

A mini review on pyrolysis and anaerobic digestion: An optional approach to enhance energy and value product yields from waste of food waste processing

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Abstract: Residues generated from biological treatment of food waste consist about 30-35% of the actual waste. These are difficult to degrade or indigestible residues of aerobic and anaerobic fermentation process. However, the food waste feedstock might contain recalcitrant and difficult to degrade matters such as lignin and some plastics matters. Adopted residues disposal routes exerts environmental pressure and underutilization of the waste as resources. To overcome these challenges, innovative strategies for enhancement of energy value from residues of biological treated food waste was proposed in this review. The strategies considered involved coupling of pyrolysis and anaerobic digestion, a new concept receiving attention from researchers. It will open up new routes in combination of thermochemical and biological process for optimal utilization of the residues as resources and also for bio-energy production. Pyrolysis techniques completely treat the indigestible and non-degradable residues; producing various value added and bio-energy products such as pyrogenic bio-char, syn-gas and bio-oil. Anaerobic digestion can utilize these products for robust performance enhancement and bio-methane upgrade. In addition, this review highlighted challenges of coupling both process and future optimizations routes.

Key words: Anaerobic digestion, Bio-methanation, Food waste, Pyrolysis, Waste materials

I. INTRODUCTION

Globally, interest on biomass based energy and upgrade is on the rise. Efforts to harness energy value from food waste had been explored via thermal and bio-chemical process. Considering the characteristics of the residual waste matters as degradable and non-bio degradable, bio-gas can be obtained from the waste. Biogas mainly consists of methane and carbon dioxide but may also contain minor impurities of other components (Giwa et al., 2020a). The residual waste matters of bio-disposed food waste can generate high energy value with appropriate application of technological route. To obtain biogas from easily degradable wastes such as food wastes, a biochemical approach called anaerobic digestion process is traditionally employed. While the difficult and non-biodegradable fractions of the waste can be appropriately treated with thermal process of pyrolysis/gasification to generate products of bio-char, bio-oil and syn-gas. Papuga et al.(2013)reported that unlike most other renewable energy sources, biomass could be converted into solid, liquid and gas fuel forms. In the bio-chemical process, complex polymers of organic substances are degraded easily by microorganisms through the different steps of the anaerobic fermentation process(Gerardi, 2003).

Solid residual matters generated from the bio-chemical process are plastics and high lignin matters incapable to undergo complete degradation during bio-chemical treatment. Nizami et al. (2009)reported that recalcitrance of these difficult to degrade biomass sources, such as the coverage of lignin or the crystallinity of

cellulose, limits the access of the microorganisms and enzymes for efficient digestion. Disposal consideration of the plastics and lignin from bio-chemical process had postured a lot of treatment challenges. In china, after fermentation process of the food waste in most treatment facilities, huge aggregates of non-biodegradable residues become an important environmental issues. These residues eventually were mainly disposed via landfill, open burning and incineration routes. However, these materials have potentials for resources and energy utilization.

An optional route considered sustainable would be to convert the non-bio-degradable and difficult to degrade matters into bio-fuels through gasification to syn-gas and further upgrade the energy value through anaerobic fermentation. Pöschl et al.(2010) reported that the carbon dioxide in digester biogas is inert as a fuel and dilutes the energy content of the biogas, preventing the introduction of biogas as a renewable natural gas into the current natural gas pipeline infrastructure. In addition, with a 30–50% carbon dioxide content, biogas has an energy density of ~18–23MJ per cubic meter, while natural gas has an energy density of 37 MJ per cubic meter (Pöschl et al., 2010). To upgrade bio-gas, that is to increase the methane contents three options were proposed by (Martin et al., 2013) ; (1) removing carbon dioxide from biogas via post processing technologies;(2) supplying a reduced substrate (e.g., hydrogen gas) to the organic waste stream of the anaerobic digester with the goal to convert carbon dioxide into methane in situ; or (3) converting carbon dioxide from biogas into methane via post processing technologies.

