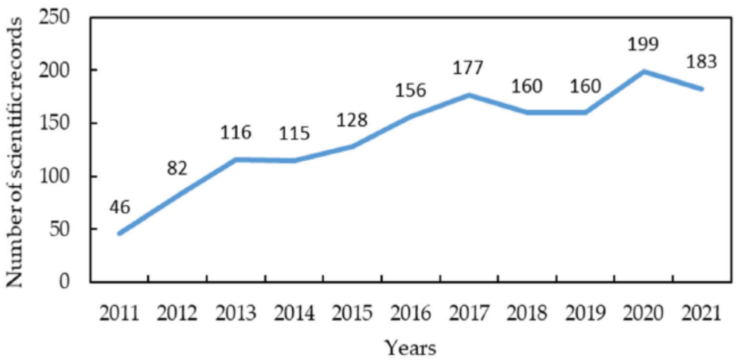

Fig. 1 Number of research articles related to seaweeds published in Web of Science from 2011–2021 [31]

Besides, Nigeria has an estimated 79 species of seaweed that have been recognized, with the majority composed of red algae (~ 38 species) [32,33]. However, *Sargassum spp.* (Fig. 2) form periodic blooms, which when cast upon the beaches places a high financial cost on the country for clearance [33].

Fig. 2 Red Algae (*Sargassum spp.*).

This alga can not only interfere with navigation activities but also clog fishing nets instigating extra work for fishermen [33-35]. The red algae have a chemical composition of carbohydrate (30-60%) [36,37], protein (10-25%) [38-40], lipid (0.6-4%) [41-43], mineral (26-48%) [43,44], and also a good water content (70-80%) [45] that can enhance the first phase (hydrolysis) of AD process. High biomethane potential (BMP) values have been found in the brown seaweed Macrocystis (0.39-0.41 m^3 CH4/kg Volatile Solids (VS) [46,47] and the red seaweed Gracilaria (0.28-0.4 m^3 CH4/kg VS) [48]. This study therefore examined the co-digestion of animal manures with red algae (*Sargassum spp*) with the exact objectives to: digest animal manures (i.e., cow manure, pig manure, poultry manure, and sheep manure) separately, digest *Sargassum spp* separately, co-digest animal manures and *Sargassum spp.*, evaluate optimum biogas yield, and determine the best mesophilic temperature for optimum biogas yield.

2 Materials and methods

Fresh *Sargassum spp.* and animal manure (i.e., cow, pig, goat, and chicken manure) were collected from the ocean and respective farms in Nigeria. The abundance of animal manure waste and its improper disposal without proper treatment in the study area necessitates the development of an alternative management strategy, such as an AD system. Furthermore, during co-digestion, the low inhibitory compounds in animal manures will promote coactive effects with *Sargassum spp.* The experimental set-up as shown in Fig. 3 was to enhance biogas yield via co-digestion of animal manures and seaweed.

The red algae (*Sargassum spp.*) and animal manures were mono-digested and co-digested under a mesophilic temperature range of 25 °C to 37 °C. The mesophilic temperature range is preferred in this study because anaerobic digestion performance by psychrophilic bacteria and thermophilic bacteria is slower than those of mesophilic bacteria [49]. Also, it is difficult to maintain anaerobic digestion plants under psychrophilic temperature condition due to low process temperature. Furthermore, thermophilic bacteria are known to be very sensitive to disturbances, which require costly process monitoring and control [50]. In general, optimum mesophilic temperature brings about shorter HRT (more production of biogas) since more methanogenic bacteria are working upon substrate [51]. A digester made of a plastic bottle of 25 liters capacity was used as the batch reactor. The digesters were connected with a displacement bottle and water collector. Rubber tubes were used to connect the reactors and the displacement bottles. The eight (8) batch reactors were fed manually with the same mass (15 kg) of feedstocks with water in a ratio of 3:2. The biogas produced were carefully monitored for 25 days to determine the highest biogas yield among the eight (8) batch reactors. Table 1 shows the summary of experimental requirements.

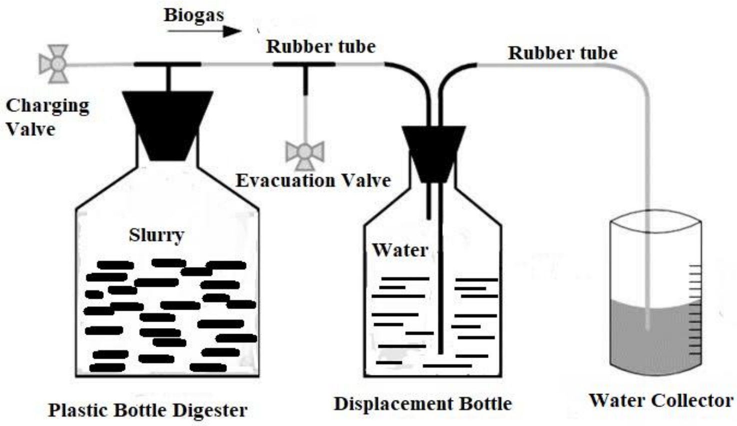

Fig. 3 Experimental setup.

Table 1 Summary of experimental requirements.

