



Anaerobic Co-Digestion of Palm Oil Effluent and Food Waste

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Abstract: The yearly expansion of oil palm plantations in Nigeria is accompanied by an increase in the number of palm oil mills that produce crude palm oil (CPO) from fresh fruit bunches (FFB). In Okada alone, there are several palm oil mills, and Igbinedion University just acquired a palm oil farm that is currently undergoing development. The production process in a palm oil mill consists of sterilization, stripping, clarification, and palm kernel oil recovery. This generates solid waste and liquid waste. The liquid waste (i.e., palm oil effluent), when discharged directly into the environment without proper treatment, can pollute the environment, emitting greenhouse gases (GHG) that cause global warming. In this study, palm oil mill effluent and food waste were evaluated for biogas production under. Food waste and palm oil effluent from Okada town were co-digested in a fixed dome anaerobic digester at a mesophilic temperature range. The highest cumulative biogas yield was achieved from the co-digestion of palm oil effluent and food waste. Besides, the digestates obtained at the end of the complete hydraulic retention time were odourless, which is an indication of thorough treatment of the palm oil effluent. More so, such digestates can serve as organic manure for Okada palm oil farms.

Keywords: Palm oil effluent, Food waste, co-digestion, biogas yield, mesophilic temperature

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1.0 Introduction

Palm oil is one of the vital commercial crops for edible oil production. Palm oil mill effluent (POME) is the wastewater characterized by thick yellowish liquid and high organic contents, having chemical oxygen demand (COD) and biochemical oxygen demand (BOD) respectively [1, 2]. These are major concerns in environmental pollution due to their adverse effects on many forms of life. The direct discharge of POME into the environment is a matter of concern for both

toxicological and aesthetic reasons. The majority of the palm oil mills use the addition of water during the extraction process of crude palm oil (CPO) from the fresh fruit bunch (FFB) [3]. As a result, a considerable amount of wastewater will be generated and disposed of in ponds, drainage systems, streams, and rivers [4–8]. However, POME is suitable for generating electricity through biogas. POME has a low pH (pH 3.4–5.2) because it contains many organic acids produced by the initial fermentation process. It has a high concentration of total solids (40,500 mg/l) and a high concentration of suspended solids (18,000–46,011 mg/l). The concentration of oil and grease ranges from 4,000–9,341 mg/l, depending on milling processes [9–12]. The characteristics of POME depend on the quality of the raw material (fresh palm-oil fruit bunches) and the efficiency of palm oil extraction processes [13]. POME has become a commodity rather than undesirable wastewater, providing energy cost savings and additional income for the palm oil mills (POMs).

The main reasons for its suitability for anaerobic digestion are its high organic content, which is relatively easily digestible, and its low toxicity to the working microorganisms. POME supply is dependable both in terms of quality and quantity. POME composition also falls into the optimal range of C/N ratios (20–30) [14–16].

Municipal solid wastes (MSW) are generated and dumped indiscriminately in Nigeria due to poor implementation of standards, thus causing environmental and public health hazards [17–20]. Food waste (FW) that is a component of MSW is defined as consumable food for humans that is thrown, decayed, deteriorated, or infested by pests that originate at any stage [21]. Food waste (FW) is inevitably generated throughout the whole food supply chain (FSC), from production to packaging, processing to distribution, and finally through consumption [22]. The disposal of FW poses an environmental issue due to the emission of methane gas and hence must be handled properly. As it is a suitable feedstock for AD, waste can be transformed into energy via a sustainable method. In this study, anaerobic

digestion (AD) of FW is being investigated as a more sustainable method involving waste to energy (WTE) technology. The AD process is a technology that recovers energy and nutrients from organic waste streams in usable forms in the absence of oxygen [23, 24]. It is a sustainable, renewable, and zero-carbon form of energy supply. The anaerobic digestion process can be used to recover some of this energy in the form of biogas, typically a mixture of flammable gases with a composition of 40–70% CH₄, 20–60% CO₂, and 5–10% of other gases, which include siloxane [25–28]. The ratio of CH₄ to CO₂ is normally stable in the reactor; any variation in the ratio is due to a process imbalance. The quality of biogas generated by organic waste materials does not remain constant but varies with the period of digestion [29–31]. In the absence of the process, there is an uncontrolled release of methane to the atmosphere due to the biodegradation of organic matter at open waste dump sites. Annually, natural biodegradation of organic matter is estimated to release 500–800 million tons of methane gas into the atmosphere [32]. Therefore, this study is focused on the anaerobic co-digestion of palm oil effluent and food waste

