Overview of biogas production from different feedstocks

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Abstract- Renewable energy could replace the conventional sources of energy such as fossil fuel and oil, serving as an alternative source of energy. Non-renewable energy sources have been found to pose various environmental problems such as greenhouse gas emissions as they tend to deplete at faster rates. Biological processes such as fermentation and anaerobic digestion for the past decades have given rise to the production of biofuels such as biogas and bioethanol. Biogas production is environmentally friendly and simple to produce although some drawbacks have limited its full exploitation in the past decades such as the physical and chemical treatment techniques required in the process. The most important parameter to consider in the application of anaerobic digestion is the type of feedstock as almost any organic material can be processed under this process. An incipient gain in the shift for a renewable source of energy is that the feedstock is often a by-product, a residue or waste product of other processes. Feedstocks include waste paper, grass clippings, leftover food, sewage, and animal waste which are obtainable without the need for competition of arable land. In general, some of these energy crops have been found to also contain the major constituents required of them such as sugar, starch, and oils. However, the measure of how digestible a particular feedstock is determined the yield of bioenergy it can produce. Thus the greater the digestibility of the feedstock, the higher the gas yield. Data available in this review include the amount of each potential source of raw material serving as feedstock for bioenergy production. This review, therefore, highlights the various types of feedstock that have been used in the few decades to produce bioenergy.

Index Terms- Biofuel, Biogas, Bioethanol, Feedstock, Renewable energy.

I. Introduction

The over-reliance on renewable forms of energy such as coal, increase in fuel prices, and the emission of greenhouse gases has braved researchers in the past few decades to find alternative methods to obtain a sustainable form of energy [1]. Biological processes such as fermentation and anaerobic digestion have given rise to the production of biofuels such as biogas and bioethanol. Thus the most important parameter to consider in the application of anaerobic digestion is the type of feedstock, as almost any organic material can be processed under this process. Feedstock has been defined to include substrates than can be converted to methane by anaerobic digestion [2]. This could range from biodegradable waste water to complex high-solid waste. Toxic compounds could also be degraded anaerobically according to the same study.

According to Sawatdeenarunat, et al. [3], renewable energy such as biogas can be produced from different types of organic materials (feedstock) such as industrial wastewater, agricultural waste, food waste, and sewage sludge. Biogas is a renewable fuel that largely consists of 60-70% methane, 20-30% carbon dioxide and other trace gases such as hydrogen sulfide. The gas produced, can be used to generate electricity and also in the production of combined heat and power generation using appropriate technologies [4]. Plant residues which are rich in lignocellulose signify the most favorable renewable organic feedstock for bioenergy production such as biogas production without the competition for arable land [3, 5].

A major challenge in the utilization of lignocellulosic feedstock in the fermentative process is the transformation of the complex polysaccharides into simple sugars which can then be assimilated by a large consortium of microorganisms [6]. Pretreatment of lignocellulosic biomass to remove lignin, however, alters the physical and chemical structures of lignocellosic feedstock significantly thereby improving the cellulose activity for higher yield of sugars [7]. The lignin portion of the feedstock protecting the structure of the cell wall of lignocelluloses tends to resist the direct accessibility of cellulose to microorganisms during the bioconversion of feedstock to bioenergy [8]. In this case, the need for pretreatment is essential as technique targets the disruption or removal of lignin and hemicellulose present in the biomass making cellulose porous and accessible to the microorganisms for further digestion to yield energy [1]. These, together with the low nutrient content (nitrogen, phosphorous, trace elements, etc.) makes lignocellulosic materials a poor nutrient source for degrading microorganisms [5]. In other to counterbalance these nutrient losses, some micronutrients required by microorganisms for anaerobic digestion have been employed by researchers to supplement the carbon to nitrogen ratio as commonly employed in mono-digestion [9].

Also, fermentation and distillation have been used for thousands of years to produce bioethanol from sugar but was until the mid-18th century that the process was fully explained [10]. Sugarcane bagasse, among several feedstocks investigated worldwide, is considered in Brazil for the use as a raw-material for cellulosic bioethanol production [11, 12]. However, the use of this feedstock for second generation ethanol is hypothetically remarkable as it is readily made from the first generation plants [11, 13]. Drawbacks such as process instability, process failure, poor methane yield, the larger retention times, and reactor failures have limited the full exploitation for the production of bioenergy from feedstocks [9].

This paper, however, highlights the various types of feedstock that have been used in the few decades to produce bioenergy.

