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Effect of Activated and Non-activated Carbons on Biogas Production from Municipal Organic Wastes

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Abstract

Because carbon-based additives are very adaptable to large-scale deployment and have minimal running costs, they are a suitable strategy to increase biogas yield. These Carbonaceous additives have been shown to have a positive effect on biogas generation with beneficial effects in the anaerobic digestion (AD) process as explained by the mechanism of direct interspecies electron transfer (DIET), the utilization of which is linked to a variety of additional mechanisms. This study investigated the effect of activated and non-activated carbons on biogas production from municipal organic wastes. In this study, a set of three (3) bio-digesters was used to process organic municipal wastes (food wastes) supplemented with activated carbon (AC) and non-activated carbon. In comparison to the control set-up without the carbonaceous additive, the results demonstrated a direct link between the activated carbon and the non-activated carbon. The biogas yield and rate of anaerobic digestion (measured based on the biogas yield per gram of the substrate per day; results not shown) are significantly increased when 5 - 10 gL^{-1} of activated or non-activated carbon is used. During biogas production, the bio-digester with activated carbon displayed more encouraging outcomes. During the 14-day retention period, the total Biogas produced by the set-up with activated carbon was the highest (12 870 mL) and most flammable (+++), followed by the non-activated carbon set-up, which produced 11, 250 mL of moderately flammable (++) Biogas. The lowest (9, 755 mL) and least flammable (+) biogas yield were, however obtained from the control set-up having no carbon additive. The activated carbon was shown to significantly improve biogas yield and its quality (flammability) due to its high surface area and porosity, high chemical stability, electrical conductivity, effective biofilm formation as well as its ability to remove harmful substances (micro-pollutants), which collectively improved the performance of the methanogens, thereby accelerating microbial methanogenesis. This study, therefore, revealed that carbonaceous additives supplementation enhances biogas production and, ultimately the overall biogas quality.

Keywords: Anaerobic digestion, Biogas, activated carbon, electron transfer, methanogenesis

INTRODUCTION

One of the most commonly used essential gases, methane, is a greenhouse gas that is lackadaisical to the earth's climate. Anaerobic digestion (AD), a process that produces biomethane from biomass decomposition, is thought to be carbon neutral. (Xiao *et al.*, 2022). Anaerobic digestion processes require four steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. These steps involve several types of microbes, including hydrolytic bacteria, acid-producing bacteria, acetogenic bacteria, and methanogens (Evans *et al.* 2019). These bacteria break down biomass made of macromolecular organic matter into smaller molecules like methane, hydrogen, acetate, and carbon dioxide through a sequence of processes. A variety of anaerobic digestion enhancement techniques, including biogas upgrading, operating condition tuning, and two-stage anaerobic digestion, have been developed (Wang *et al.*, 2014). These tactics do not, however, see widespread application because of their laborious parameter adjustment processes, excess energy consumption, and capital cost. Methanogens, mostly from the Archaeal phylum Euryarchaeota, carry out the final step of anaerobic digestion to create biomethane, a process known as methanogenesis (Liu and Whitman, 2008). The use of anaerobic digestion for the treatment of various organic wastes has received increased attention in recent years.

A number of studies have been conducted to improve the anaerobic digestion performance and energy efficiency of Biogas producing technologies in order to meet the global demand for a clean and dependable energy source (Rasapoor *et al*., 2020)

Given the nature of organic waste, various techniques have been used to increase the waste materials' digestibility. These techniques include co-digestion, pre-treatments, and the use of carbonaceous additives to accelerate microbial activity and lower the concentration of some inhibitory byproducts (Romero-Güiza, 2016). The good impact that carbonaceous additions have on biogas generation, their widespread accessibility, and their inexpensive implementation costs have all demonstrated their effectiveness (Zhang *et al*., 2018). Char, a byproduct of gasifying woody biomass, can be used to create inexpensive activated carbon (AC) by steam activation, as reported by Maneerung *et al*. (2016).