2.0 Materials and Methods

2.1 Substrates Collections

The palm oil mill effluent (POME) and food waste (FW) were collected from the palm oil processing mill and households in Okada town. The POME was stored in a tightly closed 50-liter water container. The POME and FW were analyzed for total solids, volatile solids, carbon/nitrogen (C/N) ratio, chemical oxygen demand (COD), and pH.

2.2 Preparation of Substrates

The stored POME in 50-liter containers and food waste were taken out of the cool room. The substrate was thawed until its temperature increased to room temperature. Pre-treatments were carried out on the food waste. This includes mechanical and thermal pre-treatment. The mechanical treatment involves reducing the size of the food waste. The food waste was passed through a grinder. Reduction in particle size increases the solubilisation of organic material [33]. The surface area exposed to contact with microorganisms also increases. Thus, the degradability of organic material increases, enhancing methane generation. Thermal pre-treatment such as sterilization was also conducted on the FW prior to anaerobic co-digestion [34]. The thermal pre-treatment before AD causes the breakdown of complex molecules such as polysaccharides and proteins into smaller molecules and releases the organic content into the liquid phase. Sterilization is carried out at 121°C [35] and a portion of the stored POME was measured using a measuring cylinder. After being measured (30 liters), the ground FW (20 kg) was poured into a bucket to be mixed with POME. The mixture was continuously stirred in the bucket for proper mixing. After that, the mixture was charged into a fixed-dome anaerobic digester.

Experimental Setup

An anaerobic co-digestion bioreactor was used to co-digest the POME and FW. The bioreactor is a 100-liter fixed-dome anaerobic digester. The experiment was conducted at a

mesophilic temperature range of 36°C–38°C. A 10.55 mm external diameter, a 10 mm internal diameter, a pressure gauge, a thermometer, and a 0.25 inch internal diameter valve of U-tube were connected to the fixed dome digester. Pressure testing was carried out on the digester, and this was mainly to look out for possible leakages. A plastic gas bag was used for biogas collection. Prior to charging the digesters with the substrates, the U-tube was charged with tap water at a marked level. Nitrogen gas was purged through to expel oxygen from the digester and make it airtight in order to ensure anaerobic conditions in the headspace of anaerobic digesters [36]. The prepared mixture was charged into the digester and allowed for anaerobic co-digestion to take place for a complete hydraulic retention time. The digesters were then attached to a biogas bag for gas collection. The gas generated was measured daily using the water displacement method by reading the volume of water displaced in the U-tube, which is equal to the volume of gas generated. The total solids (TS), volatile solids (VS), pH, C/N ratio and COD were determined using standard method [37].

3.0

Results and Discussion

3.1

Results of Characteristics of Substrates

Table 1 shows the results of the characterization of the substrates used in anaerobic co-digestion. It shows the changes in pH, COD, TS, VS, and C/N ratio at the start, after 10 days, and at the completion of the hydraulic retention time (46 days). The pH of the collected POME substrate was acidic (weak acidic, 5.30), and the pH of the collected FW substrate was alkaline (weak alkaline, 8.76). However, their mixture was tending toward neutrality (7.04 m) at day 10 of co-digestion, and this neutrality was maintained to the end of the hydraulic retention time (HRT). The neutral pH obtained is an indication of a stable anaerobic co-digestion process [38–39]. Thus, methanogenesis bacteria that will enhance optimum biogas production are in favor, and this has consequently resulted in a continuous increase in cumulative biogas yield, as shown in Table 2.

