energies

Supplementary Materials: Improvement of biogas quality and quantity for small scale biogas-electricity generation application in off-grid settings; A field-based study.

Henry Wasajja [1,4]*, Saqr A.A. Al-Muraisy[1], Antonella L. Piaggio[1], Pamela Ceron-Chafla[1], P.V. Aravind [2,3], Henri Spanjers[1] , Jules B. van Lier and Ralph E.F. Lindeboom[1]

[1] Water Management Department, Sanitary Engineering Section, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands.
[2] Process and energy department, Faculty of 3mE, Delft university of technology, Leeghwaterstraat 39, 2628 CB, Delft, The Netherlands.
[3] Energy and Sustainability Research Institute Groningen, Faculty of Science and Engineering, University of Groningen, Nijenborgh 6, 9747 AG Groningen, The Netherlands.
[4] Department of Electrical Engineering, Faculty of Engineering, Ndejje University, P.O. Box 7088, Kampala (Uganda).
* Correspondence: H.Wasajja-1@tudelft.nl, jjhwasajja@yahoo.com; Tel.: +31(0)152786987

Received: Date; Accepted: Date; Published: Date

Literature identification of operational practices and AD reactor designs suitable for small scale digesters

Literature on biogas is extensive and many parameters have been shown to influence the quality and quantity of biogas produced from AD. The aim of this section is to derive hypotheses for the relevance of parameters given the local physical and socio-economic conditions. The outputs have been summarised in table 2 of the main article .

1.1 Pre-treatment

Pre-treatment is mostly applied to feedstock from complex organic sources such as plant waste, whose biodegradability needs to be improved to enhance methane production [1]. Pre-treatment can be categorised as physical, chemical, physicochemical, biochemical and biological pre-treatments [2]. If more than one feedstock is to be used for AD, often only the most complex organic source is considered for pre-treatment to reduce the associated costs [1].

Physical pre-treatment methods include milling, chipping, gridding, ultra-sonication and irradiation. Milling is used to reduce the size of the substrate, which increases the particle surface area available for enzyme attack. Colloid mills, fibrillator, and dissolvers are majorly used for wet materials and fats whereas for dry materials, extruders, rollers, as well as cryogenic and hammer milling are majorly applied [2]. Although, milling pre-treatment methods have some drawbacks which include high energy consumption [2], for small scale application, manual milling can be considered. For small scale biogas applications in Uganda, there is a huge potential of biogas feedstock, especially from plant waste such as locally available banana leaves. If pre-treatment, such as using a simple mechanical grinder is embraced, it would distinctly increase feedstock availability for co-digestion with the usual animal waste.
Irradiation such as gamma rays, electron beam and micro wave can be used as a pre-treatment method for lignocellulosic wastes. Gamma rays pre-treatment helps to increase accessible surface area and pore size, decreases the degree of polymerization and cellulose crystallinity in biomass hence improving enzymatic hydrolysis in lignocelluloses [3]. For this type pre- pretreatment to be applied in small scale digesters, the sun can be used as a source of radiation especially for sunbelt countries. Other physical such as ultra-sonication, lysis centrifugation and high pressure pre-treatment may not be readily applicable in small scale settings due to their high energy consumption which may not be compensated by extra methane yield [1,2,4].

Physicochemical pre-treatment usually concerns thermal treatment (hot water and steam explosion) and ammonia fiber explosion [5]. Thermal pre-treatment can be categorized as high temperature pre-treatment (150 ˚C - 220 ˚C), which sometimes involves steam explosion and mildly elevated temperature pre-treatment (60 ºC - 90 ºC) [1]. High temperature pre-treatment requires a reliable source of heat if it is to be applied in AD which may not be readily available especial for small scale digesters.

Pasteurization methods or relatively low temperature pre-treatment have been investigated by a number of researchers. An increase in the methane yield by 30-40% has been reported when low temperature pre-treatment is applied to feedstock [6]. For some feedstocks, such as waste activated sludge (WAS), this type of pre-treatment, has shown a positive impact on the AD process [4], however, feedstock with high concentration of carbohydrates may not be suitable for pre-treatment at temperatures exceeding 70-80 ºC [7]. The low efficiency at these temperatures was attributed to the occurrence of the Maillard-reaction, creating refractory organic matter from carbohydrates with proteins [4,7]. The availability of easily harvestable solar energy, especially in tropical countries, may facilitate thermal pre-treatment by means of solar thermal concentration. This could provide an alternative pre-treatment method for small scale applications. In addition, for a biogas-electricity generation system, the waste heat from devices such as SOFCs with a typical operating temperature above 700 ºC, can also be used as a thermal source for feedstock pre-treatment.