According to Caizan-Jüanarena *et al*. (2020), raw materials like coal, wood, and coconut shells are used to make activated carbon (AC). Granular activated carbon (GAC) and powdered activated carbon are two categories of activated carbon based on particle size. Compared to powdered activated carbon, GAC has a higher particle size and a smaller exterior surface. Because of its exceptional adsorbing capability, great mechanical strength, and superior chemical stability, activated carbon is effective in anaerobic digestion during the production of Biogas. The use of GAC is both environmentally and financially viable.

In conclusion, due to its high conductivity, activated carbon increased the synthesis of biomethane through direct interspecies electron transfer (DIET) associated with CO2 reduction (Yang *et al*., 2020). The high conductivity of activated carbon, as demonstrated by microbial abundance analysis, has led to a rise in DIET, which has shown promising improvement in substrate decomposition and biomethane production. In addition to its conductive properties, activated carbon's porous nature makes it a great adsorbent for enriching substrates and perhaps removing hazardous substances, which promotes the creation of biofilms. It plays a crucial function in improving anaerobic digestion by acting as a capacitor to receive or release electrons. (Xiao *et al*., 2022). It was predicted that augmentation with AC could enhance the anaerobic digestion of food waste (FW) for higher methane yield, stable operation process, and effective color removal of the liquid phase of AD digestate (Zhang *et al*., 2018). Recently, AC has been successfully used in anaerobic digestion as an additive to enhance process efficiency in wastewater treatment (Monser and Adhoum, 2002; Malik, 2004; Skouteris *et al*., 2015). In order to treat food wastes and produce biomethane, this study focused on assessing the effect of adding activated and non-activated carbons to anaerobic digesters during biogas production.

MATERIALS AND METHODS

Sampling Area

The source of municipal organic wastes (food wastes) was Samaru, Zaria, Kaduna State, Nigeria, which is situated at 11.0855°N, 7.7199°E.

Start-up culture, consisting of fresh rumen content was obtained from Zaria abattoir situated in Zangon-Shanu, Samaru, Zaria. Using hand gloves, the sample was taken from a newly slaughtered cattle rumen and placed in an airtight glass bottle (Container). It was then transported immediately to the Department of Microbiology for subsequent processing.

Fabrication of Anaerobic Digesters and Experimental Set-Up

Three (3) digesters, each with a capacity of five (5) liters, were constructed in a modified procedure of Atta *et al*. (2021) to facilitate the digestion of a substrate for the production of Biogas. Using a nail, a hole was bored into the cover/lid of every gallon to accommodate the flexible collection tubes. To allow the created Biogas to move from the digester to the biogas-collecting vessel, an aperture was drilled. To prevent any infiltration into the anaerobic digester and biogas escape, the tubes were securely inserted into the entrance and sealed with "A & B" adhesive gum. Prior to loading the substrate, the digesters were completely cleaned to get rid of any substances that would restrict microbial development and the production of Biogas. The substrate was also made to be firmly anoxic to help with the anaerobic fermentation process.

Preparation of Reagent

A solution of 1 % w/v potassium hydroxide (KOH) was prepared by dissolving 1 g of KOH in 99 mL of water. A total volume of 6000 mL of the solution was prepared, where 60 g of KOH was dissolved in 5940 mL of water and then used for purification during gas collection in the collection jar (1000 mL measuring cylinder).

Plate I: Experimental Set-up for the Anaerobic Digestion of Municipal Organic Wastes