S/N	Reactors	Feedstocks Composition	Quantity of Feedstock	Volume of Water Used	Biogas measurement
1	ADR1	Cow manure	15 kg	10 liters	2 days
2	ADR2	Pig manure	15 kg	10 liters	2 days
3	ADR3	Goat manure	15 kg	10 liters	2 days
4	ADR4	Chicken manure	15 kg	10 liters	2 days
5	ADR5	*Sargassum spp.*	15 kg	10 liters	2 days
6	ADR6	Cow manure and *Sargassum spp.*	15 kg	10 liters	2 days
7	ADR7	Pig manure and *Sargassum spp.*	15 kg	10 liters	2 days
8	ADR8	Goat manure and *Sargassum spp.*	15 kg	10 liters	2 days
9	ADR9	Chicken manure and *Sargassum spp.*	15 kg	10 liters	2 days

3 Results and discussion

The animal manures and *Sargassum spp.* used in this study was digested and co-digested under mesophilic conditions of ±37 °C, at a hydraulic retention time of 25 days and the results of the study on biogas yield are presented in Figs. 4-11. The results are presented in terms of the daily, cumulative, total biogas yield, and the effect of mesophilic temperature on biogas yield. The biogas yield graph for several samples of animal manures and *Sargassum spp.* over 25 days is displayed in Fig. 4. Biogas yields rise from the second to the eighteenth day, when they reach their peak, and then begin to fall for the remaining production days. The maximum biogas generation of 0.30 m^3 per day was achieved with chicken manure (ADR4). The 18th day also saw the acquisition of 0.27 m^3, 0.24 m^3, 0.19 m^3, and 0.11 m^3 of daily biogas for cow manure, pig manure, goat manure, and *Sargassum spp.* Furthermore, it was shown that the best daily biogas yield for digestion alone comes from chicken dung, which is followed in order by cow, pig, goat, and *Sargassum spp*.

The low inhibitory compounds of animal manures to promote coactive effects with *Sargassum spp.* in co-digestion may be the reason for the improved biogas yields [45], as shown in Fig. 5. Because both substrates have excellent characteristics that make them easily biodegradable, the data displayed in Figure 5 clearly reveal a synergistic impact in the co-digestion of animal manures with *Sargassum spp.* The sequence of co-digestion of chicken manure and sargassum spp. > cow manure and sargassum spp. > pig manure and sargassum spp. > goat manure and sargassum spp. was documented in the improved daily biogas yield, as shown in Fig. 5. The results in Fig. 5 agreed with the research work of

[20,21,26,27]. In their research works, they all reported improved in biogas yield with co-digestion of feedstocks with animal manures.

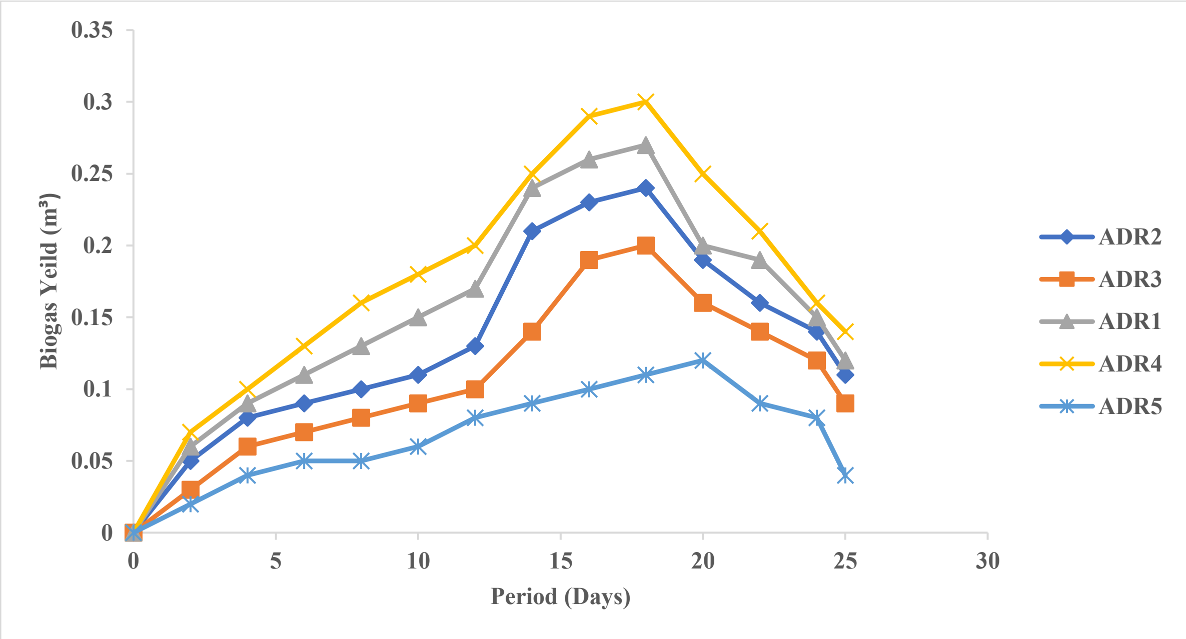

Fig. 4 Graph of biogas yields for different samples of animal manures and Sargassum spp. against period of production.

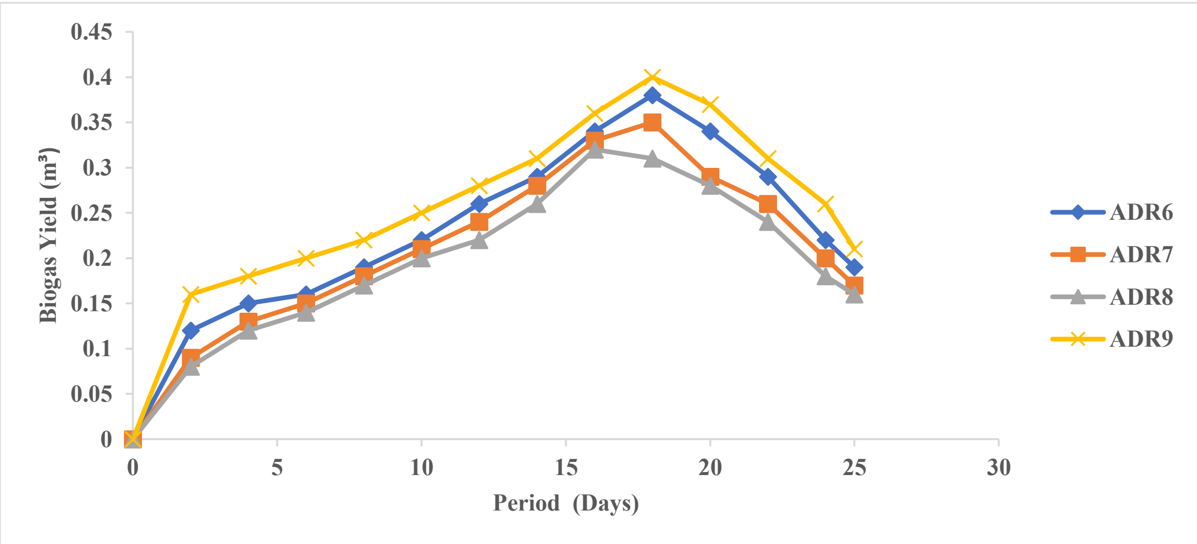

Fig. 5 Graph of biogas yields for co-digestion of animal manures with *Sargassum spp.* against period of production.