II. FEEDSTOCK FOR BIOGAS PRODUCTION

Biodegradable feedstocks are known for biogas production and could be solid, slurries, and in both dilute and concentrated liquid forms [14]. This feedstock includes agricultural wastes and crop residues, animal wastes, aquatic waste, forest residues and municipal solid wastes [15, 16].

Agricultural: animal and crop residues

Several agricultural crops and activities produce residues that can be used as a feedstock for biogas production such as biogas. There is an abundance of biomass in the form of agricultural waste and crop residue which can be used as feedstock for anaerobic digestion [17, 18]. Bioenergy production has been achieved in the past decades from various agricultural feedstocks such as straw, sugarcane bagasse, corn silage, wood chips, weeds, tobacco waste, crop stubbles, fruit and vegetable processing wastes, and oil cakes [17]. A significant amount of waste is also produced by animals as the activity of animal breed has gained an increasing recognition [19]. Cattle dung has been used as one of the solid waste feedstock for most parts of rural India as about 354 million tonnes of dung is available per year [17]. Countries like the Philippines and Taiwan predominantly used pig manure as feedstock for the bioenergy production [20]. Generally, mostly used animal wastes include cow dung, pig waste, poultry manure, horse dung, camel dung, elephant dung, fishery waste and slaughter house wastes. Studies have found that poultry wastes are rich in organic nitrogen and relatively lower carbon source [21].

Aquatic plants as feedstock for bioenergy production

Feedstocks such as water hyacinth, micro and macro algae, sea weeds are suitable for bioenergy production [22]. These feedstocks have easily hydrolysable sugars, contain low lignin content, and they do not compete with land resources used in arable food crop cultivation [23]. Methane production has been found in the co-digestion of alga sludge and waste paper. In this study, the maximum methane production rate of 1607 ± 17ml/day of algae sludge at a combined 5 gVS/l day loading rate with 60 % VS of paper added in alga sludge feedstock [22]. Both water hyacinth and micro algae are mostly used as feed material because of their higher gas yield [20].

III. Biogas production

The anaerobic digestion process to produce biogas offers a range of benefits such as the lowering of fossil fuel usage, mineral fertilizer replacement (from the digestate), renewable energy production and in wastewater treatment [24]. The hydrolysis process which is the rate-determining step of the overall process converts a wide range of solid organic materials (polymeric) as feedstocks into sugars, fatty acids and amino acids [25]. Fermentation of these materials produces volatile fatty acids. Acidogenesis forms hydrogen, carbon dioxide and acetate from VFAs. The methanogenesis produces biogas, a mixture of methane, carbon dioxide, and numerous trace elements such as hydrogen sulfide, ammonia, carbon monoxide [26]. The hydrolysis process of anaerobic digestion is often the rate-limiting step when the fibrous material is used as the feedstock because of the recalcitrant presence of lignin [27]. In this case, substrate pretreatment could be an alternative to improve the AD process by increasing the accessible surface area, modifying the crystalline structure or partially depolymerizing cellulose, solubilizing hemicellulose and lignin or modifying lignin structure. Table 1 presents the feedstock type and the biogas yield per dry matter estimated.

Table 1: Different feedstocks with biogas yield according to Maurya, et al. [28].

Feedstock	% dry matter	Biogas yield (m^3/wet tonne)
Purpose grown crops	30	50-220
Sewage sludge	10	9-16
Animal slurry and manure	15	12-23
Food and drink	18	20-14

Lignocellulosic feedstocks for biogas production

The availability of lignocellulosic materials is abundant worldwide as these materials have been found to be estimated to account for approximately 50% of the biomass in the world [29]. Lignocellulosic feedstock consists largely of three different forms of polymeric units, namely, cellulose, hemicellulose, and lignin, and are observed to be cross-linked to each other [30]. The cellulose is vastly crystalline, resists depolymerization, shows insolubility in water, rigid and heart, making it not easily to be broken [1, 31]. In regards to the structure of the cellulose, efficient alteration of cellulose has been hindered. The structural component of a lignocellulosic biomass such as that of the crystallinity of cellulose has affected the rate of enzymatic hydrolysis [32]. Pretreatment methods thus aid to disrupt the inter- and intra- hydrogen bonding of the cellulose chain even though it is not completely broken as it was found in the case of hydrothermal pretreatment according to Fan, et al. [32]. Various pretreatment that feedstocks for biogas production have undergone is presented in Table 2. Renewable energy from biomass is one of the most efficient and effective options for the various other alternative sources of energy [33]. It is however available as a domestic resource in the rural areas which are not subject to world fluctuations. Rao, et al. [33] proposed that biomass is a potentially reliable energy resource because of its availability as a sewage sludge, animal manure, industrial waste and agricultural waste. Feedstock has been defined to include any substrate that can be converted to methane by anaerobic bacteria [2]. This ranges from readily degradable wastewater to complex high-solid waste and that it is required of this given solid waste or wastewater to contain a substantial amount of organic matter which is finally converted mainly to methane and CO_2. Steffen, et al. [2] categorize the sources of substrates for anaerobic digestion as energy crops, agricultural wastes, industrial wastewater and municipal biowaste. Applying different feedstock improvement solutions to feedstock investigated such as nutrient addition, co-digestion and biomass pretreatment have been demonstrated as effective means of enhancing the methane yield of the feedstock thereby improving the overall anaerobic digestion process [9].