Chemical pre-treatment may include alkali pre-treatment, alkali peroxide pre-treatment, organosolv (lignocelluloses is mixed with organic solvent and water, the mixture is then heated), wet oxidation, diluted acid at high temperature or concentrated acid at low temperature (acid hydrolysis) [2]. This pre-treatment is reported to be effective in enhancement of methane production and feedstock bio-digestibility [8–10]. However, it should be noted that the use of chemicals may have a negative effect on the quality and quantity of biogas due to inhibition caused by, for example, the accumulation of cations [11]. Alkalis such as NaOH may result into excess Na^+ concentration which may slow down microbial growth [11]. Therefore, chemical pre-treatment methods may distinctly increase the operation cost of small-scale biogas-electricity generation system since it involves the use of chemicals. Moreover, the logistic management associated with chemical dosage need to be carefully considered against its merits.

Biological pre-treatment using different species of fungi generally enhances biodegradation of feedstock and hence improves biogas yield [2,12,13]. Utilization of biological methods is attractive from the economic point of view however these methods are slow and require a large area as well as careful control of bacterial or fungal growth [14]. Although this pre-treatment is cost effective, it may not be technically feasible in small scale biogas-electricity generation applications.

1.2 Co-digestion

Co-digestion is the simultaneous treatment of two or more waste streams with complementary characteristics [15][16]. Traditionally, co-digestion was focused on common feedstocks such as cow dung and pig manure and less attention was given to other feedstocks. However, recently research is being carried out on various types of feedstocks in order to develop a more efficient waste treatment strategy and widen the scope of energy generation by AD depending on feedstock availability in a particular location.

Different feedstocks have different properties and composition and even cow dung from different breeds may have different composition [17]. Co-digestion can potentially counter solve drawbacks linked to feedstock properties in single feedstock AD, apart from improving the quality and quantity of biogas [1]. Such drawbacks include low content of biodegradable organic matter for substrates like WAS and animal dung, high concentration of N in substrates such as animal manure, which may inhibit methanogenesis; the presence of heavy metals in substrates such as municipal solid waste (MSW), and seasonal availability as in the case of agricultural waste [1]. Therefore, co-digestion is likely to balance the feedstock composition with in the non-toxic ranges for microbial growth.

Co-digestion of various organic feed stocks has been reported to enhance biogas yield from anaerobic digesters by over 60% [18]. Feedstocks, such as mixed food waste were reported to have a high methane yield [19]. Co-digestion may enhance the economic returns of small energy systems through increased biogas production. Kaparaju et al. [20] reported that co-digestion could have both economic and bio-technical advantages as far as energy generation from biogas is concerned. They further reported that co-digestion helps in maintaining the pH in optimal ranges during methanogenesis and overcoming ammonia inhibition, which is associated with pure manure digestion. This in turn, increases the methane yield and hence reduces the investment costs of biogas-based power plants.

Callaghan et al. [21] investigated the effect of co-digestion on the methane yield on a laboratory scale digester at a loading rate of 3.2 to 5.0 kg VS m^{-3} d^{-1} and hydraulic retention time (HRT) of 21 days. They found that co-digestion of cow dung with food and vegetable waste in a ratio of up to 1:1 (cow dung: food and vegetable waste) increased the rate of biogas production, whereas co-digestion of cow dung with chicken manure did not yield satisfactory results. This was attributed to the high concentration of free ammonia in the liquor of more than 100 mg/l. Bothi et al. [22] reported that addition of food waste to cow dung can potentially reduce the H_2S content in biogas and also increase the methane yield depending on the elemental composition of food waste. Co-digestion of cow dung with coffee pulp was studied by Corro et al. [23]. They observed that co-digestion of cow dung and coffee pulp increased the C/N ratio of the substrate from 5 to over 50 and this enhanced methane yield. They also observed that co-digestion of cow dung with coffee pulp can potentially reduce the

H_2S content of biogas [23]. This occurs due to a synergistic effect: cow dung contains a high concentration of microorganisms, whereas coffee pulp contains nutrients that are essential for bacterial growth or may precipitate with H_2S [23]. Co-digestion of cow and pig dung was reported to increase the methane yield and an optimal ratio of 1:1 by volume is proposed by these researchers [24]. Moreover, wall paper has been reported to be a potential co-feedstock for cow dung [25]. Even under cold climate conditions where digesters operate at psychrophilic conditions, co-digestion of cow and sheep dung was reported to increase biogas production by 100% in comparison to cow dung mono digestion [26].