As shown in Fig. 6, the comparative analysis of biogas yield for sole digestion and co-digestion of animal manures and *Sargassum spp.* It was observed that improved biogas yields were achieved with all samples of co-digested (ADR9, ADR6, ADR7, and ADR8), unlike the samples of solely digested (ADR5, ADR4, ADR3, ADR2, and ADR1). The improvement in biogas yield from the co-digestion of animal manures and Sargassum spp. is credited to the willingly biodegradable organic content, such as carbohydrates, lipids, and proteins, present in the feedstocks, which plays a crucial role in their conversion into biogas by microbial species, as reported by [36–43, 52–55]. Also, the good moisture content of *Sargassum spp.* (70–80%) [45] was beneficial for the anaerobic co-digestion process, thus promoting the fast decomposition of the animal manure.

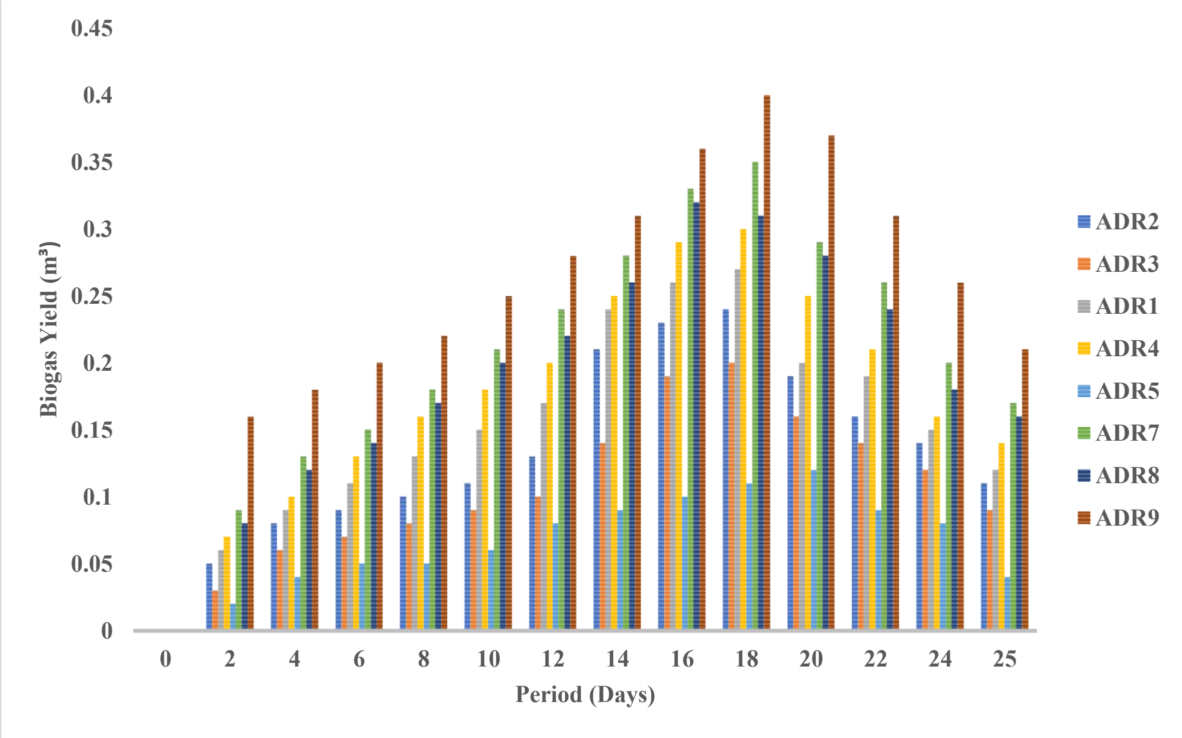

Fig. 6 Comparative analysis of biogas yield for solely digestion and co-digestion of animal manures and Sargassum spp.

Also, there was a continuous increase in biogas yield solely in digestion feedstocks (Fig. 7) and co-digestion of animal manures and *Sargassum spp.* (Fig. 8) throughout the hydraulic retention time of 25 days. These are indications of good biogas potential from animal manures and *Sargassum spp.* These findings are in line with the research work of [8,9,20,21,52-55] that reported good biogas yield potentials from farm animal manures and seaweeds. According to [20], co-digestion of animal manure and *Sargassum spp.* alleviated $NH4^+$–N toxicity and hence upsurged biogas production. The mixture of *Sargassum spp.* with animal manure enhances a balanced carbon/nitrogen ratio for optimum methane production and digester stability [21]. As reported by [8,9], adding a co-feedstock such as *Sargassum spp.* helps in balancing the C/N ratio and trace element content will meaningfully increase biogas yield. Thus, the improvement attained can be credited to the high content of cellulosic carbon and the low presence of microbial inhibitors such as $NH4^+$–N and sodium ions. Besides, abattoir wastes, pig, cattle, chicken, sheep manure, and any other type of manure from livestock farms remain with a high protein content. When dealing with this substance, ammonia buildup may cause complications for effective reactor performance if a balancing carbon source is not added to balance the C/N ratio of the feeding recipe.