Table 2: Different pretreatment methods versus feedstock applied in literature

Pretreatment Methods	**Feedstocks**	**References**
Thermochemical	Water hyacinth	[34]
Ultrasonic	Activated sludge	[35]
Acidic	Newspaper	[36]
Steam	Softwood	[37]
Carbon dioxide	Sugarcane bagasse	[38]
Lime	Switch grass and corn stover	[39]
Liquid hot water	Wheat straw	[40]
Liquid hot water	Corn fibre	[41]
Liquid hot water	Sugarcane bagasse	[42]
Biological	Olive mill wastewater	[43]

Influence of the operating parameters for biogas production

A biogas plant can be measured by studying and monitoring the variation in parameters like temperature, loading rate, hydraulic retention time and pH, as a sharp change in these could adversely affect the biogas production process. Some of the influence of these parameters on feedstock from literature is presented in Table 3.

Table 3: Selected operating parameters and feedstocks for biogas production

Feedstock	**Parameter of interest**	**Parameter range**	**Results**	**Reference**
Water hyacinth	Solid to water content	Six different solid concentrations from 5g/L to 30g/L	Maximum yield of biogas obtained at 25g/L	[44]
Water hyacinth	Solid to water content	Substrates with five different solid concentrations 3,5,7, 9,11% of total solids experimented	7% of total solids produced the best yield	[45]
Food waste	Temperature	Temperature from 30 to 55˚C	Highest gas production and COD removed rate was achieved at 50˚C	[46]
Algae sludge and waste paper	Organic loading rate	From 4 gVs/lday to 5 gVs/lday	Maximum methane production rate of 1607 ± 17ml	[22]
Cow dung	pH	pH of 4, 7, and 9 investigated	Best biogas at pH of 7, followed by 9 and 4	[47]
Waste water and bagasse	Carbon-Nitrogen ratio	C:N ratios of 6.62, 9.27, 13.19, 19.56, 24.53, 31.76, and 64.58 were investigated	Highest methane yield at C: N of 25.53	[48]

Influence of Carbon-Nitrogen (C/N) Ratio on feedstock characterization

The relationship between the amount of carbon and nitrogen existing in a particular feedstock is represented by its C/N ratio [49]. However, maintaining a proper structure of feedstock for effective plant operation so that the C: N ratio in feed remains within the desired range is essential. It has been found that during anaerobic digestion, microorganisms make use of carbon 25-30 times faster than nitrogen and thus microbes require about 20 to 30:1 ratio of C: N [50]. Ward, et al. [16] predicted the optimum C/N ratios in an anaerobic digester to be 20-30 and that a high C/N ratio gives an indication of rapid consumption of nitrogen by methanogens resulting in lower gas production. A C/N ratio of 26:1 has also been reported to achieve the maximum biogas yield with various agricultural feedstocks [51]. Kızılkaya and Bayraklı [52] observed that C/N ratios can often be considerably lower than what is observed by Ward, et al. [16], for example, sewage sludge with a C/N ratio of approximately 9:1 has also been reported. A condition for good composting is thus a C/N ratio of 25:1 to 40:1 and that anaerobic microbe when given a steady diet at 30:1 ratio decomposes organic materials very quickly. The carbon to nitrogen ratio of some feedstock used for biogas production is shown in Table 4.