Furthermore, the COD of the POME substrates was determined at 4.50 g at the starts, while the COD for FW was obtained at 1.23 g. The COD of the mixture of the combined POME and COD was obtained at 4.15g, and after 10 days and 46 days of co-digested COD, it was recorded at 3.05 g and 1.55 g, respectively. There was a decrease in the COD of the co-digested substrates throughout the process, and this was an indication of COD removal. The removal of COD brought about an increase in biogas yields. According to El-Mashad and Zhang [40], biogas production increases with an increase in COD removal, which can be well explained by the fact that the methanogenic consortium acclimated very well, which consequently led to the co-digestion of the substrates under anaerobic conditions. Also, to confirm if the experiment was conducted at mesophilic slurry temperature, the temperature of the digester was monitored daily, as shown in Figure 2. It was observed that the experiment was actually conducted at an optimum mesophilic temperature range. According to Ebunilo *et al.* [41], temperature is considered one of the most important variables for process stability, as anaerobic bacteria populations can only survive in certain temperature ranges. Besides, sudden changes and

fluctuations in the process temperature lead to inhibition of bacteria populations. Thus, the digestion and co-digestion of substrates in a biogas digester should be run at a stable mesophilic

temperature range of 35°C–38°C that can bring about optimum biogas production.

Table 1 Characteristics of the prepared substrates used in anaerobic co-digestion

S/N	Parameters	POME Substrates	FW Substrates	Mixed POME and FW Substrates	Co-Digested POME and FW Slurry	
					After 10 Days	After 46 Days
1	pH (m)	5.30	8.76	7.65	7.04	7.00
2	COD (g)	4.50	1.23	4.15	3.05	1.55
3	TS (%)	4.78	10.12	9.75	ND	ND
4	VS (%)	3.36	86.75	87.45	ND	ND
5	C/N ratio	22.85	28.94	23.45	ND	ND

*ND—Not Determined

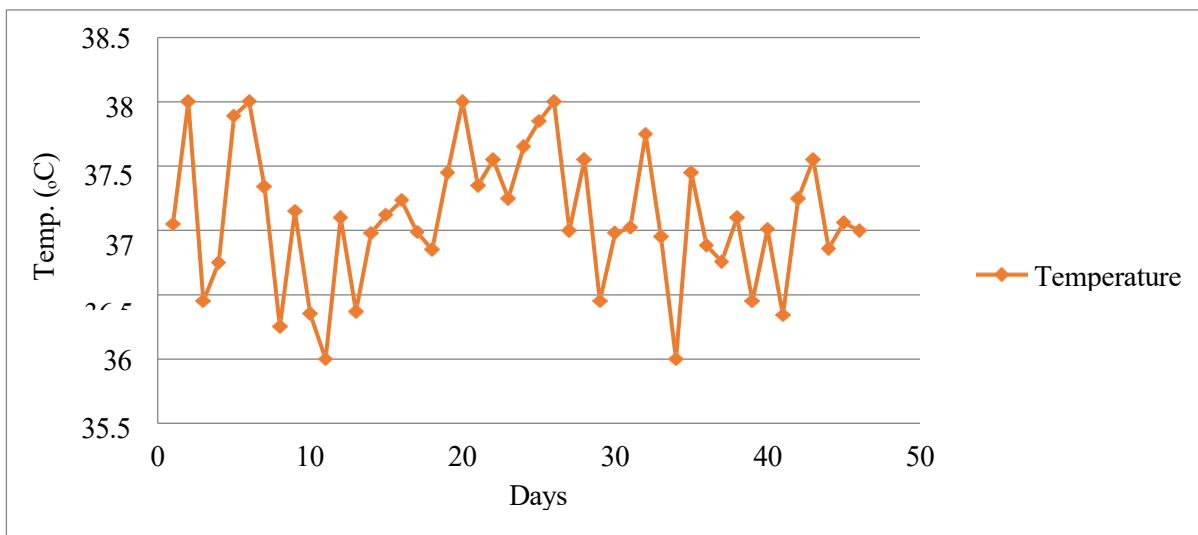


Figure 1 Evaluation of the effect of mesophilic temperature

3.2 Results of Cumulative Biogas Yield

The result of the cumulative biogas yield is shown in Table 2 and Figure 2. There was a continuous increase in biogas yield until the end of HRT. Thus, an alternative method of improving biogas yields from the AD process is co-digestion. Co-digestion leads to stabilization and improved nutrient utilization for a variety of substrate compositions [42]. Co-digestion of different

substrates leads to improved biogas yield because of positive synergisms that establish the digestion medium and supply missing nutrients [43]. Apart from the advantages derived from easier handling of mixed wastes, it can help establish the required moisture contents of the substrates [44, 45].