Our focus will be based on the second option of supplying a reduced substrate for an insitusyn-gas biomethanization. The waste matters gasified products are carbon dioxide, carbon mono-oxides and hydrogen. Their study focused extensively on the possibility to combine biomass gasification and the anaerobic digestion and techno-economic feasibility. Different from this review, this work reviews pyrolysis process as single entity and process factors for syn-gas production at the same time it provides insight on fermentation technology. The sustainable of the integration as regards energy, socio-economics and environment related issues. Therefore, our ultimate focus would be primarily to provide perceptions regarding optional approach for combination of pyrolysis and anaerobic fermentation process for pyrolysis syn-gas in-situ bio-methanization of non-biodegradables and difficult to degrade residual matters from bio-disposed food waste.

II. STAND ALONE TECHNOLOGY IN VIEW

2.1. Pyrolysis

Pyrolysis can generally be defined as the thermal decomposition of organic matrix in a non-oxidizing atmosphere resulting in liquid bio oil, solid bio-char and non-condensable gas products (Kan et al., 2016). Other thermo-chemical routes that had been extensively studied for converting bio-mass or organic matrix into energy or useful chemicals mostly comprises of combustion, Incineration, gasification, and high pressure liquefaction (HTC)(Beyene et al., 2018; Funke and Ziegler, 2011; Liu et al., 2014). Heat transfer in pyrolysis reactor to feedstock for thermal decomposition is one of the most significant factor influencing reactor selection. Different types of reactor configurations had considered challenges associated with heat transfer. Studies on heat transfer for degradation of organic feedstock with different pyrolysis device such as vacuum pyrolysis, ablative pyrolysis, and circulating fluidized bed pyrolysis was reported (Bridgwater, 2012; Scott et al., 2006). Problems with these different configurations ranges from ineffective heat contact, that is long residence time with larger sizes of biomass. Convection and conduction mode of heat transfer within a very short residence time are utilized in some reactors, but such reactors would require a smaller biomass particles sizes of about 3mm(Funke and Ziegler, 2011). Other pyrolysis reactors configuration problems could be swift eluding of char from the reactor, though, reducing the chances of volatile cracking (Scott et al., 2006).

2.1.1. Pyrolysis influencing factors: temperature, nature of waste, heating time, pressure and vapour residence time

The thermo-decomposition of waste dependent on various process parameters such as feedstock type, operating conditions and physico-chemical properties of biomass, which ultimately affect the biomass conversion time or

pyrolysis rate with product distribution and quality depending also on the objectives of your pyrolysis product desired. Pyrolysis is most convenient for waste with low moisture contents rather than highly wet food waste(Giwa et al., 2020a). (Abnisa et al., 2014) reported extensively a review studies by different authors on the co-pyrolysis of biomass mixed plastics and also proximate analysis results. Different pyrolysis conditions and varieties of waste materials was reported to be suitable for pyrolyzed(Giwa et al., 2019).

Pressure affects the pyrolysis process, with an increase in pressure, volatiles have a smaller specific volume causing higher intra-particle residence time which favors their decomposition while escaping the biomass particle. This also leads to higher concentration (partial pressure) of volatiles, thus increasing the decomposition reaction rate through secondary reactions. Vapors residence time is defined as the time required for the pyrolysis vapors to exit the reactor during thermal cracking, re-condensation and re-polymerization and reach the condensation stage in order to avoid secondary reactions. Heating rate is a basic pyrolysis process parameter that described the type of organic waste materials or biomass pyrolysis as slow, fast and flash pyrolysis. Decomposition of the waste residues are much favored through fast heating rates with yields of more gases and less production of bio-char, while bio-oil production is enhanced at fast heating rates due to decrease in mass and heat transfer limitations resulting to short available time for secondary reaction (Kan et al., 2016). Temperature plays a very important role on the products yield and properties, most especially impact on char yields and properties. The common route is that higher temperatures result into lower char yield in all pyrolysis reactions. The core reason for this is that the temperature forced out more volatile material from the bio-mass at higher temperatures causing reduction in yield(Giwa et al., 2020b; Opatokun et al., 2016). Waste such as biomass is generally composed of three main groups of natural polymeric materials which is also applicable to the Kitchen garbage in focus, these are: cellulose, hemicellulose and lignin. Though, there are other typical components which are grouped as extractives(Giwa et al., 2020a).