Table 4: Feedstocks and their C/N ratios from literature

Feedstock	**C: N ratio**	**Reference**
Pomegranate waste	80	[53]
Poultry manure	11.54	[53]
Cow dung manure	22.71	[53]
Sugarcane bagasse	131.8	[54]
Food waste	13.6	[55]
Corn stalk	60	[15]
Slaughter house waste	2-4	[15]
Sawdust	200-511	[20]

IV. CONCLUSION

Currently, the use of non-renewable energy outweighs that of the renewable energy making the globe not environmentally and economically secured. Investing in a world completely made of renewable energy which is affordable and clean is the right candidate for sustainable development. By so doing, our natural environment is not only kept clean but also protected from possible emissions. Biogas production has been found to be derived directly from plants, or indirectly from agricultural, commercial, domestic, and or industrial wastes. This paper has sought to address some types of feedstock used in the past few decades, their biogas yield, and pretreatment techniques applied. Production of bioenergy such as biogas from feedstocks with qualities such as less energy input, low cost of pretreatment, affordability, the reach of newly emerging feedstocks without the competition for arable land and the need to be environmentally friendly is the surest way for the future and thus warranted to all researchers.

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REFERENCES

[1] S. Fan, P. Zhang, F. Li, S. Jin, S. Wang, and S. Zhou, "A Review of Lignocellulose Change During Hydrothermal Pretreatment for Bioenergy Production," *Current Organic Chemistry*, vol. 20, pp. 2799-2809, 2016.

[2] R. Steffen, O. Szolar, and R. Braun, "Feedstocks for anaerobic digestion," *Institute of Agrobiotechnology Tulin, University of Agricultural Sciences, Vienna*, 1998.

[3] C. Sawatdeenarunat, K. Surendra, D. Takara, H. Oechsner, and S. K. Khanal, "Anaerobic digestion of lignocellulosic biomass: challenges and opportunities," *Bioresource technology*, vol. 178, pp. 178-186, 2015.

[4] I. Maile, E. Muzenda, and C. Mbohwa, "Biochemical methane potential of OFMSW for City of Johannesburg," 2016.

[5] R. Chandra, H. Takeuchi, and T. Hasegawa, "Methane production from lignocellulosic agricultural crop wastes: A review in context to second generation of biofuel production," *Renewable and Sustainable Energy Reviews*, vol. 16, pp. 1462-1476, 2012.

[6] S. G. Karp, A. L. Woiciechowski, V. T. Soccol, and C. R. Soccol, "Pretreatment strategies for delignification of sugarcane bagasse: a review," *Brazilian archives of biology and technology*, vol. 56, pp. 679-689, 2013.

[7] N. M. A. Liyakathali, "Ultrasonic pretreatment of energy cane bagasse for biofuel production," Master of Science, The Department of Biological and Agricultural Engineering Loiusianna State University, 2014.

[8] A. Hendriks and G. Zeeman, "Pretreatments to enhance the digestibility of lignocellulosic biomass," *Bioresource technology*, vol. 100, pp. 10-18, 2009.

[9] I. A. Nges, "Anaerobic digestion of crop and waste biomass: Impact of feedstock characteristics on process performance," Doctoral, Luund University (Media-Tryck), 2012.

[10] D. Wesolowski, "The sustainability of ethanol fuel in the United States," ed.

[11] T. L. Bezerra and A. J. Ragauskas, "A review of sugarcane bagasse for second-generation bioethanol and biopower production," *Biofuels, Bioproducts and Biorefining*, 2016.

[12] G. Rocha, A. Gonçalves, S. Nakanishi, V. Nascimento, and V. Silva, "Pilot scale steam explosion and diluted sulfuric acid pretreatments: Comparative study aiming the sugarcane bagasse saccharification," *Industrial Crops and Products*, vol. 74, pp. 810-816, 2015.

[13] L. P. Andrade, E. Crespim, N. de Oliveira, R. C. de Campos, J. C. Teodoro, C. M. A. Galvao, *et al.*, "Influence of sugarcane bagasse variability on sugar recovery for cellulosic ethanol production," *Bioresour Technol*, vol. 241, pp. 75-81, Oct 2017.

[14] A. C. Wilkies. (2017, 15/11/2017). *Biogas: A renewable Energy*. Available: http://biogas.ifas.ufl.edu/

[15] R. Khoiyangbam, N. Gupta, and S. Kumar, *Biogas Technology: towards sustainable development*: The Energy and Resources Institute (TERI), 2011.