Experimental Set-up for Biogas Production with Activated and Non-Activated Carbons
The municipal organic waste (food waste) was sorted out by removing the non-degradable wastes and shredded to a size below 3 mm to increase its surface area for easy digestion. A total of 1000 g of the substrate (food waste) was then transferred into a set of three (3) digesters of 5 litres capacity each, and 1000 mL of water was added to obtain a slurry of just 1:1(substrate: water) ratio; compared to various rations of municipal solid waste to water dilution which was reported by Haftu *et al.* (2018). A total of 19 g of activated carbon was added to one of the bio-digesters, and also 19 g of non-activated carbon was added to another digester using 5 - 10 gL^{-1} in accordance with Elvira *et al.* (2020), and the control set-up was without carbonaceous additive. The pH of the slurries was determined using a pH meter, and the temperature was kept ambient (Room temperature). An estimated 191.92 g of rumen content collected from freshly slaughtered cattle was incorporated into each of the bio-digesters, which serves as inoculum (start-up culture) for methanogens, and this was followed by occasional agitation or shaking to mix the slurry properly (Musa and Raji., 2016).
To avoid gas leaks, the digesters were sealed with "A & B" adhesive gum and stoppers. Rubber tubing was then used to link the digesters to a gas collecting jar (a measuring cylinder with a 1000 mL capacity) that was inverted over a 1 %w/v KOH solution. By using "upward delivery and downward displacement" of KOH solution, the gas was collected (Atta *et al.*, 2021). The alkaline KOH solution aids in the dissolution of acidic gases, which are regarded as contaminants in Biogas and include CO_2 and H_2S. Different techniques are used to absorb hydrogen sulfide (H_2S) and carbon dioxide (CO_2) from Biogas. The most popular and practical technique is to pass the Biogas through alkaline solutions, such as calcium, potassium, and sodium hydroxides (Muntaha *et al.*, 2022). In this study, 1 %w/v KOH solution was used.

$$2KOH + CO_2 \Longrightarrow K_2CO_3 + H_2O$$

Each experiment lasted for a hydraulic retention time (HRT) of 14 days. The production of gas was monitored using the volume displacement method every 24 hours.

Quantitative Assessment of the Biogas Produced
The following factors were taken into account when evaluating the performance of the experimental substrates: daily yield of gas, total volume of gas produced throughout the study's 14-day (HRT) period (measured by the method of upward biogas delivery and downward displacement of the KOH solution in the 1 L measuring cylinder), and time record of gas production, including when it begins, peaks, and ends (Musa and Raji, 2016).

Qualitative Assessment of the Biogas Produced
The degree of flammability of the Biogas produced was used to determine its quality. In order to do this, a match was struck, and the flame was passed over the measuring cylinder's (or gas collection jar's) nozzle to collect gas and record its degree of flammability (Atta *et al.*, 2021).

RESULTS

The results of the effect of activated carbon on biogas production from municipal organic wastes are presented in Figure 1 and Table 1.

Table 1 shows the assessment of Biogas produced from the digestion of food wastes (municipal organic wastes) under anaerobic conditions for a hydraulic retention time (HRT) of 14 days. The control set-up had an initial pH of 6.8, the set-up with non-activated carbon had 6.8, and the set-up with activated carbon had 7.2 (Table 1). Gas production started on the 1st day for all set-ups (control, non-activated and activated carbon). The day of peak production for the control set-up was the 9th day, the 1st day for the non-activated carbon set-up, and the 4th day for the activated carbon set-up. No cessation in the production for the entire Hydraulic Retention Time was observed in the control set-up, non-activated carbon set-up, and activated carbon set-up.

Flammability started on the 11th day for the control set-up, set-up with non-activated carbon started on the 9th day and activated carbon set-up started on the 8th day. The control set-up was less flammable, the non-activated carbon set-up was moderately flammable, activated carbon set-up was highly flammable (Table 1).

The control set-up had a total biogas production of 9,755 mL, the set-up containing non-activated carbon had 11,250 mL, and that containing activated carbon had 12,870 mL, as shown in Table 1

Figure 1 shows an illustration of the volume of Biogas produced by the control set-up, non-activated carbon set-up, and activated carbon set-up during the retention period of 14 d digestion of the municipal organic waste anaerobically.

Table 1: Biogas Produced during a 14 d Hydraulic Retention Time (HRT) of Anaerobic Digestion of Municipal Organic Wastes (Food Waste).

	Experimental Set-up		
Parameters	**Control**	**With Non-activated carbon**	**With Activated carbon**
Initial pH	6.8	6.8	7.2
Day production started	1st	1st	1st
Day flammability started	11th	9th	8th
Biogas flammability	+	++	+++
Day production peaked	9th	1st	4th
Day production ceased	---	---	---
Total Biogas produced (mL)	9,755	11,250	12,870

Key: +++ = Highly flammable, ++ = Moderately flammable, + = Less flammable, --- = No cessation in the production for the entire Hydraulic Retention Time (HRT).