2.1.2. Pyrolysis products yield and applications

Pyrolysis has become increasingly popular because it gives products of better quality in biomass conversion compared to other thermo-chemical routes(Al-Wabel et al., 2013; Giwa et al., 2019a). Grycova et al.(2012)reported that unlike most other renewable energy sources, biomass could be converted into solid, liquid and gas fuel forms with their respective applications as shown in the Fig.1.

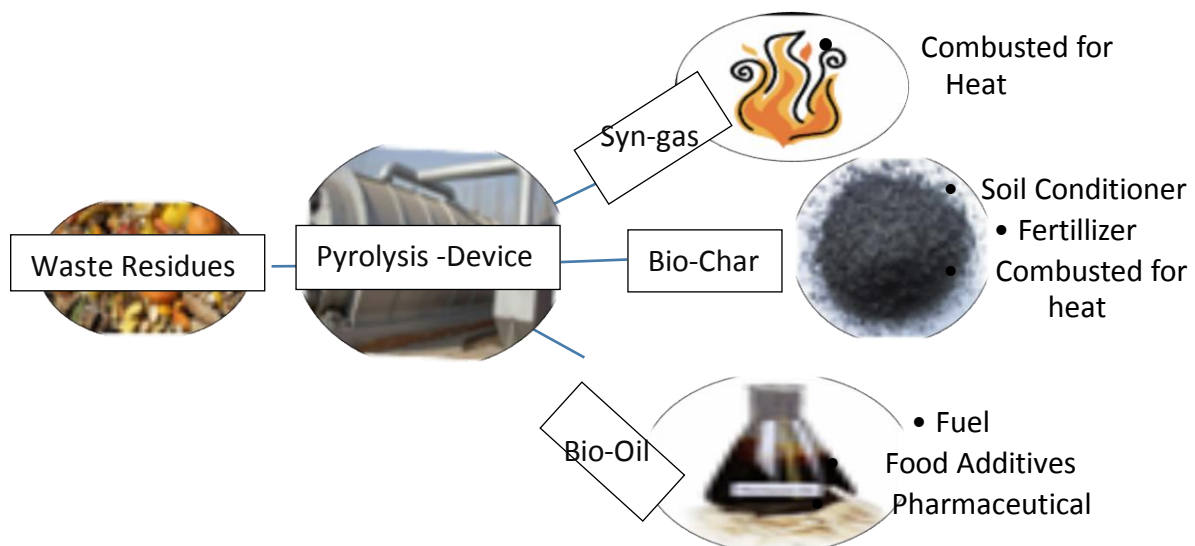


Fig.1. Shows simplified Pyrolysis chart.

Owing to the different nature of the food waste and the difficult biodegradable residues from food waste, different temperature conditions and heating rates (600–900 °C at 20 °C min⁻¹) influence different products (gas, liquid, and

solid) , further temperature increase between 700 and 900 °C, the gas yield increases, whereas oil production decreases(Giwa et al., 2021a). The table 1-3 below present pyrolysis of different biomass waste and organic waste with their product yield.

Table 1: Several studies on bio-oil yield from some selected pyrolyzed bio-mass materials

Biomass type	Pyrolysis condition	Product characteristics	yield	References
waste tyre	T: 350°C	Pyrolytic oil (wt.%): 40.54 Char (wt.%): 31.41 Gas (wt.%):28.05		(Edwin Raj et al., 2013)
Woody Biomass	T: 425-500°C	Liquid bio-oil: 60–75 wt% Solid char: 15-25 noncondensable gases : 10-20		(Keleş et al., 2011)

Table 2: Several studies on bio-char yield from some selected pyrolyzed bio-mass materials

