

# World News of Natural Sciences

An International Scientific Journal

WNOFNS 65 (2026) 217-227

EISSN 2543-5426

---

## Enhancing biogas yield and compositions from solid waste using leaves of different plants as phytocatalysts

**Oluwole Olakunle Oladele\*, Aina Victoria Jagun and Blessing Ngozi Nome**

Storage Microbiology Laboratory, Department of Biology, School of Life Sciences,  
Federal University of Technology, PMB 704, Akure, Ondo State, Nigeria

\*E-mail address: prophetoladele2014@gmail.com

### ABSTRACT

Biogas offers eco-friendly approach for waste management. Herein, enhancing biogas production from cow dung using leaves of different plants: turmeric, neem and papaya was investigated under anaerobic conditions over 30 days retention time with daily measurements of biogas yield (kg) and compositional analysis using gas chromatographic thermal conductivity Detector (GC-TCD) in the different bioreactors set up designated as cow dung with turmeric powder (CDTP), cow dung with neem powder (CDNP), cow dung with papaya powder (CDPP) and cow dung without any powder served as control (CTRL). As digestion ended by day 30, CDNP had the highest biogas yield ( $0.63 \pm 0.03$ ), followed by CDPP ( $0.29 \pm 0.09$ ), then CDTP ( $0.25 \pm 0.06$ ) while CTRL had the least yield ( $0.17 \pm 0.03$ ) and the various yields obtained were significantly different ( $p < 0.05$ ) from one another. Similarly, CDNP still showed the highest CH<sub>4</sub> concentration (77.256%), followed by CDPP (74.416%) and CDTP (70.792%) while CTRL had the lowest (64.964%). However, CO<sub>2</sub> compositions were inversely proportional to methane, with CTRL showing the highest (27.029%) and CDPP the lowest (21.490%). Trace gases (NH<sub>3</sub>, CO, H<sub>2</sub>S) were minimal but varied significantly among treatments. Thus, the leaf powders particularly neem effectively enhanced biogas yield and methane content.

**Keywords:** Biogas, yield, composition, anaerobic digestion, cow dung, GC-MS

## 1. INTRODUCTION

The surge in global population, urbanization, and industrialization has led to a significant increase in solid waste generation, posing substantial threats to environmental sustainability and public health. Agricultural wastes and animal dung make up a sizable part of municipal solid waste in many developing countries, including Nigeria. As a matter of fact, waste generation in countries like Nigeria, Kenya, and Sub-Saharan Africa far exceeds collection and disposal [1]. Much of this waste is either landfilled or dumped haphazardly, contributing to greenhouse gas emissions, groundwater pollution, and the outbreak of diseases [2]. Besides, the growing volume of waste makes continuous landfill disposal unsustainable [3]. Overcoming this menace, there has been a rising concern in eco-friendly waste management approaches, such as anaerobic digestion (AD), to generate beneficial products from organic waste, such as biogas and biofertilizers.

Organic waste contains organic compounds like carbohydrates, proteins, fats, and minerals [4]. Decomposition of these compounds yields various products like; biogas, compost, and liquid fertilizers, depending on factors like oxygen levels, temperature, pH, and microorganisms [5-7]. In fact, the anaerobic digestion process involves firstly, the breaking down of complex organic molecules into simpler compounds (hydrolysis), followed by acidogenesis conversion of these compounds into volatile fatty acids, carbon dioxide, and hydrogen (acidogenesis). The fatty acids are further decomposed into acetate and hydrogen (acetogenesis) and lastly, methanogenesis which transform acetate, hydrogen, and carbon dioxide into biogas [8, 9]. They are facilitated by synergistic of microorganisms that engage in syntrophic interactions [10]. The complex microbial community's composition is shaped by factors like substrate composition, temperature, pH, and digester design [11].