As shown in Fig. 9, the comparison study of cumulative biogas yields for co-digestion and sole digestion confirmed that co-digestion produced higher biogas yields. Also, the co-digestion of chicken manure and *Sargassum spp*. (ADR9) has the optimal total cumulative biogas yield of 3.51 m^3, as shown in Fig. 10. ADR6 (co-digestion of cow manure and *Sargassum spp.*) comes in second with a total cumulative biogas yield of 3.15 m^3, and the remaining biogas yields are as follows: ADR7 >ADR8>ADR5>ADR4> ADR1 > ADR2 > ADR3 > ADR5. Consequently, of all the substrates examined in this study, the digestion of *Sargassum spp.* alone generated the lowest cumulative biogas output. Nevertheless, goat dung (ADR3) had the lowest cumulative biogas output of 1.47 m^3 among the animal manures employed in this investigation.

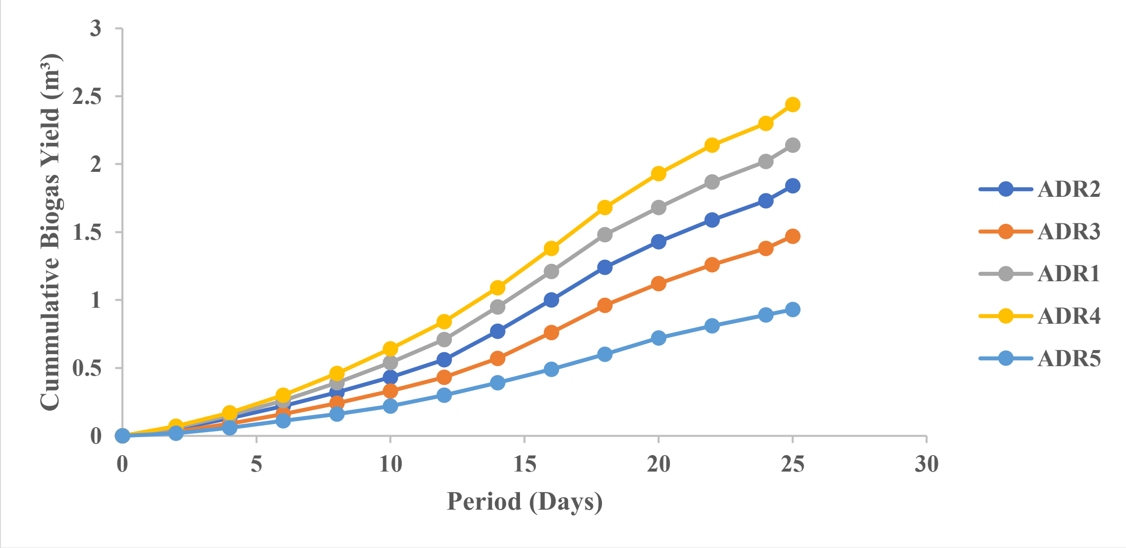

Fig. 7 Graph of cumulative biogas yields for different samples of animal manures and Sargassum spp. against period of production.

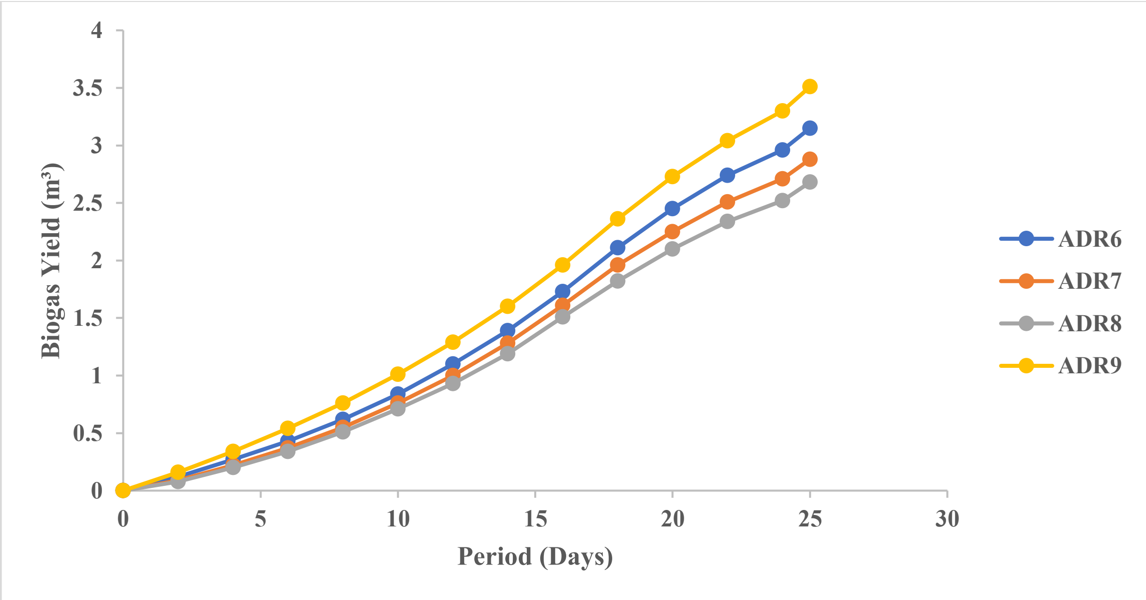

Fig. 8 Graph of cumulative biogas yields for co-digestion of animal manures with *Sargassum spp.* against period of production.

The results of the effect of mesophilic temperature on biogas yield showed that optimum biogas yield was achieved with mesophilic temperatures of 37°C and 36°C, as shown in Fig. 11, and this agreed with the research work of [51,54]. As per reference [51], the HRT is shortened and the rate of biogas evacuation is higher at higher mesophilic temperatures. Additionally, the best biogas yield can be achieved in a mesophilic temperature range of 36–38 °C. Conversely, a mesophilic temperature that is lower can lengthen the HRT and cause the yield of biogas to decrease.