Biomass type	Pyrolysis condition	Product characteristics	yield	References
Waste wood, cardboard wastes, textile wastes	T: 350–700 °C HR: 10 °C/min RT: 2 h N ₂ flowrate: 2L/min	<ul style="list-style-type: none"> • At 700 °C, the yield of char was 31–34 % of the original mass. At 350 °C, the yield of char was 21–25 % at 700 °C • At increasing nitrogen flowrate, residence time of pyrolysis reduced and re-polymerisation prevented • Char, oil and gas yields affected by nitrogen flowrate 		(Oochit et al., 2017)
Peanut shell	350-900 °C	Bio-char 43.16-30.14%		(Zhang et al., 2017)
Digestate from food waste (DFW)	300-700 °C –	60.55-35.03%		(Elkhalifa et al., 2019)
Waste tyre	T: 600	Pyrolytic oil (wt.%): 25.30 Char (wt.%): 28.70 Gas (wt.%):46.00		(Edwin Raj et al., 2013)

Table 3: Several studies on syn-gas yield from some selected pyrolyzed bio-mass materials

Biomass type	Pyrolysis condition	Product yield characteristics	References
Cotton cocoon shell, tea factory waste and olive oil husk	T: 300,400,500,700 °C HR:4.5 °C/min Catalyst : ZnCl ₂ , Na ₂ CO ₃ and K ₂ CO ₃	Gas yield raise with raising it's temperature	(Oochit et al., 2017)
Cow manure	T:600		(Tomczyk et al., 2020)
Rice straw, sawdust	P: 1 atm T: 800 °C	<ul style="list-style-type: none"> • Higher product gas yield achieved at higher heating rate • Temperature of gasifier strongly influenced gas yield • For rice straw: – Gas yield was 39 vol % at 600 C and increased to 49 % at 700 C due to tarry component cracking – Gas yield increased by 12.7 % when there is reduction in the particle size (original to 0.132 mm) • For sawdust: – Gas yield increased relatively up to 14 % when the diameter was reduced to 0.25 mm – As temperature increased, gas yield increased, but solid fraction decreased, while liquid fration yield reached a maximum at about 500 C • For rice straw and sawdust, increasing gas yield found when increase in residence time of volatile phase Due to better cracking reaction at a longer residence time 	(Oochit et al., 2017)

2.2. Anaerobic digestion (Biochemical process)

There are numerous advantages associated with the application of anaerobic digestion, these includes many environmental mitigation, the production of a renewable energy path, the prospects of nutrient recycling and substantial reduction of waste volumes (Cruz Viggi et al., 2017; Phuong et al., 2015)

Different organic substrate is Municipal solid waste, biomass and food waste can undergo degradation by consortium of mutually dependent groups of micro-organism as shown in fig.2(a,b)

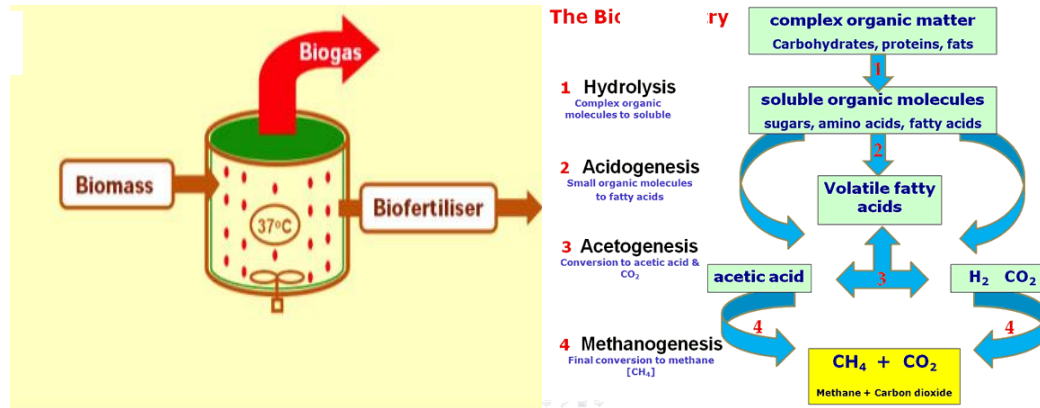


Fig.2(a,b) Anaerobic digester and (b) The stages of anaerobic digestion process (Modified from Mkoma and Mabiki 2011;Gujer W and Zehnder AJB 1983)

Meanwhile, if the process conditions are maintained and stable, high energy recoverable is obtained(Fagbohunge et al., 2017; Giwa et al., 2020a).The technology still faces three major challenges: (i) operationalinstability and (ii) the quality of the digestatethat cannot be digested by microorganisms or rather difficult and slowly digested (iii) Inhibitors that renders inhibitory phenomenon in the reactor affecting microbial performance(Fagbohunge et al., 2016; Giwa et al., 2019b). Anaerobic digestion for methane fermentation is a complex process which can be divided into four different phases: hydrolysis, acidogenesis, acetogenesis /dehydrogenation, and methanation(Giwa et al., 2019c), as shown in (Fig.2a,b), and the phases are briefly discussed as follows.