Biogas produced during anaerobic digestion is primarily composed of methane ( $\text{CH}_4$ ), carbon dioxide ( $\text{CO}_2$ ), with smaller amounts of hydrogen sulphide ( $\text{H}_2\text{S}$ ) and ammonia ( $\text{NH}_3$ ). Trace amounts of hydrogen ( $\text{H}_2$ ), nitrogen ( $\text{N}_2$ ), Carbon monoxide ( $\text{CO}$ ), saturated or halogenated carbohydrates, and oxygen ( $\text{O}_2$ ) are occasionally present in the biogas. It can be used in a gas engine to convert the energy in the gas into electricity and heat, and even for internal combustion engines. Biogas can be compressed; the same way natural gas is compressed. When it becomes bio-methane, biogas can be upgraded to natural gas standards [12, 13]

Meanwhile, cow dung is a popular substrate for biogas production due to its high organic matter content and optimal carbon-to-nitrogen ratio, which facilitates anaerobic digestion and methane generation. The diverse microbial community present in cow dung contributes to this process [14]. However, relying solely on cow dung may limit gas yield and process efficiency, making biocatalysts necessary to optimize digestion. Co-digesting cow dung with other organic materials can balance nutrient availability and enhance microbial diversity, ultimately improving biogas production. Recent studies have focused on utilizing various catalysts, including biological and phytogenic agents, to enhance biogas production efficiency [15].

Plant-derived substances with enzymatic or bioactive properties, known as phytocatalysts, are becoming increasingly promising natural additives in anaerobic digestion. These catalysts can promote microbial activity, accelerate hydrolysis, and boost biogas yield without the toxicity concern commonly associated with chemical catalysts [16, 17]. Besides, the phytocatalysts are natural, cost-effective, readily available, environmentally friendly and sustainable when compared with the commercial additives like smalllops OPS, agri flex, agri

SOS, silasil energy, etc. which helps to actually improve the digestion process but the cost and the lack of availability are major barriers to biogas operators. This study aims to assess the influence of *Curcuma longa*, *Azadirachta indica*, and *Carica papaya* as phytocatalysts on biogas production from cow dung.

## **2. MATERIALS AND METHODS**

### **2. 1. Preparation of plant powders**

Leaves of *Carica papaya*, *Azadirachta indica*, and the rhizomes of *Curcuma longa* were plucked from the parent plants, air-dried, and milled into powders.

### **2. 2. Collection of substrate**

Cow dung, used as substrate was collected freshly from the Livestock Section of the Teaching and Research Farm of the Federal University of Technology, Akure.

### **2. 3. Construction of bioreactors**

Four bioreactors were constructed using yellow gallons of 25 litres capacity according to the methods of [18]. Three of the gallons contained cow dung mixed with 50 g of each of the plant powders and designated as CDNP (cow dung mixed with neem powders); CDTP (cow dung mixed with tumeric powders), and CDPP (cow dung mixed with papaya powders) while the fourth gallon (CDTRL) served as control (cow dung without plant powders). The original opening of the gallons was used as the slurry inlet and an outlet (gas outlet) was fabricated on each of gallon's lid using a half inch pipe connected to 6.36 mm diameter gas transparent hose using the method of [19] and then connected to a tyre tube of 0.8 kg as the gas collector [20]. Each of the connections was made airtight using hose clamps.

### **2. 4. Charging of bioreactors**

The mixtures were charged into the 25 litres prototype batch bioreactor where the waste mixture was loaded once and sealed for a retention period of 30 days, allowing for anaerobic digestion to occur without further input or output. The waste was charged up to three-quarters of the bioreactor volume, leaving headspace for gas collection. The bioreactor contents were stirred adequately daily to ensure substrate homogeneity.

### **2. 5. Determination of quantity of biogas produced**

The quantity of biogas produced in kilograms was obtained by taking daily measurements of the tubes (gas collector) using a digital measuring scale (CAMMRY Model).

### **2. 6. Determination of biogas composition**

The biogas thus generated was analysed with the use of a Varian 3800/400 Gas Chromatographic Thermal Conductivity Detector (GC- TCD) with a headspace sampler having an Agilent equipped with a capillary column CP-Sil 5CB (25 meters length, 0.32 um internal diameter, 0.12um thickness and split inlet), coupled with headspace sampling vials with PTFE-lined caps, pipetting device and biogas standard solutions. The absorbed sample was lowered

into a headspace sampling vial, sealed, and transferred to the headspace sampler for analysis. All main components, including CH<sub>4</sub>, CO<sub>2</sub>, H<sub>2</sub>S, NH<sub>3</sub> and CO, were analyzed. The chromatography is electronically integrated, and the peak area is obtained for a particular biogas component. A calibration curve was made of concentration against peak area, and a response factor was obtained for each element and the results were calculated in mg/l.