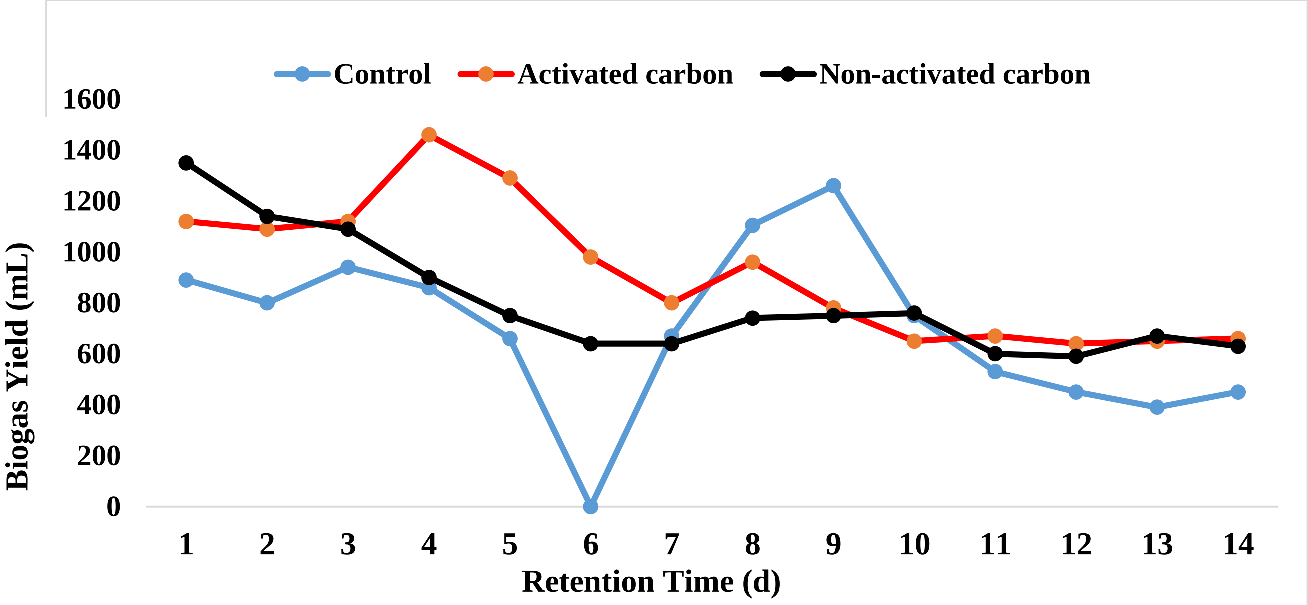

Figure 1: Biogas Yield from Anaerobic Digestion of Municipal Organic Waste during Retention Period of 14 d.

Plate II: Flammability (Quality) Test for Methane Content of the Control Set-up (without supplementation)

Plate III: Flammability (Quality) Test for Methane Content of the Set-up with Non-activated Carbon Supplementation

Plate IV: Flammability (Quality) Test for Methane Content of the Set-up with Activated Carbon Supplementation