[16] A. J. Ward, P. J. Hobbs, P. J. Holliman, and D. L. Jones, "Optimisation of the anaerobic digestion of agricultural resources," *Bioresource technology,* vol. 99, pp. 7928-7940, 2008.
[17] N. Ravindranath, H. Somashekar, M. Nagaraja, P. Sudha, G. Sangeetha, S. Bhattacharya, *et al.*, "Assessment of sustainable non-plantation biomass resources potential for energy in India," *Biomass and Bioenergy,* vol. 29, pp. 178-190, 2005.
[18] M. Macias-Corral, Z. Samani, A. Hanson, G. Smith, P. Funk, H. Yu, *et al.*, "Anaerobic digestion of municipal solid waste and agricultural waste and the effect of co-digestion with dairy cow manure," *Bioresource technology,* vol. 99, pp. 8288-8293, 2008.
[19] V. Skoulou and A. Zabaniotou, "Investigation of agricultural and animal wastes in Greece and their allocation to potential application for energy production," *Renewable and Sustainable Energy Reviews,* vol. 11, pp. 1698-1719, 2007/10/01/ 2007.
[20] B. T. Nijaguna, *Biogas Technology*. New Delhi: New Age International (P) Limited, 2006.
[21] I. M. Nasir, T. I. Mohd Ghazi, and R. Omar, "Anaerobic digestion technology in livestock manure treatment for biogas production: a review," *Engineering in Life Sciences,* vol. 12, pp. 258-269, 2012.
[22] H.-W. Yen and D. E. Brune, "Anaerobic co-digestion of algal sludge and waste paper to produce methane," *Bioresource technology,* vol. 98, pp. 130-134, 2007.
[23] V. N. Nkemka and M. Murto, "Evaluation of biogas production from seaweed in batch tests and in UASB reactors combined with the removal of heavy metals," *Journal of environmental management,* vol. 91, pp. 1573-1579, 2010.
[24] C. T. Lukehurst, "Developing the use of digestate in the UK," presented at the IEA Bioenergy Task 37 Seminar, 2009.
[25] N. M. C. Saady and D. I. Massé, "Impact of organic loading rate on psychrophilic anaerobic digestion of solid dairy manure," *Energies,* vol. 8, pp. 1990-2007, 2015.
[26] C. J. Rivard and D. Boone, "The anaerobic digestion process," National Renewable Energy Lab., Golden, CO (United States)1996.
[27] V. Vorgelegt, "Optimization of Anaerobic Digestion of Sugarcane Waste for Biogas Production in Brazil," Doctor of Engineering, University of Rostock, University of Rostock, 2017.
[28] D. P. Maurya, A. Singla, and S. Negi, "An overview of key pretreatment processes for biological conversion of lignocellulosic biomass to bioethanol," *3 Biotech,* vol. 5, pp. 597-609, 2015.
[29] S. Fan, P. Zhang, F. Li, S. Jin, S. Wang, and S. Zhou, "A Review of Lignocellulose Change During Hydrothermal Pretreatment for Bioenergy Production," *Current Organic Chemistry,* vol. 20, pp. 1-11, 2016.
[30] D. Fengel and G. Wegener, *Wood: Chemistry, Ultrastructure, Reactions.* Berlin: DeGruyter, 1984.
[31] A. D. French and M. S. Cintrón, "Cellulose polymorphy, crystallite size, and the Segal crystallinity index," *Cellulose,* vol. 20, pp. 583-588, 2013.
[32] S. Fan, P. Zhang, L. Fan, J. Shuguang, W. Siqi, and Z. Shuqiong, "A Review of Lignocellulose Change During Hy," 2016.
[33] P. V. Rao, S. S. Baral, R. Dey, and S. Mutnuri, "Biogas generation potential by anaerobic digestion for sustainable energy development in India," *Renewable and Sustainable Energy Reviews,* vol. 14, pp. 2086-2094, 2010.
[34] V. Patel, M. Desai, and D. Madamwar, "Thermochemical pretreatment of water hyacinth for improved biomethanation," *Applied Microbiology and Biotechnology,* vol. 42, pp. 67-74, 1993.
[35] Q. Wang, M. Kuninobu, K. Kakimoto, H. I. Ogawa, and T. Kato, "Upgrading of anaerobic digestion of waste activated sludge by ultrasonic pretreatment," *Bioresource Technology,* vol. 68, pp. 309-313, 1999.
[36] W. Xiao and W. W. Clarkson, "Acid solubilization of lignin and bioconversion of treated newsprint to methane," *Biodegradation,* vol. 8, pp. 61-66, 1997.
[37] J. Söderström, L. Pilcher, M. Galbe, and G. Zacchi, "Two-step steam pretreatment of softwood with SO2 impregnation for ethanol production," *Applied biochemistry and biotechnology,* vol. 98, p. 5, 2002.
[38] Y. Zheng, H. M. Lin, and G. T. Tsao, "Pretreatment for cellulose hydrolysis by carbon dioxide explosion," *Biotechnology Progress,* vol. 14, pp. 890-896, 1998.
[39] V. S. Chang, W. E. Kaar, B. Burr, and M. T. Holtzapple, "Simultaneous saccharification and fermentation of lime-treated biomass," *Biotechnology Letters,* vol. 23, pp. 1327-1333, 2001.
[40] J. A. Perez, A. Gonzalez, and J. M. Oliva, "Effect of process variables on liquid hot water pretreatment of wheat straw for bioconversion to fuel-etahnol in a batch reactor," *Journal of Chemical Technology and Biotechnology,* vol. 82, pp. 929-938, 2007.
[41] S. G. Allen, D. Schulman, and J. Lichwa, "Acomparison between hot water and steam fractionation of corn fiber," *Industrial and Engineering Chemistry Research,* vol. 40, pp. 2934-2941, 2001.
[42] M. Laser, D. Schulman, and S. G. Allen, "A comparison of liquid hot water and steam pretreatments of sugarcane bagasse for conversion to ethanol," *Bioresource Technology*