## 2. 7. Statistical analysis

The biogas yields and percentage compositions of the biogas were subjected to analysis of variance (ANOVA) using SPSS, version 26.0 and where significant, means were separated by Duncan Multiple Range Test at  $p = 0.05$

## 3. RESULTS

### 3. 1. Total biogas yields from the different bioreactors

The total biogas yield (kg) from the 4 bioreactors throughout the 30-day retention time was shown in Table 1. At day 0, there was no biogas yield ( $0.00 \pm 0.00$ ) across the cow dung treated with all the different plant powders and cow dung without treatment. However, there was significant increase in the biogas yield in all the bioreactors as observed by day 15 with CDNP having the highest biogas yield ( $0.38 \pm 0.03$ ), followed by CDTP ( $0.16 \pm 0.06$ ), then CDPP ( $0.09 \pm 0.08$ ), while CTRL had the least ( $0.07 \pm 0.03$ ) and the various biogas yields in each bioreactor were significantly different ( $p < 0.05$ ) from one another. Finally, on day 30, CDNP still maintained the highest yield ( $0.63 \pm 0.03$ ), next was CDPP ( $0.29 \pm 0.09$ ), then CDTP ( $0.25 \pm 0.06$  kg) while CTRL had the least yield ( $0.17 \pm 0.02$ ). Again, the various biogas yield in each bioreactor were significantly different ( $p < 0.05$ ) from one another.

**Table 1.** Weight (kg) of biogas produced in each bioreactor over 30 days retention time.

| Retention time (days) | CDTP              | CDNP              | CDPP              | CTRL              |
|-----------------------|-------------------|-------------------|-------------------|-------------------|
| 0                     | $0.00 \pm 0.00^a$ | $0.00 \pm 0.00^a$ | $0.00 \pm 0.00^a$ | $0.00 \pm 0.00^a$ |
| 15                    | $0.16 \pm 0.06^c$ | $0.38 \pm 0.03^d$ | $0.09 \pm 0.08^b$ | $0.07 \pm 0.02^a$ |
| 30                    | $0.25 \pm 0.05^b$ | $0.63 \pm 0.03^d$ | $0.29 \pm 0.09^c$ | $0.17 \pm 0.00^a$ |

Note: Each value represents a mean of 5 replicates and where significant, the means were separated using Duncan multiple range test (DMRT) at  $p \leq 0.05$ . Values with the same alphabet across the rows are not significantly different ( $p \leq 0.05$ ).

Key:

**CDNP** - cow dung mixed with neem powders

**CDTP** - cow dung mixed with tumeric powders

**CDPP** - cow dung mixed with papaya powders

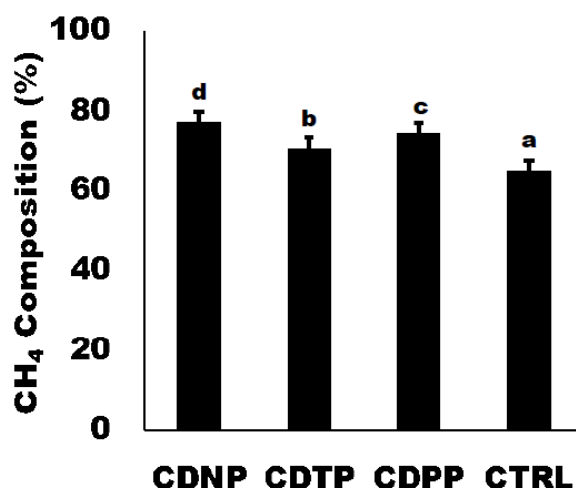
**CTRL** - control (cow dung without any powder)

### 3. 2. Percentage compositions of biogas produced

The composition of methane ( $\text{CH}_4$ ) in the total biogas produced in the different bioreactors is shown in Figure 1. Results obtained revealed that cow dung with neem powders (CDNP) had the highest composition (77.256%), followed by cow dung with papaya powders (CDPP) having 74.416%, then cow dung with tumeric powders (CDTP) recording 70.792%, while cow dung without plant powders (CTRL) had the least  $\text{CH}_4$  composition (64.964%). Notably, the various  $\text{CH}_4$  compositions in each bioreactor were significantly different ( $p < 0.05$ ) from one another. In the same vein, the composition of carbon dioxide ( $\text{CO}_2$ ) the total biogas produced in the different bioreactors is shown in Figure 2. Results however showed that CTRL had the highest composition (32.0295%), followed by CDTP (25.787%), then CDPP (21.49%), while CDNP had the least percentage (18.015). The various  $\text{CO}_2$  yield in each bioreactor were significantly different ( $p < 0.05$ ) from one another.