The effect of co-digestion of cow dung and organic fraction of municipal solid waste (OFMSW) on methane yield was investigated by Hartmann et al. [27]. They used a continuous stirred-tank reactor (CSTR) under thermophilic conditions (55 °C) at HRT of 14-18 days and organic loading rate (OLR) of 3.3 - 4.0 g VS $L^{-1}d^{-1}$. Their results showed that co-digestion of cow dung with OFMSW at a ratio of 50% (VS/VS) enabled stable operation conditions and increased methane yield. Co-digestion of OFMSW with cow dung and cotton gin waste (CGW) was analyzed by Macias-Corral et al. [28] in a two stage pilot anaerobic digester. They observed that co-digestion of cow dung with CGW yielded 87 m^3 of methane/ton on dry matter basis as compared to digestion of cow dung alone which yielded 62 m^3 of methane/ton. Co-digestion of OFMSW with cow dung had a much higher biogas production rate (172 m^3 of methane/ton) as compared to cow dung alone [28]. They further observed that cow dung contains native cellulose degrading microorganisms and nutrients, which reduces imbalances in single feedstocks and hence improves biodegradation. They also observed that a two-stage digester produces a higher methane content (more than 72% methane) as compared to a single stage digester with typical gas production containing 60% methane. The higher methane content in a two stage digester could be attributed to more CO_2 production in the first stage and less CO_2 production in the second stage.

Kaparaju et al. [20] analysed the potential of co-digestion of pig manure with potato waste (potato stillage and potato peels) in a laboratory scale digester at a loading rate of 2 kg VS m^{-3} d^{-1} in a CSTR at 35 °C. They found that potato waste increased the methane yield from 0.13 - 0.15 m^3 kg^{-1} of volatile sold to 0.30 - 0.33 m^3 kg^{-1} of volatile solids if it is co-digested with pig manure in a proportion of up to 15-20%. The increase in methane yield was attributed to the high starch content in potato waste since digestion of pig manure alone results in detrimental effect of the AD process. This waste contains more lignin, a considered refractory compound capable of inhibiting the degradation of other components like cellulose [20]. Liu et al. [29] studied the co-digestion of kitchen waste (fruits, vegetables, meat, fish and staple foods), cow and pig dung under thermophilic conditions (53 °C) at controlled pH of 7.5 - 7.8. They observed that if limited amount of kitchen waste (2-3%) is co-digested with cow and pig dung, it can potentially improve the digestion process of both cow and pig dung. The feasibility of co-digestion of food waste and piggery wastewater was investigated by Zhang et al. [30] in a laboratory scale digester. They found that piggery wastewater has trace elements such as Na, Mg, Al, etc. which supplemented the food waste and enhanced co-digestion performance.

Co-digestion has been reported to potentially enhance biogas yield and therefore increase the economic returns of the biogas-based energy system. As reported before, cow digestion of animal manure with other feedstock such as kitchen waste and plant waste can increase the efficiency of AD process. Kitchen and plant waste is commonly and locally available to small scale digester operators although some waste such as WAS may be difficult to access and possibly costly to transport. Therefore the usual animal waste can be supplement with other wastes which are available depending on the location and geographical condition. However, care should be taken when choosing the co-substrates since the selection should favor syntrophy between different microorganisms, dilute harmful compounds, optimize methane production and maintain digestate quality [1].

The literature survey on the effect of co-digestion on biogas quality and quantity in Table A.2 and A.3 show that biogas composition varies depending on types of feedstock used for co-digestion. Although, there are other parameters such as hydraulic retention times (HRT) and experimental conditions which may contribute to alter biogas composition, generally the composition depends on the type of feedstock used. It is further noted that co-digestion can have an effect on H_2S content in the biogas. The biogas analysis from both co-digestion laboratory experiments and field measurements (TableA.2 and TableA.3) showed a lower H_2S content compared to the biogas from single substrate digesters. For example, co-digestion of cow dung with coffee pulp (Appendix 2) reduced the H_2S content in the gas from 3% to 2% [23]. Co-digestion might be of interest for the biogas-electricity generation system since it can reduce the cleaning requirement of biogas fuel for appliances such as SOFCs when properly selected co-substrates are used.

Therefore, the right co-substrate has to be chosen to avoid drawbacks like unexpected overloads which can result in VFA and ammonia inhibition [1]. Co-digestion substrates need to be carefully selected to guarantee enhanced biogas production but also to lower impurities like H_2S in the biogas. As discussed in this section, co-digestion can potentially enhance biogas quality and quantity. Particularly, for small scale biogas-electricity generation applications, co-digestion may ameliorate system reliability by enhancing biogas fuel production for electrical power generation. Also, co-digestion can potentially reduce H_2S in the biogas and this in turn will lead to lower operational costs of the cleaning unit coupled to such systems [31].