vol. 81, pp. 33-44, 2002.
[43] A. Dhouib, M. Ellouz, F. Aloui, and S. Sayadi, "Effect of bioaugmentation of activated sludge with white-rot fungi on olive mill wastewater detoxification," *Letters in applied microbiology,* vol. 42, pp. 405-411, 2006.
[44] S. K. Sharma, I. Mishra, M. P. Sharma, and J. Saini, "Effect of particle size on biogas generation from biomass residues," *Biomass,* vol. 17, pp. 251-263, 1988.
[45] C. Braguglia, A. Gianico, and G. Mininni, "Laboratory-scale ultrasound pre-treated digestion of sludge: heat and energy balance," *Bioresource technology,* vol. 102, pp. 7567-7573, 2011.
[46] S. Fang, L. Ping, Z. Yang, and J. Mao, "A review of different pretreatment techniques for enhancing biogas production," in *Materials for Renewable Energy & Environment (ICMREE), 2011 International Conference on*, 2011, pp. 263-266.
[47] A. Sambo, B. Garba, and B. Danshehu, "Effect of some operating parameters on biogas production rate," *Renewable Energy,* vol. 6, pp. 343-344, 1995.
[48] V. Moset, A. Cerisuelo, S. Sutaryo, and H. B. Møller, "Process performance of anaerobic co-digestion of raw and acidified pig slurry," *Water research,* vol. 46, pp. 5019-5027, 2012.
[49] S. Verma, "Anaerobic digestion of biodegradable organics in municipal solid wastes," M.Sc. Thesis, Columbia University, 2002.
[50] T. Sreekrishnan, S. Kohli, and V. Rana, "Enhancement of biogas production from solid substrates using different techniques—a review," *Bioresource technology,* vol. 95, pp. 1-10, 2004.
[51] B. Deepanraj, V. Sivasubramanian, and S. Jayaraj, "Biogas Generation through Anaerobic Digestion Process-An Overview," *Research Journal of Chemistry and Environment,* vol. 18, pp. 1-14, 2014.
[52] R. Kızılkaya and B. Bayraklı, "Effects of N-enriched sewage sludge on soil enzyme activities," *Applied Soil Ecology,* vol. 30, pp. 192-202, 2005.
[53] V. G. Ardaji, H. Radnezhad, and M. Nourouzi, "Improving Biogas Production Performance From Pomegranate Waste, Poultry Manure and Cow Dung Sludge Using Thermophilic Anaerobic Digestion: Effect of Total Solids Adjustment," *Journal of Earth, Environment and Health Sciences,* vol. 2, p. 97, 2016.
[54] W. S. F. Simo, N. E. Jong, and C. Kapseu, "Improving Biogas Production of Sugarcane Bagasse by Hydrothermal Pretreatment," *Chemical and Biomolecular Engineering,* vol. 1, pp. 21-25, 2016.
[55] J. Yi, B. Dong, J. Jin, and X. Dai, "Effect of increasing total solids contents on anaerobic digestion of food waste under mesophilic conditions: performance and microbial characteristics analysis," *PloS one,* vol. 9, p. e102548, 2014.

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