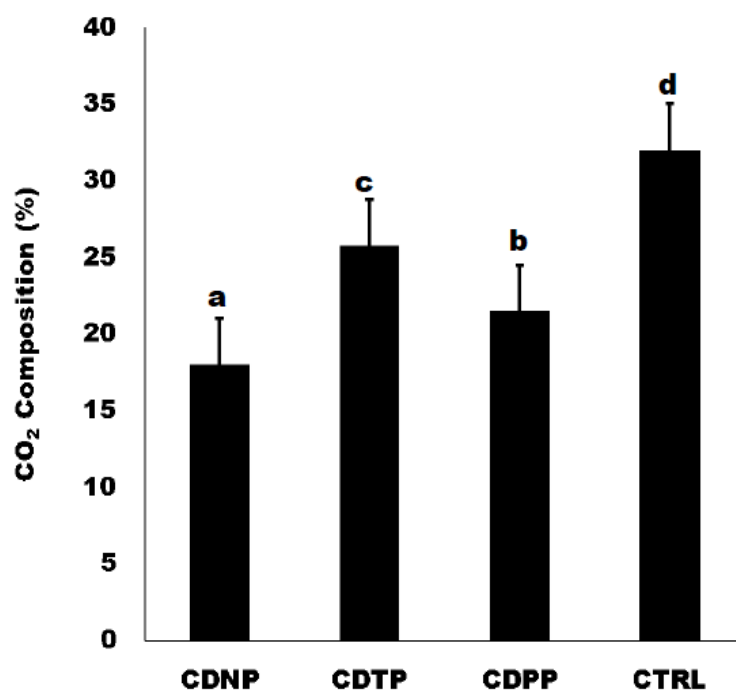
Meanwhile, the composition of CO in the total biogas produced in the different bioreactors is shown in Figure 3. Results showed that CDNP had the highest CO composition (3.263%), then CDPP (2.873%), and CDTP (2.361%), while CTRL had the least CO composition (0.368%). The various CO yield in each bioreactor were significantly different ( $p < 0.05$ ) from one another. Similarly, the composition of ammonia in the total biogas produced by the various bioreactors is presented in Figure 4. Results showed that CDNP had the highest  $\text{NH}_3$  composition (0.576%), followed by CDPP (0.508%), then CDTP (0.421%) while CTRL had the least composition (0.368%) and there was significant different ( $p < 0.05$ ) of the  $\text{NH}_3$  compositions in each bioreactor.

Lastly, the composition of hydrogen sulphide ( $\text{H}_2\text{S}$ ) in the total biogas produced by the various bioreactors is presented in Figure 5. Results showed that CDNP had the highest composition of  $\text{H}_2\text{S}$  (0.895%), then CDPP (0.782%) and CDTP (0.648%) while CTRL had the least compositions (0.566%) and the various  $\text{H}_2\text{S}$  compositions in each bioreactor were significantly different ( $p < 0.05$ ) from one another.