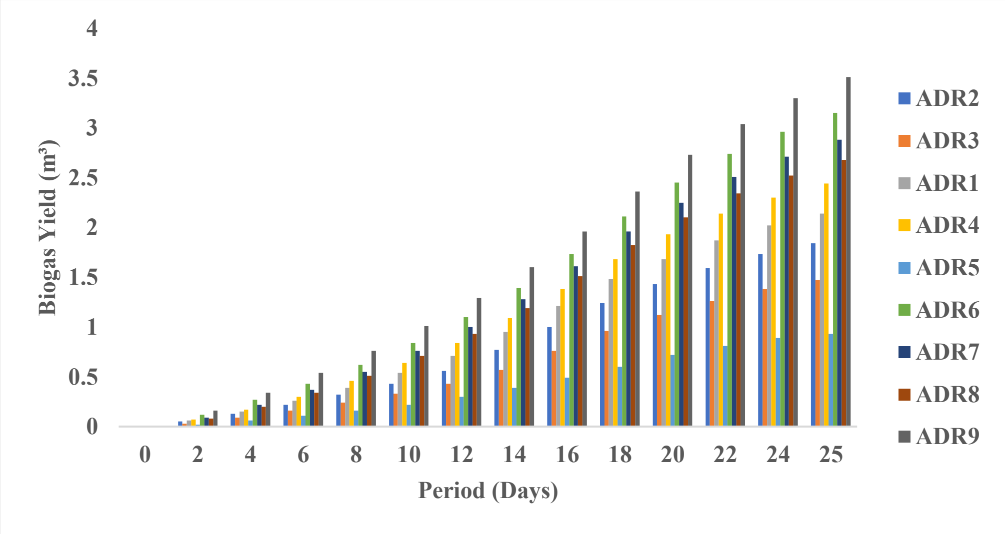

Fig. 9 Comparative analysis of cumulative biogas yield for solely digestion and co-digestion of animal manures and Sargassum spp.

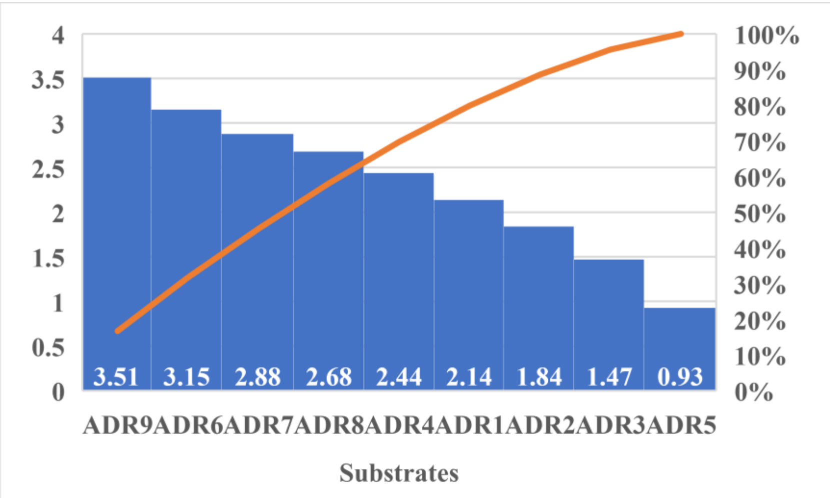

Fig. 10 Evaluation of total biogas yield at the end of hydraulic retention time of 25 days.

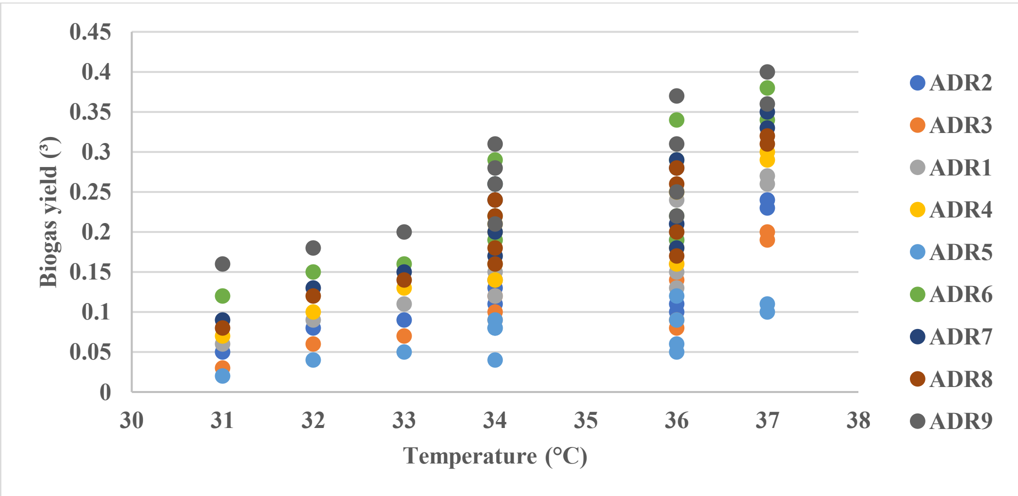

Fig. 11 Evaluation of the effect of mesophilic temperature on biogas yield.

4 Conclusion

The goal of this research is to increase the yield of biogas by co-digesting animal manure and seaweed anaerobically. An anaerobic batch reactor with a 25-day HRT was used to digest and co-digest chicken manure, cow dung, pig manure, goat manure, and *Sargassum spp.* The results showed that co-digested substrates yield more biogas than solely digested substrates. Co-digested chicken manure and *Sargassum spp.* were shown to have the maximum biogas production, both daily and cumulative. This was followed by co-digested cow manure and *Sargassum spp.,* co-digested pig manure and *Sargassum spp.,* and co-digested goat manure and *Sargassum spp.* For the solely digested feedstocks, their biogas yield potential was in this order: chicken manure > cow manure > pig manure > goat manure > *Sargassum spp*. The results also showed that mesophilic temperature had significant effects on biogas yield, with mesophilic temperatures of 37°C and 31°C having the highest and lowest biogas production, respectively.