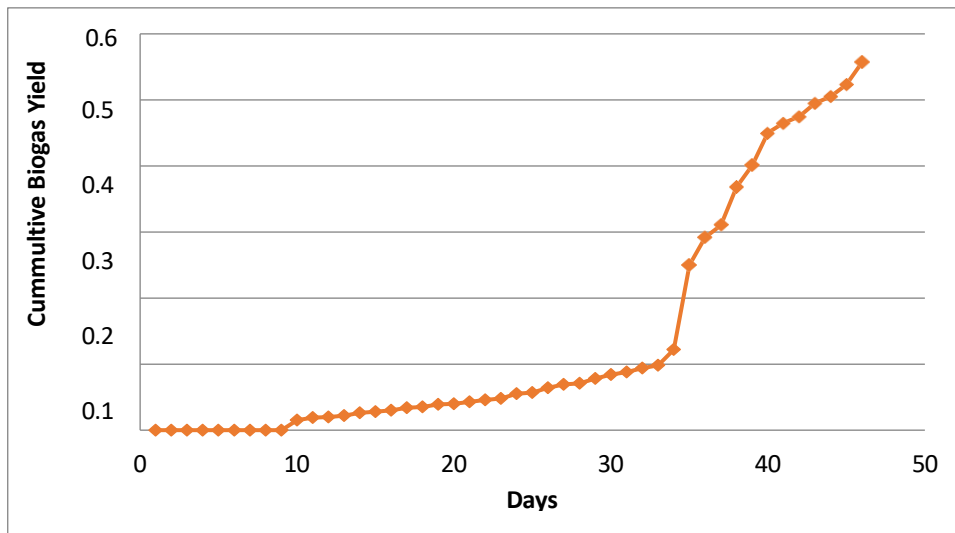


Figure 2 Evaluation of cumulative biogas yield

Tale 2 Result of cumulative Biogas Yield

Day	Temp (°C)	Remark	Cumulative Biogas Yield (m³)
1	37.05	No gas	0.00
2	38.00	No gas	0.00
3	36.45	No gas	0.00
4	36.75	No gas	0.00
5	37.89	No gas	0.00
6	38.00	No gas	0.00
7	37.34	No gas	0.00
8	36.25	No gas	0.00
9	37.15	No gas	0.00
10	36.35	Yellow flame	0.015
11	36.00	Blue flame	0.019
12	37.10	Blue flame	0.020
13	36.37	Blue flame	0.022
14	36.98	Blue flame	0.026
15	37.12	Blue flame	0.028
16	37.23	Blue flame	0.030
17	36.99	Blue flame	0.034
18	36.85	Blue flame	0.035
19	37.45	Blue flame	0.039
20	38.00	Blue flame	0.040
21	37.35	Blue flame	0.043
22	37.55	Blue flame	0.046
23	37.25	Blue flame	0.048
24	37.65	Blue flame	0.055
25	37.85	Blue flame	0.057
26	38.00	Blue flame	0.064

27	37.00	Blue flame	0.069
28	37.55	Blue flame	0.071
29	36.45	Blue flame	0.078
30	36.98	Blue flame	0.084
31	37.02	Blue flame	0.088
32	37.75	Blue flame	0.094
33	36.95	Blue flame	0.098
34	36.00	Blue flame	0.122
35	37.45	Blue flame	0.250
36	36.88	Blue flame	0.292
37	36.76	Blue flame	0.310
38	37.10	Blue flame	0.368
39	36.45	Blue flame	0.401
40	37.01	Blue flame	0.450
41	36.34	Blue flame	0.465
42	37.25	Blue flame	0.475
43	37.55	Blue flame	0.495
44	36.86	Blue flame	0.505
45	37.06	Blue flame	0.523
46	37.00	Blue flame	0.557