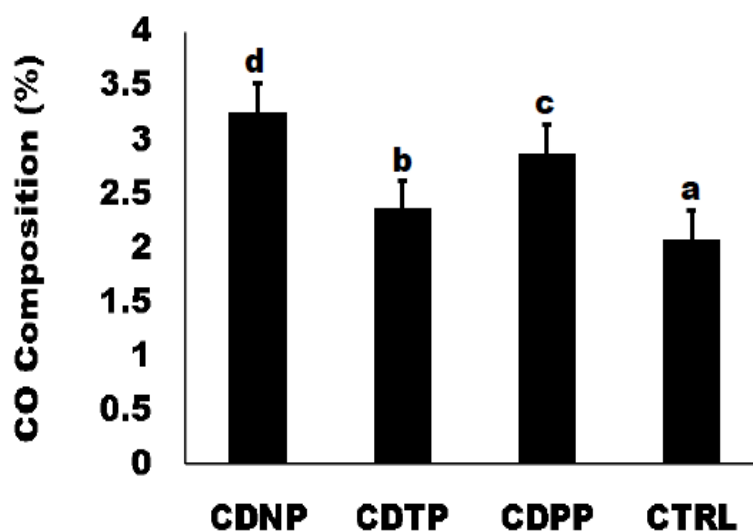


**Figure 1.** Methane composition (%) in the biogas produced in the different bioreactors.

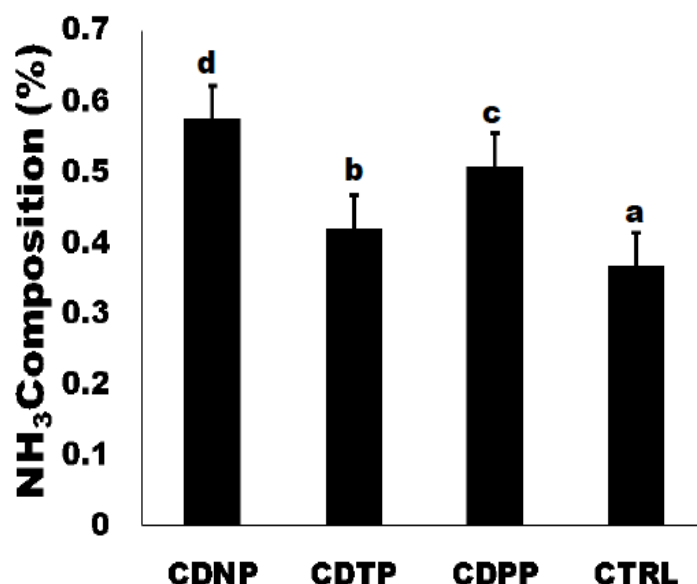
Key: **CDNP** - cow dung mixed with neem powders; **CDTP** - cow dung mixed with tumeric powders; **CDPP** - cow dung mixed with papaya powders; **CTRL** - control (cow dung without any powder).



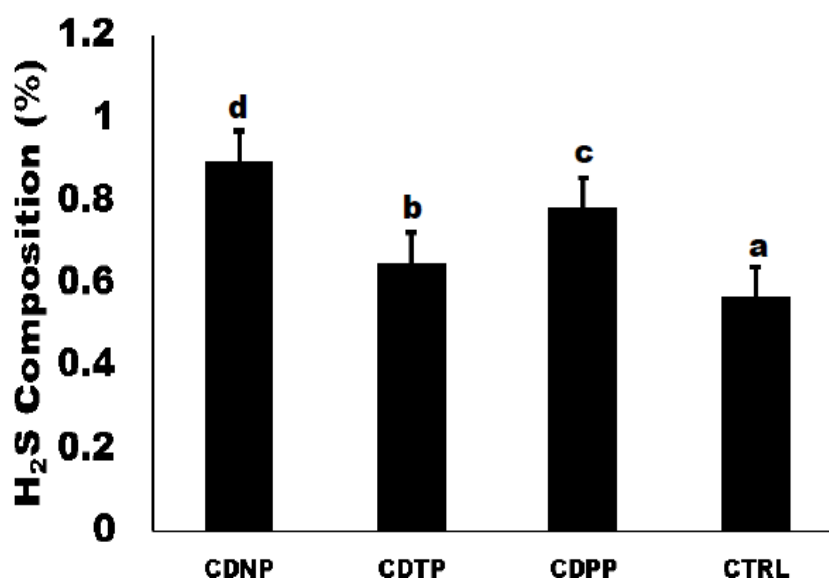
**Figure 2.** Carbon dioxide compositions (%) in the biogas produced in the different bioreactors  
Key: **CDNP** - cow dung mixed with neem powders; **CDTP** - cow dung mixed with tumeric powders; **CDPP** - cow dung mixed with papaya powders; **CTRL** - control (cow dung without any powder).



**Figure 3.** Carbon monoxide compositions (%) in the biogas produced in the different bioreactors  
Key: **CDNP** - cow dung mixed with neem powders; **CDTP** - cow dung mixed with tumeric powders; **CDPP** - cow dung mixed with papaya powders; **CTRL** - control (cow dung without any powder).