DISCUSSION

The production of Biogas is generally known to be influenced by various factors at varying degrees. In this study, the initial pH (7.0 ± 0.2) was fixed, and the performance of the digested substrates for biogas production was therefore solely dependent on the nature of the substrate's treatment with (activated or non-activated) or without carbon additive. In all the experiments, a fixed amount (19 g) of activated and non-activated carbon was separately assessed in bio-digesters alongside a control (with no additive), and the volume of Biogas generated (quantitatively and qualitatively) was recorded. Interestingly, the near-optimal levels of pH observed, especially for the bacteria, might have favored the preliminary stages of hydrolysis, acidogenesis, and acetogenesis during the biogas production. Generally, as the efficiency of these stages increases, the rate and volume of Biogas generated is ultimately expected to also increase (Atta *et al*., 2021). The work of Xu *et al*. (2018) lends credence to the findings. They reported that the addition of biochar into the AD process could increase alkalinity and solution pH, which reduces ammonia inhibition and acid stress to the microbial community, thereby enhancing the AD process. The biochar was found to elevate the alkalinity (pH = 6) of AD, promoting better microbial action for quick CH_4 production and adaptability to initial loading shock. This is similar to the work of Li *et al*. (2017) who reported a pH rise to ≥ 6 after biochar addition. Therefore, with the addition of biochar, a continuous AD system can work more efficiently and with an even shorter hydraulic retention time (HRT).

The highest volume (12,870 mL) of Biogas obtained was from the municipal food waste supplemented with activated carbon. The control set-up, having no carbon additive supplementation, produced the lowest biogas yield of 9,755 mL, as expected. On the other hand, the food waste supplemented with non-activated carbon produced a total biogas yield of 11,250 mL, which was 12.6 % lower than the set-up supplemented with activated carbon but 13.3 % higher than the control set-up. This difference might not be unconnected with the high electrical conductivity of the activated carbon added, which reduces internal resistance and increases the conductivity of the slurry by enhancing the electron transfer rate, especially during the methanogenesis of biogas production. The biochar conductivity and its microbial association in AD are, however, highly influenced by the pH, as also reported by Yin *et al*. (2019). The large pore diameter and high chemical stability of the activated carbon might also contribute to significant biogas yield obtained from the set-up supplemented with activated carbon.

Additionally, micro-pollutants, which are inhibitors of bacterial metabolism, might have been removed by the activated carbon, possibly via sequestration, thus resulting in enhanced bacterial proliferation, improved biofilm formation, and optimal metabolic activities leading to higher biogas yield. This corroborates with the work of Zhang *et al*. (2017), who also reported an interesting observation that during the biofilm formation, biochar induced the secretion of extracellular polymeric substance (EPS) from microbes, thus facilitating microbial adhesion on the biochar surface. This presents a simple and low-cost solution using biochar to avoid rapid sludge granulation and minimize the loss of methanogens in the anaerobic digesters. Sun *et al*. (2016) confirmed the enriched microbial abundance in the presence of biochar carriers.

Figure 1 shows the weekly volume of Biogas produced with the highest yield obtained during the first week of anaerobic digestion of the food wastes for both experimental treatments. However, it can be speculated that this Biogas contained mostly CO_2 rather than methane, hence less flammable at this time. The porous nature and large surface area of biochar might have promoted the colonization of bacteria and archaea, resulting in an improved AD performance during the first week of AD, as also reported by Qin *et al*. (2017) and Martínez *et al*. (2018). However, the CO_2 concentration might have decreased with a corresponding increase in the CH_4 as the AD process proceeds. This is because the abundant surface functional groups and good electrical conductivity of the biochar could enhance the methane yield via direct or indirect electron transfer mechanism among anaerobic microbes, as also reported by Chiappero *et al*. (2020) and Baek *et al*. (2018).

The flammability test in this study revealed that the Biogas obtained from the digestion of food waste supplemented with activated carbon was most flammable, particularly during the second week. The high degree of flammability observed might be due to high methane content and/or low levels of such incombustible gases as carbon dioxide, oxygen, nitrogen and ammonia as components of the Biogas. This result corroborates the finding of Jatau *et al*. (2001). The decrease in the flammability of the Biogas observed in the food waste with non-activated carbon might be due to the absence of desirable properties of the carbon supplement, including but not limited to high electrical conductivity, high porosity, and high surface area.