Declaration of Conflict of Interest

The authors declared that there is no conflict of interest with any other party on the publication of the current work.

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References

[1] A.T. Hoang, J.L. Goldfarb, A.M. Foley, E. Lichtfouse, M. Kumar, L. Xiao, S. F. Ahmed, Z. Said, R. Luque, V. G. Bui, Production of biochar from crop residues and its application for AD, Bioresource Technology 363 (2022)127970. https://doi:10.1016/j.biortech.2022.127970.

[2] E.K. Orhorhoro, P.B. Ebunilo, E.G. Sadjere, Effect of Organic Loading Rate (OLR) on biogas yield using a single and three-stages continuous anaerobic digestion reactors, International Journal of Engineering Research in Africa 39 (2017)147-155. https://doi:10.4028/www.scientific.net/JERA.39.147.

[3] R. Franqueto, J.D., da Silva, and M. Konig, Effect of temperature variation on co-digestion of animal waste and agricultural residue for biogas production. BioEnergy Research 13 (2) (2020) 630–42. https://doi:10.1007/s12155-019-10049-y.

[4] S. Bi, X. Hong, H. Yang, X. Yu, S. Fang, Y. Bai, and Y. Wang, Effect of hydraulic retention time on anaerobic co- digestion of cattle manure and food waste, Renewable Energy 150 (2020) 213–20. https://doi.org/10.1016/j.renene.2019.12.091.

[5] R. Karki, W. Chuenchart, K.C. Surendra, S. Shrestha, L. Raskin, S. Sung, and S.K. Khanal, Anaerobic co-digestion: Current status and perspectives, Bioresource Technology 330 (2021)125001. https://doi.org/10.1016/j.biortech.2021.125001.

[6] J. Zhang, C. Qi, Y. Wang, Y. Li, T. Han, X. Gong, M. Shan, G. Li, W. Luo, Enhancing biogas production from livestock manure in solid-state anaerobic digestion by sorghum-vinegar residues, Environmental Technology & Innovation 26 (2022) 102276. https://doi.org/10.1016/j.eti.2022.102276.

[7] W.L. Chow, S. Chong, J.W. Lim, Y.J. Chan, M.F. Chong, T.J. Tiong, J.K. Chin, G.T. Pan, Anaerobic co-digestion of wastewater sludge: A review of potential co-substrates and operating factors for improved methane yield, Processes 8 (2020) 39. https://doi.org/10.3390/pr8010039.

[8] A. El Nemr, M.A. Hassaan, M.R. Elkatory, S. Ragab, A. Pantaleo, Efficiency of Fe3O4 Nanoparticles with Different Pretreatments for Enhancing Biogas Yield of Macroalgae Ulva intestinalis Linnaeus, Molecules 26 (2021) 5105. https://doi.org/10.3390/molecules26165105.

[9] D. Singh, K. Malik, M. Sindhu, N. Kumari, V. Rani, S. Mehta, K. Malik, P. Ranga, K. Sharma, N. Dhull, Biostimulation of anaerobic digestion using iron oxide nanoparticles (IONPs) for increasing biogas production from cattle manure, Nanomaterials 12 (2022) 497. https://doi.org/10.3390/nano12030497.