1.3 Additives that enhance biogas quality and quantity

Heavy metals are essential as micro-nutrients for anaerobic bacteria and archaea [32]. Metals are required in a specific amount depending on the AD microbial conversion stage (hydrolyisis, acidogenesis, acetogenesis and methanogenesis) and the operating conditions such as thermophilic and mesophilic regime [32]. The commonly added metals in anaerobic growth media include Fe, Cu, Zn, Mn, Ni, Co, Mo, Se and W [14,32]. However, high concentration of metals such as Ni and Co are reported to be detrimental to methanogenic activity [33]. Also, Fe and Ni depletion could lead to a sudden accumulation of VFA due to toxicity of microorganisms [34]. Metals such as Fe have been reported to reduce the H_2S content in the biogas due to the formation of metal sulfides [34]. Apart from lowering the H_2S concentration in the biogas, metals have also been reported to enhance organic matter degradation and biogas production [35,36]. This is because, they support the microbial activity which improves feedstock degradation efficiency and hence biogas production [35]. Metal additives can also help to maintain favourable conditions in the digester such as pH which enhances biogas production [37]. Other additives such as $FeSO_4$, $FeCl_3$, Ca^{2+} and Mg^{2+} salts which enhance bacterial growth and hence improve the overall AD process efficiency [37]. Adsorbents such as charcoal and silica gel can potentially enhance the biogas yield [37], most likely due to their trace metal composition containing elements such as Fe [38,39]. However, it should be noted that inorganic additives can be a source of secondary pollution to the environment and increase the inert suspended solids of the digester; moreover, additives will increase the operational costs [40].

It has been shown that other mineral additives such as bentonite enhance resistance to ammonia inhibition during AD [41]. Moreover, the usage of mafic silicate minerals as additives has been reported to affect CH_4 content in the biogas by scavenging CO_2 and the iron present in the silicate may react with H_2S reducing its content [42].

Additives such as green biomass have been reported to enhance biogas production. Powdered legumes and leaves of some plants are reported to increase the biogas yield by over 18% [37,43]. This could be due to trace elements available within green biomass [44], or due to additional carbohydrates. It should be noted that metal trace elements such as Fe are constitutive components in most leaves of plants [44], therefore, they could be released as essential elements and favourably contribute to enhance biogas yield and quality. As well, it is hypothesized that metal trace elements composition in leaves could also reduce the concentration of H_2S in the biogas, nonetheless, further research is still required to quantify this effect.

Bio-augmentation or addition of microbial strains has also been reported to enhance biogas production by stimulating particular enzyme activity [45]. For instance, microbial strains such as rumen microorganisms can potentially enhance the biodegradability of lignocellulosic waste [40,46].

Additives like green leaves and charcoal would be ideal for small scale biogas-electricity generation applications since they are readily available in off-grid settings. This would not only enhance biogas production but may also reduce the biogas H_2S concentration which in turn, could further accelerate electricity generation from already existing biogas systems. However, research and development are still required to reveal the optimal ratio to be added in the feedstock depending on the type of leaves and feedstock available at a particular location.

1.4 Micro-aeration of anaerobic digester

Micro-aeration has been proposed by a few researchers as one of the pre-treatment methods for feedstock [47,48]. It is suggested that the introduction of limited amounts of air into AD improves several biochemical conversion processes and enhances hydrolysis of hardly biodegradable compounds. Lima et al. [47] co-digested food waste and faeces and obtained a higher COD solubilisation, greater VFA accumulation and conversion of short chain fatty acids to acetate when using micro-aeration as a pre-treatment in AD. Oxidation reduction potential (ORP) values in micro-aeration pre-treatment were comparable to a complete anaerobic reference since they were in the same range.

A few researchers found a positive effect of microaerophilic conditions on the hydrolysis of particulate matter [49]. Díaz, Pérez et al. [50] obtained a shorter lag-phase, and Johansen and Bakke [48] observed an increase in hydrolysis of carbohydrates and proteins, but no difference between the lipid content on the digested sludge. These improvements in hydrolysis can be directly linked to a higher production of biogas due to substrate availability. Even though methanogens are strict anaerobes and oxygen might result toxic for them, some authors suggested that methanogens can adapt and handle different amounts of oxygen [51–53].

Micro-aeration can reduce the H_2S content in the biogas [49]. At full scale, micro-aeration can remove up to 99% of H_2S from biogas [54,55]. Jenicek et al. [56] reported that micro-aeration increased specific methane production and decreased H_2S content in the biogas. The enhanced specific methane production was attributed to suppressed H_2S inhibition, due to oxidation of sulphide to elemental sulphur. They further noted that micro-aeration resulted in a better quality of sludge liquor in terms of lower soluble COD [57]. Although micro-aeration is a low cost intervention for H_2S removal, it can result in clogging of the walls of the digester and gas pipes with elemental sulphur [58] if air is dosed in the digester headspace. Therefore, the location of air dosing point needs to be carefully selected. Also for the removal of very high H_2S concentrations in the range of 12,000 ppm, the applied air dose could result in biogas dilution with N_2 [58]. In such cases, pure oxygen should be used instead of air. In the particular case of small scale digesters, the efficiency of H_2S oxidation during micro-aeration is correlated with the installed size of the digester liquid-gas surface area from 0.099 – 0.150 m^2 [59].