4.0 Conclusion

The anaerobic co-digestion of palm oil mill effluent with food waste effectively improves the biogas production of There was a continuous increase in biogas production after the tenth day of recorded biogas yield, and the cumulative biogas yield was obtained at 0.557 m³ at the end of the hydraulic retention time. The mesophilic temperature of the fixed dome digester was stable throughout the process, and an optimum mesophilic temperature range was recorded. The study shows that POME and food waste can be converted into useful energy rather than the direct discharge of POME and indiscriminate dumping of food waste in the environment, as is currently practiced by POME industries and households in Okada town.

References

- [1] Najafpour, G., Yieng, H.A., Younesi, H., & Zinatizadeh, A. (2005). Effect of organic loading on performance of rotating biological contactors using palm oil mill effluents. *Process Biochem.*, 40: 2879-84
- [2] Suksong, W., Kongjan, P., Prasertsan, P., Imai, T., & O-thong, S. (2016). Optimization and microbial community analysis for production of biogas from solid waste residues of palm oil mill industry by solid- state anaerobic digestion. *Bioresour Technol.*, 214:166-74.
- [3] O-Thong, S., Boe, K., & Angelidaki, I. (2012). Thermophilic anaerobic co-digestion of oil palm empty fruit bunches with palm oil mill effluent for efficient biogas production. *Appl Energy*, 93:648-54.
- [4] Orhorhor, E. K., Ebunilo, P. O. B., and Sadjere, E. G., (2017). Determination and Quantification of Household Solid Waste Generation for Planning Suitable Sustainable Waste Management in Nigeria. *International Journal of Emerging Engineering Research and Technology*, 5(8): 1-9
- [5] Sosnowski, P., Wiecezorek, A., Ledakowicz, S. (2003). Anaerobic co-digestion of sewage sludge and organic fraction of municipal solid wastes. *Adv. Environ Res.*, 7:609–16
- [6] Edelmann, W., Engeli, H., Gradenecker, M.(2000). Co-digestion of organic solid waste and sludge from sewage treatment. *Water Sci Technol.*, 41:213–21.
- [7] Ejiroghene Kelly Orhorhoro, Emmanuel E. Lindsay, Joel O. Oyejide (2022). 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: 75-87. doi:10.4028/p-a24obb
- [8] Luostarinen, S., Luste, S., & Sillanpää, M. (2009). Increased biogas production at wastewater treatment plants through co-digestion of sewage sludge with grease trap sludge from a meat processing plant. *Bioresour Technol.*, 100:79-85.
- [9] Chin, M.J., Poh, P.E., Tey, B.T., Chan, E.S., & Chin, K.L. (2013). Biogas from palm oil mill effluent (POME): opportunities and challenges from Malaysia's perspective. *Renew. Sustain. Energy Rev.*, 26: 717– 726
- [10] Loh, S.K., Lai, M.E., Ngatiman, M., Lim, W.S., Choo, Y.M., Zhang, Z., & Salimon, J. (2013). Zero discharge treatment technology of palm oil mill effluent. *J. Oil Palm Res.*, 25: 273–281.
- [11] Wu, T.Y., Mohammad, A.W., Jahim, J.Md., & Anuar, N. (2010). Pollution control technologies for the treatment of palm oil mill effluent (POME) through end-of-pipe