[10] E.K. Orhorhoro, O.W. Orhorhoro, P.O. Ebunilo, Analysis of the effect of Carbon/Nitrogen (C/N) ratio on the performance of biogas yields for non-uniform multiple feed stock availability and composition in Nigeria, International Journal of Innovative Science, Engineering & Technology 3(5) (2016) 119-126
[11] R. Chandra, H. Takeuchi, Methane production from lignocellulosic agricultural crop wastes: A review in context to second generation of biofuel production, Renewable and Sustainable Energy Reviews 16(3) (2012) 1462-1476. https://doi.org/10.1016/j.rser.2011.11.035.
[12] H. Abu-Qdais, K. Bani-Hani, N. Shatnawi, Modeling and optimization of biogas production from a waste digester using artificial neural network and genetic algorithm, Resources, Conservation and Recycling 54 (2012) 359–363. https://doi.org/10.1016/j.resconrec.2009.08.012.
[13] M.I. Tanimu, T.I.M. Ghazi, R.M. Harun, I. Adris, Effect of carbon to nitrogen ratio of food waste on biogas methane production in a batch mesophilic anaerobic digester, FOG. 24(18) (2014) 34-49.
[14] A. Tardast, M. Rahimnejad, G. Najafpour, Prediction of bioelectricity production by Neural Network, Journal of Biotechnology and Pharmaceutical Research 3(3) (2012) 62–68
[15] F. Wang, M. Pei, L. Qiu, Y. Yao, C. Zhang, H. Qiang, Performance of anaerobic digestion of chicken manure under gradually elevated organic loading rates, International Journal of Environmental Research and Public Health 16 (2019) 2239. https://doi.org/10.3390/ijerph16122239.
[16] C. Lü, Y. Shen, C. Li, N. Zhu, H. Yuan, Redox-Active biochar and conductive graphite stimulate methanogenic metabolism in anaerobic digestion of waste-activated sludge: Beyond direct interspecies electron transfer, ACS Sustainable Chemistry & Engineering 8 (2020) 12626–12636. https://doi.org/10.1021/acssuschemeng.0c04109.
[17] R. Rajagopal, D.1. Massé, G. Singh, A critical review on inhibition of anaerobic digestion process by excess ammonia, Bioresource Technology 143 (2013) 632–641. https://doi.org/10.1016/j.biortech.2013.06.030.
[18] X. Meng, D. Yu, Y. Wei, Y. Zhang, Q. Zhang, Z. Wang, J. Liu, Y. Wang, Endogenous ternary pH buffer system with ammonia carbonates-VFAs in high solid anaerobic digestion of swine manure: An alternative for alleviating ammonia inhibition, Process Biochemistry 69 (2018) 144–152. https://doi.org/10.1016/j.procbio.2018.03.015.
[19] D. Cudjoe, M.S. Han, A.P. Nandiwardhana, Electricity generation using biogas from organic fraction of municipal solid waste generated in provinces of China: Techno-economic and environmental impact analysis, Fuel Processing Technology 203 (2020) 106381. https://doi.org/10.1016/j.fuproc.2020.106381.
[20] X. Wang, G. Yang, Y. Feng, G. Ren, X. Han, Optimizing feeding composition and carbon–nitrogen ratios for improved methane yield during anaerobic co-digestion of dairy, chicken manure and wheat straw, Bioresource Technology 120 (2012) 78–83. https://doi.org/10.1016/j.biortech.2012.06.058.
[21] J. Li, L. Wei, Q. Duan, G. Hu, G. Zhang, Semi-continuous anaerobic co-digestion of dairy manure with three crop residues for biogas production, Bioresource Technology 156 (2014) 307–313. https://doi.org/10.1016/j.biortech.2014.01.064.
[22] W. Li, M.A.H. Siddhu, F.R. Amin, Y. He, R. Zhang, G. Liu, C. Chen. Methane production through anaerobic co-digestion of sheep dung and waste paper, Energy Conversion and Management 156 (2018) 279–287. https://doi.org/10.1016/j.enconman.2017.08.002.
[23] G. Ma, P. Ndegwa, J.H. Harrison, Y. Chen. Methane yields during anaerobic co-digestion of animal manure with other feedstocks: A meta-analysis, Science of The Total Environment 728 (2020)138224. https://doi.org/10.1016/j.scitotenv.2020.138224.
[24] L. Meng, K. Jin, R. Yi, M. Chen, J. Peng, Y. Pan, Enhancement of bioenergy recovery from agricultural wastes through recycling of cellulosic alcoholic fermentation vinasse for anaerobic co-digestion, Bioresource Technology 311 (2020)123511. https://doi.org/10.1016/j.biortech.2020.123511.
[25] E.K., Orhorhoro, E.E. Lindsay, J.O. Oyejide, Analysis and Evaluation of a Three-Stage Anaerobic Digestion Plant for Management of Biodegradable Municipal Solid Waste, International Journal of Engineering Research in Africa 60 (2022) 75-87. https://doi:10.4028/p-a24obb.
[26] C.B. Arenas, W. Meredith, C.E. Snape, X. Gómez, J.F. González, JE.J. Martínez. Effect of char addition on anaerobic digestion of animal by-products: Evaluating biogas production and process performance, Environmental Science and Pollution Research 27 (2020) 24387–24399. https://doi.org/10.1007/s11356-020-08828-8.
[27] D.C. Tápparo, A. Viancelli, A.C. do Amaral, G. Fongaro, R.L.R. Steinmetz, M.E. Magri, C.R. Monte-Barardi, A. Kunz. Sanitary effectiveness and biogas yield by anaerobic co-digestion of swine carcasses and manure, Environmental Technology 41 (2020) 682–690. https://doi.org/10.1080/09593330.2018.1508256.
[28] J. Xu, H. Lin, K. Sheng. Effects of hydrothermal pretreatment and hydrochar addition on the performance of pig carcass anaerobic digestion, Frontiers Microbiology 12 (2021) 62235. https://doi.org/10.3389/fmicb.2021.622235.