Addition of limited air might have several beneficial impacts on small scale digesters. Firstly, air can be added directly to the headspace in order to oxidize H_2S, minimizing its concentration in the biogas and thus improving the biogas quality. This has been effective to reduce the H_2S levels of biogas from small scale digesters [59]. Secondly, limited aeration can be introduced directly to anaerobic sludge. As mentioned before, aeration might lead to an improvement of hydrolysis, which is considered one of the bottlenecks in AD when the influent has a high content of particulate matter. Furthermore, micro-aeration can also promote areas where aerobic degradation of organic matter occurs in the digester, with an increase in bicarbonate availability as end result [60]. Due to this, the expected methane-CO_2 ratio of 60-40 % in complete anaerobic conditions might change, however, an equal distribution of these gases in biogas could be optimal for SOFC cells if dry reforming is envisaged [61–63]. Finally, adding aeration is cost demanding if active aeration of the sludge is considered. While air is easily available, added costs should be considered when planning to introduce air into the system. Hence, it is key to perform an economical assessment of the gained energy or operational performance due to improvements in biogas quantity and quality, in comparison to the energy or additional maintenance needed for aeration.

Therefore, for biogas-electricity generation application, micro-aeration can reduce on H_2S impurity for sensitive devices such as SOFCs and at the same time has the potential to increase the fuel gas production.

1.5 Other operational parameters

Apart from pre-treatment, co-digestion and additives, there are other operational parameters which can influence the biogas quality and quantity and those are discussed in this section.

Temperature regime: Temperature was found to significantly influence the performance of anaerobic digesters in comparison to other factors such as HRT, OLR and substrate characteristics [64]. The AD process is applied in a wide temperature range in which the biochemical conversions follow the Arrhenius equation [65]. Thermophilic AD (50-60 ^{o}C) has a faster reaction rate and a higher loading capacity compared to mesophilic AD (30-40 ^{o}C) [40,66]. As a result, higher biogas production rate are expected from thermophilic digesters as compared to mesophilic ones. However, when not properly operated, thermophilic digesters may have drawbacks such as acidification, decreased stability, low quality effluent, increased sensitivity to toxicity, susceptibility to environmental conditions, larger investments, and higher energy input [40]. Moreover, it has been observed that sudden changes in the temperature regime can drastically reduce the rate of biogas production [66].

pH: Although the different microbial sub-populations in AD have different pH ranges and pH optima, the optimal range reported in literature for the process is about 6.5 - 8 [67]. A reactor pH outside the optimal range can potentially affect the quantity and quality of biogas yield. For small scale digesters, an average pH of 6.7 - 7.3 has been reported [68]. This is within the optimal range proposed in literature [67]. It should be noted that the pH influences the speciation of HS^- and therefore H_2S in the gas phase. An increase in pH decreases the H_2S concentration in the biogas, therefore, a higher operational pH (7.5 - 8.0) is desired for biogas-electricity generation applications.

Particle size: The particle size of the feedstock also has an influence on the rate of biogas production. A decrease in particle size increases the rate of hydrolysis which is limiting in the AD process [65]. Large particles could result in clogging of the digester, whereas small particles provide a large surface area for adsorption of microorganisms, enhancing microbial activity and hence biogas production [37].

Mixing: Mixing enhances the contact time between microorganisms and substrates and prevents local pH drops or high concentrations of intermediates. Mixing can be done in a number of ways, including daily feeding, using biogas recirculation and mechanical stirring. Proper mixing ensures intimate contact between the microorganisms and the substrate, which results in a more efficient digestion process with increased biogas production [37]. According to Jegede et al. [69] in small scale digesters, mixing depends on the type of the digester. For digesters of Chinese dome-type, mixing is achieved by pressure build-up due to gas storage, usage and influent flow. For plug-flow digesters, mixing is achieved by flow of the feedstock from the inlet to the outlet and gas production . For the biogas-electrical generation application, a high and constant biogas production is preferred, meaning reactor operation at an increased loading rate. Increased biogas production would enhance mixing but this can be coupled with regular active mechanical mixing for a more efficient AD process.

Type of reactor: Optimization in terms of retention time, organic loading, low sludge production for waste water treatment plant digesters and reduced footprint seems to be the focus of current research [40]. The reactor design criteria depends on the location, for example, if psychrophilic conditions are expected, longer HRT are required as compared to mesophilic conditions [64]. Different reactor designs may have an effect on the biogas quality and quantity since reactor configuration affects the overall AD process. Innovative reactor designs are discussed in detail in section 3.1.7 of the main article.