**Figure 4.** Ammonia compositions (%) in the biogas produced in the different bioreactors  
Key: **CDNP** - cow dung mixed with neem powders; **CDTP** - cow dung mixed with tumeric powders; **CDPP** - cow dung mixed with papaya powders; **CTRL** - control (cow dung without any powder).



**Figure 5.** Hydrogen sulphide compositions (%) in the biogas produced in the different bioreactors.  
Key: **CDNP** - cow dung mixed with neem powders; **CDTP** - cow dung mixed with tumeric powders; **CDPP** - cow dung mixed with papaya powders; **CTRL** - control (cow dung without any powder).

#### 4. DISCUSSION

Among all the different bioreactors (CDNP, CDTP, CDPP and CTRL) and over the 30 days retention time, the anaerobic digestion of CDNP generated the highest quantity of biogas when compared with the CTRL that produced the least biogas yield. This cannot but be connected with the swift hydrolysis and acidogenesis enhanced by the stronger antimicrobial effects of azadirachtin present in *Azadirachta indica*, which control microbial populations and then enriched methanogenic consortia [21].

This is supported by the works [22] who reported that plant extracts are said to maintain favourable conditions for enhanced biogas production in anaerobic digestion by enhancing enzymes that extensively degrade lignin and break down cellulose and hemicellulose. Among all the different bioreactors, CDNP had the highest biogas weight. This may not be unconnected with the activity of azadirachtin, a bioactive compound present in neem, ultimately boosting biogas yield [23, 24].

The swift hydrolysis and acidogenesis may be enhanced by the stronger antimicrobial effects of azadirachtin present in neem, which enriched the growth of methanogens. In fact, biogas production peaks over 30 days retention time in this study due to the acclimatization of biogas-producing microorganisms after substrate hydrolysis.

Meanwhile, the biogas produced in this study contained methane as a major component, as evidenced by its combustible characteristics, when the gas from the various bioreactors was tested using a bunsen burner connected to the bioreactors, it ignited and burned. The flame's colour (blue colour), confirmed the presence of methane. This was in accordance with the report of Asikong *et al.* [25] who reported blue colour flame as a result of methane gas presence from the combustion of biogas produced during single and co-digestion of cow dung and rice husk. Remarkably, methane and carbon dioxide had the largest percentage of the gas compositions in all different bioreactors, though CDNP and CTRL showed the highest and lowest methane composition respectively.

The addition of neem, papaya and tumeric plant powders synergistically enhanced methane composition of the biogas yields at high volumes in CDNP, CDTP and CDPP digester systems compared with CTRL. Particularly, CDNP digester system had the highest CH<sub>4</sub> yields. This is in agreement with the works of Sang-Ryong *et al.* [22] who reported higher methane compositions from their study on biogas production from cow dung enhanced by *Acanthus mollis*. Additionally, carbon dioxide was observed to be least in CDNP compared with CTRL, CDTP and CDPP digester systems. This is as a result of efficient methanogenesis (methane production).

This is buttressed by the works of Mata-Alvarez *et al.* [26] who reported that biogas majorly composed of methane and carbon dioxide. In fact, this finding is consistent with Demirel and Scherer [27], who noted that anaerobic digestion involves a sequence of bacterial groups, including hydrolyzing, acidifying, acetogenic, and methanogenic bacteria, ultimately producing CO<sub>2</sub> and methane.

Methanogens often dominate during the later stages of the anaerobic digestion, playing a crucial role in methane synthesis [28]. Also, results from this study revealed that the biogas produced contains other gases like hydrogen sulphide, carbon monoxide, and ammonia but in trace amounts. This could be as a result of differences in anaerobic digestion conditions or feedstock makeup [29, 30]. Although depending on biogas usage, additional purification steps may be needed to remove NH<sub>3</sub>, CO, or other trace gases affecting biogas quality.

## 5. CONCLUSION

This study demonstrates the potential of cow dung catalyzed by plant powders as a valuable substrate for biogas production over 30 days retention time. The plant powders positively influenced the production of biogas with neem plant powder being the most effective for optimizing biogas yield than other treatments. Besides, the high methane and low carbon dioxide content of CDNP equally confirmed the effectiveness of neem plant powders in the biogas production.