Hydrolysis; at this phase the feed stock polymer and monomers are disintegrated by the action hydrolyzing and fermentative bacteria(Gerardi, 2003).Products obtained at this phase are simple sugars, amino acids, and fatty acids. This phase has been reported as the difficult to digest biomass, such as lignocellulose and keratin rich waste(Leung and Wang, 2016; Weiland, 2010). Acidogenesis, is the second phase, here the monomers from the hydrolysis are converted into short chain organic acids, alcohols, and few organic- sulfur, organic –nitrogen compounds, together with hydrogen and carbon-dioxide(Patinvoh et al., 2017). In the acetogenic stage , which is the third step, the bacteria transform the volatile fatty acid into carbon monoxide, acetate, and hydrogen. The fourth stage is the Methanogenesis is the last step, and the acetogenesis process offered the substrates for biogas production with methane contents and carbondioxide , among other small proportions of compounds(Debruyne and Hilborn, 2007).

III. OPTIONAL CONCEPTUAL TECHNOLOGY: PROCESS DESCRIPTION

Integrating pyrolysis and anaerobic digestion had recently been of interest, the conceptual route can be achievable from three different types of approach. (I) Combination of anaerobic digestion with pyrolysis (ii) Combination of Pyrolysis with anaerobic digestion (iii) The combination of Pyrolysis to anaerobic digestion and viz –viz (Anaerobic digestion – Pyrolysis and Anaerobic digestion)(Giwa et al., 2020a, 2019c; Monlau et al., 2016). This technique will promote high product yield from biomass, organic fractions of municipal solid wastes and food waste, including difficult to biodegrade waste from food waste processing industries.

3.1. Description of the integration process

The initial step one approach offered route for the application of pyrolysis products such as syn- biochar, gas, and bio-oil into anaerobic digestion as additives or feed substrate to enhance anaerobic digestion improved performance and also optimize the gas production and energy content (Feng and Lin, 2017). The second route proposed anaerobic digestion to first cater for raw food waste treatment. Various research on the application of anaerobic digestion for food waste, organic waste, sludge and biomass including difficult biodegradable waste treatment had been reported by (Feng and Lin, 2017; Giwa et al., 2021b, 2020a; Luo et al., 2013). The by-products obtainable are digestates and biogas, traditionally applied for energy and agricultural purposes respectively (Fagbohunbe et al., 2017; Mata-Alvarez et al., 2011). The proposed anaerobic-Pyrolysis integration route would allow channeling the digestate into a pyrolysis system for further conversion and subsequent diverting the pyrolysis aqueous phase back into the anaerobic digester. This route would provide for not only bio-treatment in anaerobic digestion, but also enhanced biogas production. The third proposed route shows the feasibility for optimal utilization and recycling of almost all by products is presented in anaerobic digestion and pyrolysis. With consideration to this route, the heat and energy can be stated to be self-sufficient for the combined system. Inhibition from utilization of pyrolysis products obtained from variable temperatures and feedstock nature cannot be totally ruled out in the combined system (Feng and Lin, 2017; Giwa et al., 2019c).

IV. CONCLUSION

The preliminary reviews presents the feasibility that food waste, biomass, and associated difficult to biodegrade products of food processing can be disposed of with the integration of anaerobic digestion and pyrolysis simultaneously. The anaerobic digestion is a competent technology for the treatment of organic waste or biomass that can easily be biodegraded, while the pyrolysis can be applied for the treatment of difficult to biodegrade waste. Products such as biochar from pyrolysis and syn-gas can enhance further optimization of the anaerobic digestion biogas if used as additives, while the product of anaerobic digestion such as the digestates can be applied for agronomy value. This direction will offer an approach to totally dispense off waste materials and improve on waste management system for optimal resource recovery.