[29] J. Procházka, P. Dolejš, J. Máca, M. Dohányos, Stability and inhibition of anaerobic processes caused by insufficiency or excess of ammonia nitrogen, Applied Microbiology and Biotechnology 93 (2012) 439–447. https://doi.org/10.1007/s00253-011-3625-4.
[30] R.E. Hernández-Regalado, J. Häner, D. Baumkötter, L. Wettwer, E. Brügging, J. Tränckner, Continuous co-digestion of agro-industrial mixtures in laboratory scale expanded granular sludge bed reactors, Applied Sciences 12 (2022) 2295. https://doi.org/10.3390/app12052295.
[31] Y. Zhao, N. Bourgougnon, J.L. Lanoisellé, T. Lendormi, Biofuel production from seaweeds: A comprehensive review, Energies 15 (2022) 9395. https://doi.org/10.3390/en15249395.
[32] K.A. Fakoya, F.G. Owodeinde, S.L. Akintola, M.A. Adewolu, M.A. Abass, P.E.N. Ndimele, An exposition on potential seaweed resources for exploitation, culture and utilization in West Africa: a case study of Nigeria, Journal of Fisheries and Aquatic Science 6 (2011)37–47. https://doi.org/10.3923/jfas.2011.37.47.
[33] B.B. Solarin, D.A. Bolaji, O.S. Fakayode, R.O. Akinnigbagbe, Impacts of an invasive seaweed Sargassum hystrix var. fluitans (Børgesen 1914) on the fisheries and other economic implications for the Nigerian coastal waters, IOSR Journal of Agriculture and Veterinary Science 7 (2014) 01–06.
[34] J.L. Pelegrin, and J. Pena-Izquierdo, Eastern boundary currents off North-West Africa. In: Valdes L, Deniz - Gonzalez I (eds) Oceanographic and biological features in the Canary Current Large Marine Ecosystem. IOCUNESCO, Paris, IOC Technical Series 115 (2015) 81–92.
[35] V. Hormann, R. Lumpkin, G.R. Foltz. Interannual North Equatorial Countercurrent variability and its relation to tropical Atlantic climate modes, Journal of Geophysical Research: Oceans 117 (2012) 1–17. https://doi.org/10.1029/2011JC007697.
[36] E. Aparicio, R.M. Rodríguez-Jasso, A. Lara, A. Loredo-Treviño, C.N. Aguilar, E.T. Kostas, H.A. Ruiz, Chapter 15—Biofuels production of third generation biorefinery from macroalgal biomass in the mexican context: An overview. In Sustainable Seaweed Technologies; Torres, M.D., Kraan, S., Dominguez, H., Eds.; Advances in Green and Sustainable Chemistry; Elsevier: Amsterdam, The Netherlands. (2020) 393–446. ISBN 978-0-12-817943-7.
[37] H. Chen, Seaweeds for biofuels production progress and perspectives, Renew. Renewable and Sustainable Energy Reviews 11 (2015) 427–437. https://doi.org/10.1016/j.rser.2015.03.086.
[38] N. Bourgougnon, A. Gervois, Les Algues Marines: Biologie, Écologie et Utilisation; Ellipses: Paris, France, 2021, ISBN 978-2-340-05654-1
[39] S. Kumar, D. Sahoo, I. Levine, Assessment of nutritional value in a brown seaweed sargassum wightii and their seasonal variations, Algal Research 9 (2015) 117–125. https://doi.org/10.1016/j.algal.2015.02.024.
[40] G. Jard, H. Marfaing, H. Carrère, J.P. Delgenes, J.P. Steyer, C. Dumas, French brittany seaweeds screening: Composition and methane potential for potential alternative sources of energy and products, Bioresour. Technol. 144 (2013) 492–498. https://doi.org/10.1016/j.biortech.2013.06.114.
[41] A.I. Usov, G.P. Smirnova, N.G. Klochkova, Polysaccharides of Algae: 55. Polysaccharide Composition of Several Brown Algae from Kamchatka, Russian Journal of Bioorganic Chemistry 27 (2001) 395–399. https://doi.org/10.1023/A:1012992820204.
[42] B.S. Padam, F.Y. Chye, Chapter 2—Seaweed Components, Properties, and Applications. In Sustainable Seaweed Technologies; Torres, M.D., Kraan, S., Dominguez, H., Eds.; Advances in Green and Sustainable Chemistry; Elsevier: Amsterdam, The Netherlands, (2020) 33–87. ISBN 978-0-12-817943-7.
[43] F. Monlau, C. Sambusiti, A. Barakat, M. Quéméneur, E. Trably, J.P. Steyer, H. Carrère, Do furanic and phenolic compounds of lignocellulosic and algae biomass hydrolyzate inhibit anaerobic mixed cultures? A comprehensive review, Biotechnology Advances 32 (2014) 934–951. https://doi.org/10.1016/j.biotechadv.2014.04.007.
[44] B.S. Padam, F.Y. Chye, Chapter 2—Seaweed Components, Properties, and Applications. In Sustainable Seaweed Technologies; Torres, M.D., Kraan, S., Dominguez, H., Eds.; Advances in Green and Sustainable Chemistry; Elsevier: Amsterdam, The Netherlands. (2020) 33–87. ISBN 978-0-12-817943-7
[45] A. Jensen, Present and future needs for algae and algal products, Hydrobiologia 260 (1993) 15–23. https://doi.org/10.1007/BF00048998.
[46] Y.N. Barbot, H. Al-Ghaili, R. Benz, A review on the valorization of macroalgal wastes for biomethane production, Marine Drugs 14 (2016) 120. https://doi.org/10.3390/md14060120.
[47] J. Singh, S. Gu, Commercialization potential of microalgae for biofuels production, Renewable and Sustainable Energy Reviews 14 (2010) 2596–2610. https://doi.org/10.1016/j.rser.2010.06.014.
[48] K.T. Bird, D.P. Chynoweth, D.E. Jerger, Effects of marine algal proximate composition on methane yields, Journal of Applied Phycology 2 (1990) 207–213. https://doi.org/10.1007/BF02179777.
[49] O.O. Osita, U.G. Lawan, The optimum mesophilic temperature of batch process biogas production from animal-based wastes, Research Journal of Applied Sciences, Engineering and Technology 8(16) (2014) 1772-1776. http://dx.doi.org/10.19026/rjaset.8.1163.

[50] M.A. Rahman, R. Shahazi, S.N.B. Nova, M.R. Uddin, M.S. Hossain, A. Yousuf. Biogas production from anaerobic co-digestion using kitchen waste and poultry manure as substrate—part 1: Substrate ratio and effect of temperature, Biomass Conversion and Biorefinery 13 (2021) 1-11. https://doi.org/10.1007/s13399-021-01604-9.

[51] P.O. Ebunilo, E.K. Orhorhoro, V. Oboh, P.U. Onochie. Effect of temperature on biogas yields using south-south nigeria as a case study, International Journal of Technology Enhancements and Emerging Engineering Research 4(6) (2016) 50-54.

[52] H.K. Ahn, M.C. Smith, S.L. Kondrad, J.W. White. Evaluation of biogas production potential by dry anaerobic digestion of switchgrass–animal manure mixtures, Applied Biochemistry and Biotechnology 160 (2010) 965–975. https://doi.org/10.1007/s12010-009-8624-x.

[53] F. Wang, M. Pei, L. Qiu, Y. Yao, C. Zhang, H. Qiang. Performance of anaerobic digestion of chicken manure under gradually elevated organic loading rates, International Journal of Environmental Research and Public Health 16(2019) 2239. https://doi.org/10.3390/ijerph16122239.

[54] P. Mahato, B. Goyette, M. Rahaman, R. Rajagopal. Processing high-solid and high-ammonia rich manures in a two-stage (liquid-solid) low-temperature anaerobic digestion process: start-up and operating strategies, Bioengineering 7 (2020) 80. https://doi.org/10.3390/bioengineering7030080.

[55] Z. Ning, J. Ji, Y. He, Y. Huang, G. Liu, C. Chen. Effect of lipase hydrolysis on biomethane production from swine slaughterhouse waste in China, Energy Fuels 30(2016) 7326–7330. https://doi.org/10.1021/acs.energyfuels.6b01097.