## References

- [1] A. Kumar, and A. Agrawal, Recent trends in solid waste management status, challenges, and potential for the future Indian cities - A Review: *Curriculum Research Environmental Sustainable* 2 (2020) 100011. doi: 10.1016/j.crsust.2020.100011
- [2] C. Zurbrugg, M. Gfrerer, M. Ashadi, H. Brenner, and W. Kühr, Determinants of sustainability in solid waste management–The Gianyar Waste Recovery Project in Indonesia. *Journal of Waste Management* 32(11) (2012) 2126-2133
- [3] R. Basu, Solid Waste Management-A Model Study. *Journal of Waste Management* 6 (2009) 20-24
- [4] D.V. Paritosh, S.Y. Olosunde, and A.B. Omokanju, Evaluation of Ratio Variation of Water Hyacinth (*Eichhornia crassipes*) on the Production of Pig Dung Biogas. *International Research Journal of Biological Sciences* 2(3) (2013) 44-48  
<https://doi.org/10.30954/2249-4660.2013.00008>
- [5] C.J. Hwang, G.T. Baoy, D.B. Calangi, A.C. Castillo, M.O. Averion, S.C. Elefano, R.S. Santos, R. Bentent, and R. Hocon, Biodegradable effluent as protein supplement for indigenous (*Bos indicus*) growing bulls. *Livestock Research for Rural Development*. 11(2) (2004) 1-5 <http://www.lrrd.org/lrrd11/2/chow112.htm>
- [6] K. Mckeown, and N. Shagufta, Isolation and Characterization of Microbial Community in Biogas Production from Different Commercially Active Fermentors in Different Regions of Gujranwala. *International Journal of Water Resources and Environmental Sciences* 2(2) (2013) 28-33
- [7] H. Xia, C.A. Brebbia, and S.S. Zubir 2014) Energy and Sustainability V Textbook, 5<sup>th</sup> edition, edited by *International Conference on Energy and Sustainability* 186 (2014) 79  
<https://doi.org/10.2495/ESUS140081>
- [8] C.O. Nwuche, E.O.Ugoji, Effects of heavy metal pollution on the soil microbial activity. *International Journal of Environmental Science Technology* 5(3) (2008) 409-414
- [9] C.O. Nwuche, E.O. Ugoji, Effect of co-existing plant species on soil microbial activity under heavy metal stress. *International Journal of Environmental Science Technology* 7(4) (2010) 697-704