- processes, *J. Environ. Manag.*, 91: 1467– 1490
- [12] Wang, J., Mahmood, Q., Qiu, J.P., Li, Y.S. Chang, L.N., Chi, L.N., & Li, X.D. (2015). Zero discharge performance of an industrial pilot-scale plant treating palm oil mill effluent. *BioMed Res. Int.*,: 1–9.
- [13] Rupani, F.P., Singh, R.P., Ibrahim, M.H., & Esam, N. (2010). Review of current palm oil mill effluent (POME) treatment methods: vermicomposting as a sustainable practice. *World Appl. Sci. J.*, 11: 70–81.
- [14] Wang, X., Yang, G., Feng, H., Ren, G., & Han, X. (2012). Optimizing feeding composition and carbon– nitrogen ratios for improved methane yield during anaerobic co-digestion of dairy, chicken manure and wheat straw, *Bioresour. Technol.*, 120: 78–83.
- [15] Habiba, L., Hassib, B., & Moktar, H. (2009). Improvement of activated sludge stabilisation and filterability during anaerobic digestion by fruit and vegetable waste addition. *Bioresour. Technol.*, 100: 1555–1560.
- [16] Kayhanian, M. (1999). Ammonia inhibition in high-solids biogasification: an overview and practical solutions. *Environ. Technol.*, 20: 355–365.
- [17] Orhorhor, E.K., Ebunilo, P.O.B., and Sadjere, E.G. (2017). Determination and Quantification of Household Solid Waste Generation for Planning Suitable Sustainable Waste Management in Nigeria. *International Journal of Emerging Engineering Research and Technology*, 5(8): 1-9
- [18] Owamah, I.H., Izinyon, O.C., Igbinewekan, P. (2015). Characteristics and quantification of solid waste generation in the Niger Delta Region of Nigeria: a case study of Ogbe-Ijoi community in Delta State. *Journal of Material Cycles and Waste Management*, 19(1): 366-373
- [19] Igbinomwanhia, D.I., Obonor, A.I., Olisa, Y.P. (2017). Characterisation of Domestic Solid Waste for the Determination of Waste Management Option in Amassoma, Bayelsa State, Nigeria”. *J. Appl. Sci. Environ. Manage*, 18(2): 211-215
- [20] Igoni, A.H., Ayotamuno, M.J., Eze, C.L., Ogaji, S.O.T., and Probert, S.D. (2008). Designs of anaerobic of digesters for producing biogas from municipal solid-waste. *Appl. Energ.*, 85: 430-438
- [21] Food and Agriculture Organisation. E-conference: Utilization of Food Loss and Waste as Well as Non-Food Parts as Livestock Feed’|FAO. 2015. Available online: <http://www.fao.org/save-food/news-and-multimedia/events/detail-events/en/c/325893/>
- [22] Zin, N.M., Saim, M., Suhaimi, A.H.M.S. (2018). Household food wastage prevention in Malaysia: An Issue Processes Model perspective. *Econ. Technol. Manag. Rev.*, 13, 51–62
- [23] Gaida, D., Wolf, C., Meyer, A., Stuhlsatz, J., Lippel, T., Bäck, T., Bongards, M. and McLoone, S. (2012). State estimation for anaerobic digesters using the ADM1. *Water Science and Technology*, 66 (5), 1088
- [24] Ge, X., Matsumoto, T., Keith, L., and Li, Y. (2014). Biogas energy production from tropical biomass wastes by anaerobic digestion. *Bioresource Technology*, 169: 38–44
- [25] Franco, C., Gianluca, C., Alessandro, P., Valentina, C. (2015). Lignocellulosic biomass feeding in biogas pathway: state of the art and plant layouts. *Energy Procedia (Science Direct)*, 81: 1231 – 1237
- [26] Ray, N. H. S., Mohanty, M. K., and Mohanty, R. C. (2013). Anaerobic digestion of kitchen waste: Biogas production and pretreatment waste, a review. *International Journal of Scientific and Research Publication*, 3: 11-18
- [27] Orhorhor E.K., Orhorhor, O.W., Atumah, E.V. (2018): “Performance Evaluation of Design AD System Biogas Purification Filter. *International Journal of Mathematical, Engineering and Management Sciences*, 3(1): 17–27
- [28] Ebunilo, P.O., Orhorhor, E.K., Adegbayi, O.A. (2016). Investigation of the purification of biogas from domestic wastes using local materials in Nigeria. *International Journal of Scientific & Engineering Research*, 7(2): 505-515
- [29] Ejiroghene Kelly Orhorhor, Emmanuel E. Lindsay, Joel O. Oyejide (2022). 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: 75-87. doi:10.4028/p-a24obb
- [30] Qiao, W., Yan, X., Ye, J., Sun, Y., Wang, W., and Zhang, Z. (2011). Evaluation of biogas production from different biomass wastes with/without hydrothermal pretreatment. *Renewable Energy*, 36: 3313-3318
- [31] Orhorhor E.K., Ebunilo, P.B., Sadjere E.G. (2017). 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: 147-155. Doi:10.4028/www.scientific.net/JERA.39.147.
- [32] Esposito, G, Frunzo L, Liotta, F, Panico, A. and Pirozzi, F. (2012). BMP tests to measure the biogas production from the digestion and co-digestion of Complex organic substrates. *Open Journal of Environmental Engineering*, 5: 1–8.
- [33] Krishna, D., Kalamdhad, A.S. (2014). Pre-treatment and anaerobic digestion of food waste for high rate methane production—A review. *J.Environ. Chem. Eng.*, 2, 1821–1830
- [34] Ariunbaatar, J., Panico, A., Esposito, G., Pirozzi, F., Lens, P.N.L. (2014). Pretreatment methods to enhance anaerobic digestion of organic solid waste. *Appl. Energy*, 123: 143–156
- [35] Lee, B., Park, J.G., Shin, W.B., Kim, B.S., Byun, B., Jun, H.B. (2019). Maximizing biogas production by pretreatment and by optimizing the mixture ratio of co-digestion with organic wastes. *Environ. Eng. Res.*, 24: 662–669
- [36] Hassan, M.A., Yacob, S. and Shirai, Y. (2004). Treatment of palm oil wastewaters. In: Wang, L.K., Hung, Y., Lo, H.H. and Yapijakis, C., editors. *Handbook of industrial and hazardous wastes treatment*. New York. Marcel Dekker, Inc. 719– 36.
- [37] Raposo, F., Fernández-Cegri, V., De la Rubia, M.A., Borja, R., Béline, F., Cavinato, C., Ganesh, R. (2011). Biochemical methane potential (BMP) of solid organic