Seeding: Seeding is basically done to enrich bacteria into the digester to facilitate/accelerate the start-up process of AD. Re-seeding is considered when intermediate VFA accumulate during digester operation, which results in decreased quality and quantity of biogas production. Even daily-use materials like wood-ash have been reported to enhance biogas production if they are used as part of seeding materials for the digester [70]. It should be noted that, ash also contains earth alkaline and metal elements such as Ca, Mg, Fe, whose concentration depends on the material source and that are often present in the oxidized form [71]. Such elements can also act as additives to the digester to buffer the pH, enhance biogas production and achieve the required quality for electrical production by reducing impurities such as H_2S in the gas phase. Although ash may have elements which can enhance biogas quantity and quality, it may be harmful to AD when dosage is not controlled. Therefore, the use of ash as seed for off-grid digesters needs to be carefully evaluated to understand the optimal condition under off-grid anaerobic conditions, which could vary depending on the available feedstocks.

The effect of modifying some of these operational parameters on biogas quality and quantity needs to be carefully evaluated for small scale biogas-electrical generation applications. Some of these operational practices such as daily feeding and agitation can easily be adapted in small scale digester operation with marginal increase in operational costs. Other operational parameters such as the C/N ratio, organic loading rate (OLR), HRT and solids concentration can influence the biogas quality and quantity. Their effect to the AD process is summarised in Table 2 of the main article, which shows the effect of operational parameters and their optimal condition for biogas-electricity generation application. It should also be noted that some of the parameters like OLR and HRT are influenced by users' behaviour depending on their respective needs such as fertilizers [72]. Furthermore, HRT can be influenced by the gas pressure [73,74]. Therefore, efforts to optimize small scale digesters should include social-cultural status of the given community, although this is out of scope of this current paper.

Table S1. Quality of Biogas From Lab experiments

Gas Composition	Concentration	Feed stock		Protocol	Analysis Equipment	Ref	pH	Temp	S Concentration in feed stock
CH_4	68.6-71.4% [1]	Fish waste		BMP	GC-2014	[75]			
	62.2% [1]	Brewery grain Waste		BMP	GC-2014	[75]			
	53.1% [1]	Bread Waste		BMP	GC-2014	[75]			
	5-15%	Cow dung	Batch		FTIR spectroscopy	[23]			
	15-25%	Coffee pulp	Batch		FTIR spectroscopy	[23]			
	45-55%	Cow dung + Coffee Pulp (40% Wt coffee pulp, 40% Wt Cow dung, 20% Water)	Batch		FTIR spectroscopy	[23]			
	56.5% [2]	Apple Pomace				[76]			
	71.8% [2]	Cauliflower + Radish				[76]			
	68% [2]	Rotten cabbage				[76]			
	72.8% [2]	Cauliflower + Radish + Cow dung				[76]	6.91 [2]		
	70.8%v [2]	Cauliflower + Radish + Cow dung + Apple Pomace				[76]	7.22 [2]		
	60-86%	Cow dung				[17]			
	66.6%	Cow dung	Batch	BMP		[77]			
	65.9%	Pig dung	Batch	BMP		[77]			
	76.9%	Sludge	Batch	BMP		[77]			
	63.4%	Fruit/Vegetable waste	Batch	BMP		[77]			
	68.0%	Food waste	Batch	BMP		[77]			

	59.4-60.6%	OFMSW	CSTR			[27]	7.0-7.5	
	62.8-64.6%	OFMSW + Cow dung at a proportion of 50% (VS/VS)	CSTR			[27]	7.2-7.5	
	71.4-81.2%	Mixed Sludge	Batch	BMP	Awite Serie 4 analyzer[3]	[78]		
	67.6-78.4%	Leachate	Batch	BMP	Awite Serie 4 analyzer[3]	[78]		
	70.9-83.3%	Oil	Batch	BMP	Awite Serie 4 analyzer[3]	[78]		
	62.1-66.7%	SHW				[79]		
	55.3-67.1%	SHW+OFMSW in ratio of SHW:OFMSW is 1:5 in weight				[79]		
CO_2	36.1%[2]	Apple Pomace				[76]		
	22.5%[2]	Cauliflower + Radish				[76]		
	25.1%[2]	Rotten cabbage				[76]		
	21.9%[2]	Cauliflower + Radish + Cow dung					6.91[2]	
	23.1%[2]	Cauliflower + Radish + Cow dung + Apple Pomace					7.22[2]	
	13-28%	Cow dung				[17]		
	33.3-37.9%	SHW				[79]		
	32.8-44.7%	SHW+OFMSW in ratio of SHW:OFMSW is 1:5 in weight				[79]		
H_2S								
ppm	850-2872	Fish waste				[75]		
	382-2260	Brewery grain Waste				[75]		
	900-3270	Bread Waste				[75]		
	17000-35000	Sea weed + Pig dung				[80]	6.71-7.76	2.60 g S/L