REFERENCES:

- [1.] Abnisa, F., Mohd, W., Wan, A., 2014. A review on co-pyrolysis of biomass : An optional technique to obtain a high-grade pyrolysis oil. *Energy Convers Manag* 87, 71–85. <https://doi.org/10.1016/j.enconman.2014.07.007>
- [2.] Al-Wabel, M.I., Al-Omran, A., El-Naggar, A.H., Nadeem, M., Usman, A.R.A., 2013. Pyrolysis temperature induced changes in characteristics and chemical composition of biochar produced from conocarpus wastes. *Bioresour Technol* 131, 374–379. <https://doi.org/10.1016/j.biortech.2012.12.165>
- [3.] Beyene, H.D., Werkneh, A.A., Ambaye, T.G., 2018. Current updates on waste to energy (WtE) technologies: a review. *Renew Energy Focus* 24, 1–11. <https://doi.org/10.1016/j.ref.2017.11.001>
- [4.] Bridgwater, A. V., 2012. Review of fast pyrolysis of biomass and product upgrading. *Biomass and Bioenergy* 38, 68–94. <https://doi.org/10.1016/j.biombioe.2011.01.048>
- [5.] Cruz Viggì, C., Simonetti, S., Palma, E., Pagliaccia, P., Braguglia, C., Fazi, S., Baronti, S., Navarra, M.A., Pettiti, I., Koch, C., Harnisch, F., Aulenta, F., 2017. Enhancing methane production from food waste fermentate using biochar: the added value of electrochemical testing in pre-selecting the most effective type of biochar. *Biotechnol Biofuels* 10, 303. <https://doi.org/10.1186/s13068-017-0994-7>
- [6.] Debruyne, J., Hilborn, D., 2007. *Anaerobic Digestion Basics*. Small 2007, 1–6.
- [7.] Edwin Raj, R., Robert Kennedy, Z., Pillai, B.C., 2013. Optimization of process parameters in flash pyrolysis of waste tyres to liquid and gaseous fuel in a fluidized bed reactor. *Energy Convers Manag* 67, 145–151. <https://doi.org/10.1016/j.enconman.2012.11.012>
- [8.] Elkhalfifa, S., Al-Ansari, T., Mackey, H.R., McKay, G., 2019. Food waste to biochars through pyrolysis: A review. *Resour Conserv Recycl* 144, 310–320. <https://doi.org/10.1016/j.resconrec.2019.01.024>
- [9.] Fagbohunbe, M.O., Herbert, B.M.J., Hurst, L., Ibetu, C.N., Li, H., Usmani, S.Q., Semple, K.T., 2017.