- substrates: evaluation of anaerobic biodegradability using data from an international interlaboratory study. *J. Chem. Technol. Biotechnol.*, 86:1088-98
- [38] Orhorhor, E.K., Ebunilo, P.O., and Ikpe, A.E., (2016). Effect of pH on Anaerobic Digestion (AD) of Organic Municipal Solid Waste in Benin City, Nigeria. *Journal of the Nigerian Association of Mathematical Physics*, 36(01): 369-374
- [39] Paramagurua, G., Kannanb, M., Lawrence, P. (2017). Effect of pH on Biogas Production through Anaerobic Digestion of Food Waste. *Journal of Advanced Engineering Research*, 4(1): 59-62
- [40] El-Mashad, H.M., and Zhang, R. (2010). Biogas production from Co-digestion of dairy manure and food waste. *Bioresource Technology*, 101: 4021-4028
- [41] Ebunilo, P.O., Orhorhor, E. K., Oboh, V., Onochie, P. U (2016). Effect of Temperature on Biogas Yields Using South-South Nigeria as a Case Study. *International Journal of Technology Enhancements and Emerging Engineering Research*, 4(3): 50-54
- [42] Zhou, Q., Shen, F., Yuan, H., Zou, D., Liu, Y., Zhu, B., and Li, X. (2014). Minimizing asynchronism to improve the performances of anaerobic co-digestion of food waste and corn stover. *Bioresource Technology*, 166: 31–36. <http://dx.doi.org/10.1016/j.biortech.2014.04.074>
- [43] Zhou, P., Elbeshbishy, E., and Nakhla, G. (2013). Optimization of biological hydrogen production for anaerobic co-digestion of food waste and wastewater biosolids. *Bioresource Technology*, 130, 710–718
- [44] Zhang, Y., Banks, C. and Heaven, S. (2012). Co-digestion of source segregated domestic food waste to improve process stability. *Bio-resource technology*, 114: 168-178
- [45] Mahanty, B., Zafar, M. and Park, H.S. (2013). Characterization of Co-digestion of industrial sludges for biogas production by artificial neural network and statistical regression models. *Environ Technol.*, 34: 2145–2153