- [10] I. Angelidaki, L. Ellegaard, and B.K.A. Ahring, Mathematical model for dynamic simulation of anaerobic digestion of complex substrates with a focus on ammonia inhibition. *Biotechnology Bioengineering* 42 (1993) 159–166  
<https://doi.org/10.1002/bit.260420203>
- [11] W. Roland, K. Etelka, M. Gergely, B. Zoltan, R. Gabor, and L.K. Kornel, (2012). Characterization of a biogas-producing microbial community by short-read next generation DNA sequencing. *Biotechnology Biofuels* 5(41) (2012) 231-241
- [12] [12] M. Benali, T. Hamad, A. Belkhair, Y. Hamad, Investigating the Use of Combined Hydrogen, Heat and Power System for Omar Al-Mukhtar University Campus. *Advances in Biological Chemistry* 9 (2019) 31-44.  
<https://doi.org/10.4236/abc.2019.91003>
- [13] M. Benali, T. Hamad, Y. Hamad, and A. Belkhair, The Hydrogen Energy Potential of Solid Waste: A Case Study of Misrata City. *Advances in Biological Chemistry* 9 (2019) 45-53. <https://doi.org/10.4236/abc.2019.92004>
- [14] Z. Zhang, I.M. O'Hara, S. Mundree, B. Gao, A.S. Ball, N. Zhu, Z. Bai, and B. Jin, Biofuels from food processing wastes. *Journal of Environmental Science* 12 (2016) 97-105 <https://doi.org/10.1016/j.copbio.2016.01.010>
- [15] M. Garfi, L. Ferrer-Martí, V. Villegas, and I. Ferrer, Psychosocial and technical assessment of small-scale biogas plants for rural communities. *Journal of Renewable and Sustainable Energy* 15(2) (2011) 822–830
- [16] R. Singh, S.K. Mandal, V.K. Jain, Enhancement of biogas production from solid wastes using biological additives. *Journal of Waste Management* 102 (2020) 396–403.
- [17] T. Adeyanju, M.O. Ogedengbe, D.I. Olorunfemi, Application of phytocatalysts in biogas production: A review. *Renewable Energy and Environmental Sustainability* 7(4) (2022) 1-9
- [18] A.U. Ofoefule, and E.O. Uzodinma, Optimization of the qualitative and quantitative biogas yield from poultry waste. Proceedings of the IX World Renewable Energy Congress. University of Florence Italy. (2006) 9–25
- [19] A.K. Kalia, and S.P. Singh, A biogas plant is a suitable technology for developing countries. *Journal of Applied Energy* 77(1) (2004) 33-43 [https://doi.org/10.1016/S0306-2619\(04\)00023-2](https://doi.org/10.1016/S0306-2619(04)00023-2)
- [20] A.A Adeyanju, Performance evaluation of a modified low-cost anaerobic digester with tyre tube gas storage. *International Journal of Renewable Energy Research* 2(3) (2012) 476-481 <https://doi.org/10.18818/ijerr.v2i3.356>
- [21] J. Mata-Alvarez, J. Dosta, M.S. Romero-Güiza, X. Fonoll, M. Peces, S. Astals, A critical review on anaerobic co-digestion achievements and limitations. *Bioresource Technology*. 36 (2014) 412-427 <https://doi.org/10.1016/j.rser.2014.04.039>
- [22] S. Sang-Ryong, L. Mo-kwon, I. Seongwon, and K. Dong-Hoon, Effect of seaweed addition on enhanced anaerobic digestion of food waste and sewage sludge. *Environmental Engineering Research* 24(3) (2019) 449-455  
<http://dx.doi.org/10.4491/eer.2018.275>

- [23] G. Fuentes, J.M Santamaría, Papaya (*Carica papaya* L.): Origin, domestication, and production. In Genetics and Genomics of Papaya. Springer: Berlin/Heidelberg, Germany. (2014) 3-15 [https://doi.org/10.1007/978-1-4614-8087-7\\_1](https://doi.org/10.1007/978-1-4614-8087-7_1)
- [24] N.K. Soudamini, R. Kuttan, Inhibition of chemical carcinogenesis by curcumin. *Journal of Ethnopharmacology* 27 (1989) 227-233 [https://doi.org/10.1016/0378-8741\(89\)90094-9](https://doi.org/10.1016/0378-8741(89)90094-9)
- [25] B.E. Asikong, S.O. Idire, and D.R. Tiku, Microbial Consortia Associated with Biogas Production Using Vegetable Wastes (Telfairia occidentalis), Banana Peels, and Pig Dung as Substrates. *British Microbiology Research Journal* 16(3) (2016) 1-12 <https://doi.org/10.9734/BMRJ/2016/28294>
- [26] J. Mata-Alvarez, J. Dosta, S. Macé, S. Astals, Codigestion of solid wastes: A review of its uses and perspectives including modeling. *Critical Reviews in Biotechnology* 34(1) (2014) 1-15. <https://doi.org/10.3109/07388551.2010.525496>
- [27] B. Demirel, P. and Scherer, Roles of Acetotrophic and Hydrogenotrophic Methanogens during Anaerobic Conversion of Biomass to Methane. *Review of Environmental Science and Technology* 7 (2008) 73-901 <https://doi.org/10.1007/s11313-008-0088-5>
- [28] P. Dhevagi, R. Ramasamy, and G. Oblisami, Biological Nitrogen Fixation and Biogas Technology. *Bioresource Technology* 6 (1992) 14-23
- [29] L. Amiri, M. Nikaeen, and B. Hashemzadeh, Optimization of biogas production from cattle manure and food waste using the response surface method. *Bioresource Technology Reports* 6 (2019) 32–38. <https://doi.org/10.1016/j.biteb.2018.11.006>
- [30] W. Parawira, M. Murto, R. Zvauya, and B. Mattiasson, Anaerobic digestion of solid potato waste alone and in combination with sugar beet leaves. *Journal of Renewable Energy* 29 (2004) 1811-1823 <https://doi.org/10.1016/j.renene.2004.02.005>