- The challenges of anaerobic digestion and the role of biochar in optimizing anaerobic digestion. *Waste Manag.* <https://doi.org/10.1016/j.wasman.2016.11.028>
- [10.] Fagbohungebe, M.O., Herbert, B.M.J., Hurst, L., Li, H., Usmani, S.Q., Semple, K.T., 2016. Impact of biochar on the anaerobic digestion of citrus peel waste. *Bioresour Technol* 216, 142–149. <https://doi.org/10.1016/j.biortech.2016.04.106>
- [11.] Feng, Q., Lin, Y., 2017. Integrated processes of anaerobic digestion and pyrolysis for higher bioenergy recovery from lignocellulosic biomass: A brief review. *Renew Sustain Energy Rev* 77, 1272–1287. <https://doi.org/10.1016/j.rser.2017.03.022>
- [12.] Funke, A., Ziegler, F., 2011. Heat of reaction measurements for hydrothermal carbonization of biomass. *Bioresour Technol* 102, 7595–7598. <https://doi.org/10.1016/j.biortech.2011.05.016>
- [13.] Gerardi, M.H., 2003. *The Microbiology of Anaerobic Digesters*. *Microbiol Anaerob Dig.* <https://doi.org/10.1002/0471468967>
- [14.] Giwa, A.S., Ali, N., Vakili, M., Guo, X., Liu, D., Wang, K., 2020a. Opportunities for holistic waste stream valorization from food waste treatment facilities: A review. *Rev Chem Eng.* <https://doi.org/10.1515/revce-2019-0064>
- [15.] Giwa, A.S., Chang, F., Xu, H., Zhang, X., Huang, B., Li, Y., Wu, J., Wang, B., Vakili, M., Wang, K., 2019a. Pyrolysis of difficult biodegradable fractions and the real syngas bio-methanation performance. *J Clean Prod* 233, 711–719. <https://doi.org/10.1016/j.jclepro.2019.06.145>
- [16.] Giwa, A.S., Xu, H., Chang, F., Wu, J., Li, Y., Ali, N., Ding, S., Wang, K., 2019b. Effect of biochar on reactor performance and methane generation during the anaerobic digestion of food waste treatment at long-run operations. *J Environ Chem Eng* 7, 103067. <https://doi.org/10.1016/j.jece.2019.103067>
- [17.] Giwa, A.S., Xu, H., Chang, F., Zhang, X., Ali, N., Yuan, J., Wang, K., 2019c. Pyrolysis coupled anaerobic digestion process for food waste and recalcitrant residues: Fundamentals, challenges, and considerations. *Energy Sci Eng* 7, 1–15. <https://doi.org/10.1002/ese3.503>
- [18.] Giwa, A.S., Xu, H., Fengmin, C., Wang, B., Guo, X., Wang, K., 2021a. Recalcitrant organic residue compositions and the resource recovery from a food waste treatment facility. *J Mater Cycles Waste Manag* 23, 1479–1489. <https://doi.org/10.1007/s10163-021-01229-0>
- [19.] Giwa, A.S., Zhang, X., Memon, A.G., Ali, N., 2021b. Co-Digestion of Household Black Water with Kitchen Waste for a Sustainable Decentralized Waste Management: Biochemical Methane Potential and Mixing Ratios Effects. *Environ Eng Sci.* <https://doi.org/10.1089/ees.2020.0276>
- [20.] Giwa, A.S., Zhang, X., Xu, H., Vakili, M., Yuan, J., Wang, K., 2020b. Pyrolyzed waste stream and biochar performance evaluation in food waste anaerobic digestion. *Clean Technol Environ Policy* 22, 1199–1211. <https://doi.org/10.1007/s10098-020-01862-7>
- [21.] GRÝCOVA, B., STEPKOVA, K., KUCA, R., FIEDOR, J., OBROUCKA, K., 2012. Application of Pyrolysis Process in the Processing of Food Waste. *12th Int Multidiscip Sci GeoConference SGEM 2012* 5, 59–66. <https://doi.org/10.5593/SGEM2012/S20.V5009>
- [22.] Kan, T., Strezov, V., Evans, T.J., 2016. Lignocellulosic biomass pyrolysis: A review of product properties and effects of pyrolysis parameters. *Renew Sustain Energy Rev* 57, 1126–1140. <https://doi.org/10.1016/j.rser.2015.12.185>
- [23.] Keleş, S., Kaygusuz, K., Akgün, M., 2011. Pyrolysis of woody biomass for sustainable bio-oil. *Energy Sources, Part A Recover Util Environ Eff* 33, 879–889. <https://doi.org/10.1080/15567030903330652>
- [24.] Leung, D.Y.C., Wang, J., 2016. An overview on biogas generation from anaerobic digestion of food waste. *Int J Green Energy* 13, 119–131. <https://doi.org/10.1080/15435075.2014.909355>
- [25.] Liu, H., Zhang, Q., Hu, H., Li, A., Yao, H., 2014. Influence of residual moisture on deep dewatered sludge pyrolysis. *Int J Hydrogen Energy* 39, 1253–1261. <https://doi.org/10.1016/J.IJHYDENE.2013.10.050>
- [26.] Luo, G., Wang, W., Angelidaki, I., 2013. Anaerobic digestion for simultaneous sewage sludge treatment and CO biomethanation: process performance and microbial ecology. *Environ Sci Technol* 47, 10685–93. <https://doi.org/10.1021/es401018d>
- [27.] Martin, M.R., Fornero, J.J., Stark, R., Mets, L., Angenent, L.T., 2013. A single-culture bioprocess of methanothermobacter *thermautotrophicus* to upgrade digester biogas by CO₂-to-CH₄ conversion with