	1500-3000	Pig dung		[80]		0.36 g S/L
	3.01%v	Cow dung	FTIR spectroscopy	[23]	6.5-7.0	
	0	Coffee Pulp	FTIR spectroscopy	[23]	4.5-7.2	
	2.12%v	Cow dung+ Coffee Pulp (40% Wt coffee pulp, 40% Wt Cow dung, 20% Water)	FTIR spectroscopy	[23]	5.4-7.2	
	7.3%v[2]	Apple Pomace		[76]		
	5.7%v[2]	Cauliflower + Radish		[76]		
	6.9%v[2]	Rotten Cabbage		[76]		
	5.3%v[2]	Cauliflower + Radish + Cow dung		[76]	6.91[2]	
	6.1%v[2]	Cauliflower + Radish + Cow dung + Apple Pomace		[76]	7.22[2]	
N_2	0.177-11.484%	Cow dung		[17]		
CO	0.001-0.05%	Cow dung		[17]		
Air (N+O)	0.0110-0.05%	Cow dung		[17]		

[1] Weighted average methane content. [2]Averages.[3] automated gas analyzer with infrared and electrochemical sensors

Table S2. Quality of Biogas From field measurements

	Biogas Plat type			Main feed stock for Organic waste Digesters	Measuring Procedure/Equipment	Analysis Conditions	Ref	This Research
Gas Composition	Land Fills	WWTPs	Organic waste digesters/farm/ domestic digesters					
CH_4 (%v)	47-62	60-67	55-70	Cow and pig dung, waste water, industrial and agricultural waste	Infra-red gas analyser	Laboratory	[81]	
	59.4-67.9				Hewlett Packard (HP) 5890 gas chromatography with thermal conductivity detector	Laboratory	[82]	
			41-59	Cow and Pig dung			[83]	
			62.94-67.76[3]	Pig dung	GA5000 multifunctional portable gas analyser (Geotech, Leamington Spa, UK)	On site measurement	[84]	
			59.42-62.46[6]	Cow dung	GC	Laboratory	[22]	
			61.7%[7]	Cow dung	An IR-30M hydrocarbon meter (Environmental Sensors Co.)	On site measurement	[85]	
			61.4-72.5%[7]	Pig Dung	An IR-30M hydrocarbon meter (Environmental Sensors Co.)	On site Measurement	[85]	
			40-59%	Mainly cow dung	Gas Analyser (Geotech, GA 2000 plus)	On site	[68]	47-52
			60%	Pig manure			[86]	

			60%[9]	Cow dung	The ATEX Certified, Portable Gas Detector		[87]	
CO_2 (%v)	32-43	33-38	29-40	Cow and pig dung, waste, industrial and agricultural waste	Infra-red gas analyser	Laboratory	[81]	
	29.9-38.6				Hewlett Packard (HP) 5890 gas chromatography with thermal conductivity detector	Laboratory	[82]	
	35.1-40.0				GC/MS		[88]	
			30-49	Cow and Pig dung			[83]	
			26.59-31.89[3]	Pig dung	GA5000 multi-functional portable gas analyser (Geotech, Leamington Spa, UK)	On site measurement	[84]	
			38.21%[5]	Cow dung	GC	Laboratory	[22]	
			30-49.3%	Mainly cow dung	Gas Analyser (Geotech, GA 2000 plus)	On site	[68]	40-45
			30%				[86]	
			40%[9]	Cow dug	The ATEX Certified, Portable Gas Detector		[87]	
N_2 (%v)	<1-17	< 2	<1	Cow and pig dung, waste, industrial and agricultural waste	Infra-red gas analyser	Laboratory	[81]	N/A
	4-15.8				GC/MS	Laboratory	[88]	
			1.52%[5]	Cow dung	GC	Laboratory	[22]	
			10%	Pig manure			[86]	
O_2 (%v)	<1	<1	<1-2	Cow and pig dung, waste, industrial and agricultural waste		Laboratory	[81]	1-3
	0.9-3.7				GC/MS	Laboratory	[88]	

H_2 (%v)	< 0.01-0.01				GC/MS	Laboratory	[88]	N/A
NH_3 (%v)			0.03-0.05[3]	Pig dung	GA5000 multifunctional portable gas analyser (Geotech, Leamington Spa, UK)		[84]	N/A
Common Trace Elements								
H_2S								
ppm	27-500	<1-4	3-1000	Cow and pig dung, waste, industrial and agricultural waste	-Infra red gas analyser equipped with electro-chemical cell -Draeger and Rae Systems gas tubes -Portable gas chromatograph.	Laboratory	[81]	
	15.1-427.5				HP 5890 series II GC with sulfur chemiluminescence detector	Laboratory	[82]	
mg m^{-3}	220-420				GC/MS	Laboratory	[88]	
			0-312	Cow and pig dung			[83]	3-500 ppm
ppm			130[1]-1,600[2]		Draeger tubes	Onsite measurement	[89]	
%vol			0.07-0.22[3]	Pig dung	GA5000 multifunctional portable gas analyser (Geotech, Leamington Spa, UK)	On site measurement	[84]	100-600ppm
ppm			991-2923[4]	Cow dung	GC	Laboratory	[22]	0-1400 ppm
			4.8[7]	Cow dung	Z-900 hydrogen sulfide (H_2S) meter (Environmental Sensors Co.)	On site measurement	[85]	
			0.37-84.4[7]	Pig dung	Z-900 hydrogen sulfide (H_2S) meter (Environmental Sensors Co.)	On site measurement	[85]	