Previous studies also highlighted the importance of biochar in addition to its capability of electron transfer processes between archaea and anaerobic bacteria, which improves methane yield and, ultimately, the biogas flammability. The efficiency of the AD system is primarily dependent upon the syntrophic interactions between methanogens and bacteria, which trade electrons to comply with their energy necessities (Martins *et al.*, 2018). This occurs through multiple routes: DIET via a conductive medium (e.g. magnetite, carbon cloth, biochar) (Zhang *et al.*, 2018), membrane-bound transporter proteins (Martins *et al.*, 2018), electric conductive pili (Barua and Dhar, 2017), and indirect interspecies electron transfer (IIET) through insoluble (humic compounds) as reported by Roden *et al.* (2010) as well as soluble (acetate, formate, hydrogen) substances which was reported in the work of Schink *et al.* (2017).

Additionally, the non-activated carbon could not have removed the micro-pollutants such as ammonia in the Biogas, and this might have reduced the flammability since ammonia is non-combustible. One of the prime features offered by biochar to elevate AD functioning is its inhibitor adsorption potency. The surface area of biochar is considered one of the key factors, along with others, in the adsorption of environmental contaminants (Luz *et al.*, 2018). According to Shanmugam *et al.* (2018) and Cheng *et al.* (2018), CH_4 yield was elevated due to biochar adsorption of volatile fatty acids (VFAs) and acid alleviation. Wang *et al.* (2018) also observed a direct proportionality between hydrochar surface area and NH_4 adsorption. In an investigation on CO_2 adsorption by biochars obtained from chickory wood and bagasse, Creamer *et al.* (2014) realized that it was effectively achieved due to the physical adsorption through a high surface area and N_2 groups.

CONCLUSION

Biogas was produced from municipal organic waste (food waste). The supplementation of activated carbon during biogas production has significantly improved the performance of the anaerobic digestion process. This is indicated in the total amount of Biogas produced, with the set-up containing activated carbon having the highest biogas yield (12,870 mL) within the hydraulic retention period (14 d).

In terms of quality, the Biogas produced in the set-up containing activated carbon was the most flammable (+++) compared to that with non-activated carbon, which was moderately flammable (++), and that of the control set-up, which was least flammable (+). This clearly indicated that there was the highest methane (flammable gas) content in the Biogas produced with activated carbon supplementation.

REFERENCES

Atta, H.I, Mustapha, F., Goni, A.B., Musa, B. (2021). A laboratory-based study of biomethanation by the co-digestion of municipal solid waste with domestic food waste and wastewater Sludge. *International Journal of Biomass & Renewables*, **10**(2): 25 - 34. doi: **[Crossref]**.

Baek, G., Kim, Jaai, Kim, Jinsu, Lee, C. (2018). Role and potential of direct interspecies electron transfer in anaerobic digestion. *Energies*, **11**(1):107. **[Crossref]**

Barua, S., Dhar, B.R. (2017). Advances towards understanding and engineering direct interspecies electron transfer in anaerobic digestion. *Bioresource Technology*, **244**:698-707. **[Crossref]**.

Caizán-Juanarena, L., Sleutels, T., Borsje, C., Heijne, A. (2020). Considerations for Application of Granular Activated Carbon as Capacitive Bioanode in Bioelectrochemical Systems, *Renewable Energy*, **157**:782-792, **[Crossref]**

Cheng, Q., de los Reyes, F.L., Call, D.F. (2018). Amending anaerobic bioreactors with pyrogenic carbonaceous materials: the influence of material properties on methane generation. *Environmental Science: Water Research & Technology*, **4**:1794-1806. **[Crossref]**.

Chiappero, M., Norouzi, O., Hu, M., Demichelis, F., Berruti, F., Di Maria, F., Masek, O., Fiore, S. (2020). Review of biochar role as additive in anaerobic digestion processes. *Renewable and Sustainable Energy Reviews*, **131**:110037. **[Crossref]**.

Creamer, A.E., Gao, B., Zhang, M. (2014). Carbon dioxide capture using biochar produced from sugarcane bagasse and hickory wood. *Chemical Engineering Journal*, **249**:174-179. **[Crossref]**.