- H2. *Archaea* 2013. <https://doi.org/10.1155/2013/157529>
- [28.] Mata-Alvarez, J., Dosta, J., Macé, S., Astals, S., 2011. Codigestion of solid wastes: A review of its uses and perspectives including modeling. *Crit Rev Biotechnol* 31, 99–111. <https://doi.org/10.3109/07388551.2010.525496>
- [29.] Monlau, F., Francavilla, M., Sambusiti, C., Antoniou, N., Solhy, A., Libutti, A., Zabaniotou, A., Barakat, A., Monteleone, M., 2016. Toward a functional integration of anaerobic digestion and pyrolysis for a sustainable resource management. Comparison between solid-digestate and its derived pyrochar as soil amendment. *Appl Energy* 169, 652–662. <https://doi.org/10.1016/j.apenergy.2016.02.084>
- [30.] Nizami, A.S., Korres, N.E., Murphy, J.D., 2009. Review of the integrated process for the production of grass biomethane. *Environ Sci Technol* 43, 8496–8508. <https://doi.org/10.1021/es901533j>
- [31.] Oochit, D., Selvarajoo, A., Arumugasamy, S.K., 2017. Pyrolysis of biomass, in: *Waste Biomass Management - A Holistic Approach*. Springer International Publishing, pp. 215–229. https://doi.org/10.1007/978-3-319-49595-8_10
- [32.] Opatokun, S.A., Kan, T., Al Shoaibi, A., Srinivasakannan, C., Strezov, V., 2016. Characterization of Food Waste and Its Digestate as Feedstock for Thermochemical Processing. *Energy and Fuels* 30, 1589–1597. <https://doi.org/10.1021/acs.energyfuels.5b02183>
- [33.] Papuga, S., Musi, I., Gvero, P., Vuki, L., 2013. Preliminary Research of Waste Biomass and 1, 76–83. <https://doi.org/10.7251/COMEN1301076P>
- [34.] Patinvoth, R.J., Osadolor, O.A., Chandolias, K., Sárvári Horváth, I., Taherzadeh, M.J., 2017. Innovative pretreatment strategies for biogas production. *Bioresour Technol* 224, 13–24. <https://doi.org/10.1016/j.biortech.2016.11.083>
- [35.] Phuong, T., Pham, T., Kaushik, R., Parshetti, G.K., Mahmood, R., Balasubramanian, R., 2015. Food waste-to-energy conversion technologies: Current status and future directions. *Waste Manag* 38, 399–408. <https://doi.org/10.1016/j.wasman.2014.12.004>
- [36.] Pöschl, M., Ward, S., Owende, P., 2010. Evaluation of energy efficiency of various biogas production and utilization pathways. *Appl Energy* 87, 3305–3321. <https://doi.org/10.1016/J.APENERGY.2010.05.011>
- [37.] Scott, S.A., Dennis, J.S., Davidson, J.F., Hayhurst, A.N., 2006. Thermogravimetric measurements of the kinetics of pyrolysis of dried sewage sludge. *Fuel* 85, 1248–1253. <https://doi.org/10.1016/j.fuel.2005.11.003>
- [38.] Tomczyk, A., Sokołowska, Z., Boguta, P., 2020. Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. *Rev Environ Sci Biotechnol* 19, 191–215. <https://doi.org/10.1007/s11157-020-09523-3>
- [39.] Weiland, P., 2010. Biogas production: Current state and perspectives. *Appl Microbiol Biotechnol* 85, 849–860. <https://doi.org/10.1007/s00253-009-2246-7>
- [40.] Zhang, Q., Jun, S.R., Leuze, M., Ussery, D., Nookaew, I., 2017. Viral phylogenomics using an alignment-free method: A three-step approach to determine optimal length of k-mer. *Sci Rep* 7, 1–13. <https://doi.org/10.1038/srep40712>

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