Elvira E. Ziganshina, Svetlana S. Bulynina, and Ayrat M. Ziganshin. 2022. "Impact of Granular Activated Carbon on Anaerobic Process and Microbial Community Structure during Mesophilic and Thermophilic Anaerobic Digestion of Chicken Manure" *Sustainability*, **14(**1): 447. **[Crossref]**

Evans, P.N., Boyd, J.A., Leu, A.O., Woodcroft, B.J., Parks, D.H., Hugenholtz, P. (2019). An evolving view of methane metabolism in the Archaea. *Nature Reviews Microbiology*, **17**(4):219–32. **[Crossref].**

Haftu Gebretsadik, Solomon Mulaw, Giday Gebregziabher. (2018). Qualitative and Quantitative Feasibility of Biogas Production from Kitchen Waste. *American Journal of Energy Engineering*, **6(**1):1-5. **[Crossref]**

Jatau, E. D., Machido, D. A. and Akpan, E. E. (2001). The Potential of Six Organic Wastes as Substrates in Biogas Production. *Journal of Agriculture and Environment*, **2**(1): 57-60.

Li, H., Dong, X., da Silva, E.B., de Oliveira, L.M., Chen, Y., Ma, L.Q. (2017). Mechanisms of metal sorption by biochars: biochar characteristics and modifications. *Chemosphere*, **178**: 466-478. **[Crossref].**

Liu, Y., Whitman, W.B. (2008). Metabolic, phylogenic, an ecological diversity of the methanogenic archea. *Annals of NY Academy of Science*, **1125**:1271-89. **[Crossref]**

Liu, Y., Whitman, W.B. (2008). Metabolic, phylogenic, an ecological diversity of the methanogenic archea. *Annals of NY Academy of Science*, **1125**:1271-89. **[Crossref]**

Luz, F.C., Cordiner, S., Manni, A., Mulone, V., Rocco, V. (2018). Biochar characteristics and early applications in anaerobic digestion-a review. *Journal of Environmental Chemical Engineering*, **6**:2892-2909. **[Crossref].**

Malik, P.K. (2004). Dye removal from waste using activated carbon developed from sawdust: adsorption equilibrium and kinetics. *Journal of Hazardous Materials*, **113**:81-88. **[Crossref]**

Maneerung, T., Liew, J., Dai, Y., Kawi, S., Chong, C., Wang, C.H. (2016). Activated carbon derived from carbon residue from biomass gasification and its application for dye adsorption: kinetics, isotherms and thermodynamic studies. *Bioresource Technology*, **200**:350-359. **[Crossref]**

Martínez, E.J., Rosas, J.G., Sotres, A., Moran, A., Cara, J., Sanchez, M.E., Gomez, X. (2018). Codigestion of sludge and citrus peel wastes: evaluating the effect of biochar addition on microbial communities. *Biochemical Engineering Journal*, **137**: 314-325. **[Crossref].**

Martins, G., Salvador, A.F., Pereira, L., Alves, M.M. (2018). Methane production and conductive materials: a critical review. Environ. Sci. Technol., **52**: 10241-10253. **[Crossref].**

Monser, L., Adhoum, N. (2002). Modified activated carbon for the removal of copper, zinc, chromium and cyanide from wastewater. *Separation and Purification Technology*, **26**: 137-146. **[Crossref]**

Muntaha N, Rain MI, Goni LKMO, Shaikh MAA, Jamal MS, Hossain M. (2022). A Review on Carbon Dioxide Minimization in Biogas Upgradation Technology by Chemical Absorption Processes. *ACS Omega*, **7**(38):33680-33698. doi: **[Crossref]**

Musa, B. and Raji, H.M. (2016) Quantitative and Qualitative Analysis of Biogas Produces from Three Organic Wastes. *International Journal of Renewable Energy Research*, **6**(1): 1562-1568. **[Crossref]**

Qin, Y., Wang, H., Li, X., Cheng, J.J., Wu, W. (2017). Improving methane yield from organic fraction of municipal solid waste (OFMSW) with magnetic rice-straw biochar. *Bioresource Technology*, **245**:1058-1066. **[Crossref]**

Rasapoor, M., Young, B., Brar, R., Sarmah, A., Zhuang, W.Q., Baroutian, S. (2020). Recognizing the challenges of anaerobic digestion: Critical steps toward improving biogas generation. *Fuel*, **261**: (116):497. **[Crossref]**

Roden, E.E., Kappler, A., Bauer, I., Jiang, J., Paul, A., Stoesser, R., Konishi, H., Xu, H. (2010). Extracellular electron transfer through microbial reduction of solid-phase humic substances. *Nature Geoscience*, **3**:417-421. **[Crossref]**

Romero-Güiza, M.S., Vila, J., Mata-Alvarez, J., Chimenos, J.M., Astals, S. (2016). The role of additives on anaerobic digestion: a review. *Renewable and Sustainable Energy Reviews*, **58**: 1486-1499. **[Crossref]**

Schink, B., Montag, D., Keller, A., Müller, N. (2017). Hydrogen or formate: alternative key players in methanogenic degradation. *Environmental Microbiology Reports*, **9**:189-202. **[Crossref].**

Shanmugam, S.R., Adhikari, S., Nam, H., Kar Sajib, S. (2018). Effect of bio-char on methane generation from glucose and aqueous phase of algae liquefaction using mixed anaerobic cultures. *Biomass & Bioenergy*, **108**: 479-486. .**[Crossref].**

Skouteris, G., Saroj, D., Melidis, P., Hai, F.I., Ouki, S. (2015). The effect of activated carbon addition on membrane bioreactor processes for wastewater treatment and reclamation – a critical review. *Bioresource Technology*, **185**: 399-410. [Crossref]

Sun, D., Hale, L., Crowley, D. (2016). Nutrient supplementation of pinewood biochar for use as a bacterial inoculum carrier. *Biology and Fertility of Soils*, **52**:515-522. [Crossref]

Wang, B., Nges, I. A., Nistor, M., and Liu, J. (2014). Determination of methane yield of cellulose using different experimental set ups. *Water Science Technology*, **70**(4): 599-604. [Crossref]

Wang, C., Liu, Y., Gao, X., Chen, H., Xu, X., Zhu, L. (2018). Role of biochar in the granulation of anaerobic sludge and improvement of electron transfer characteristics. *Bioresource Technology*, **268**: 28-35. [Crossref].

Xiao, L., Liu, J., Kumar, P. S., Zhou, M., Yu, J., Lichtfouse, E. (2022). Enhanced methane production by granular activated carbon: A review, *Fuel*, **320**:123903. [Crossref]

Xu, F., Li, Yangyang, Ge, X., Yang, L., Li, Yebo (2018). Anaerobic digestion of food waste -challenges and opportunities. *Bioresource Technology*, **247**: 1047-1058. [Crossref].

Yang, B.., Xu, H., Liu, Y., Li, F., Song, X., Wang, Z., Sand, W. (2020). Role of GAC-MnO_2 catalyst for triggering the extracellular electron transfer and boosting CH_4 production in syntrophic methanogenesis. *Chemical Engineering Journal*, **383**:123211, [Crossref]

Yin, C., Shen, Y., Yuan, R., Zhu, N., Yuan, H., Lou, Z. (2019). Sludge-based biochar-assisted thermophilic anaerobic digestion of waste-activated sludge in microbial electrolysis cell for methane production. *Bioresource Technology*, **284**: 315-324. [Crossref].

Zhang, D., Li, W., Hou, C., Shen, J., Jiang, X., Sun, X., Li, J., Han, W., Wang, L., Liu, X. (2017). Aerobic granulation accelerated by biochar for the treatment of refractory wastewater. *Chemical Engineering Journal*, **314**: 88-97. [Crossref].

Zhang, J., Zhao, W., Zhang, H., Wang, Z., Fan, C., Zang, L. (2018). Recent achievements in enhancing anaerobic digestion with carbon-based functional materials. *Bioresource Technology*, **266**: 555-567. [Crossref]

Zhang, L., Zhang, J., Loh, K.C. (2018) Activated carbon enhanced anaerobic digestion of food waste-Laboratory-scale and Pilot-scale operation. *Waste Management*, **75**:270-9. [Crossref]