ppm			149-310[8]		Gas Analyser (Geotech, GA 2000 plus)	On site measurement	[68]	
			2400[9]				[86]	
			100[9]	Cow dung, manure, biowaste and food waste	The ATEX Certified, Portable Gas Detector		[87]	
			2000-6000				[90]	
				Cow dung+ fecal waste				20-2000 ppm
								2000-4000 ppm
Siloxanes (ppm)					Thermal desorption gas chromatograph-mass spectrometry	Laboratory	[81]	
Mercaptans (ppm)	0.7-4	1.5-10.6	<0.4	Cow and pig dung, waste water, industrial and agricultural waste	Thermal desorption gas chromatograph-mass spectrometry	Laboratory	[81]	
	9.3-13.2				HS-GC/MS	Laboratory	[88]	
	12.1-84.9				HP 5890 series II GC with sulfur chemiluminescence detector	Laboratory	[82]	
Other VOCs (TVOCs) (mg m^{-3})	46-173	13-268	5-8	Cow and pig dung, waste water, industrial and agricultural waste	Thermal desorption gas chromatograph-mass spectrometry	Laboratory	[81]	
mg m^{-3}	48-728				B, GC/MS	Laboratory	[88]	
				Cow and pig dung, human dung				0-30ppm

[1]Mean for measurements every two weeks for 6 months with 95% CI: 95 - 150 ppm, [2]mean for measurements every two weeks for 6 months with 95% CI:1300 - 2000 ppm, [3]maximum upper and minimum lower bound of the mean at 95% CI, [4]daily average with standard deviation of 34 - 277 +/- ppm of H_2S, [5]monthly average, [6]weekly average, [7]average percentages, [8]maximun values and [9]average.

[91]

References

1. Mata-alvarez, J.; Dosta, J.; Romero-güiza, M.S.; Fonoll, X.; Peces, M.; Astals, S. A critical review on anaerobic co-digestion achievements between 2010 and 2013. *Renewable and Sustainable Energy Reviews* **2014**, *36*, 412–427, doi:10.1016/j.rser.2014.04.039.
2. Karlsson, A.; Björn, A.; Yekta, S.S.; Svensson, B.H. *IMPROVEMENT OF THE BIOGAS PRODUCTION PROCESS; Explorative project (EP1)*; Linköping, 2014;
3. Taherzadeh, M.J.; Karimi, K. *Pretreatment of Lignocellulosic Wastes to Improve Ethanol and Biogas Production : A Review*; 2008; ISBN 8415683111.
4. Gonzalez, A.; Hendriks, A.T.W.M.; van Lier, J.B.; de Kreuk, M. Pre-treatments to enhance the biodegradability of waste activated sludge: Elucidating the rate limiting step. *Biotechnology Advances* **2018**, *36*, 1434–1469, doi:10.1016/j.biotechadv.2018.06.001.
5. Kim, D. Physico-chemical conversion of lignocellulose: Inhibitor effects and detoxification strategies: A mini review. *Molecules* **2018**, *23*, doi:10.3390/molecules23020309.
6. Ferrer, I.; Ponsá, S.; Vázquez, F.; Font, X. Increasing biogas production by thermal (70 ◦ C) sludge pre-treatment prior to thermophilic anaerobic digestion. **2008**, *42*, 186–192, doi:10.1016/j.bej.2008.06.020.
7. Rodríguez-abalde, A.; Fernández, B.; Silvestre, G.; Flotats, X. Effects of thermal pre-treatments on solid slaughterhouse waste methane potential. **2011**, *31*, 1488–1493, doi:10.1016/j.wasman.2011.02.014.
8. Carrere, H.; Rafrafi, Y.; Battimelli, A.; Torrijos, M.; Delgenes, J.P.; Motte, C. Improving methane production during the codigestion of waste-activated sludge and fatty wastewater : Impact of thermo-alkaline pretreatment on batch and semi-continuous processes. *Chemical Engineering Journal* **2012**, *210*, 404–409, doi:10.1016/j.cej.2012.09.005.
9. Affes, R.; Palatsi, J.; Flotats, X.; Carrère, H.; Steyer, J.P.; Battimelli, A. Bioresource Technology Saponification pretreatment and solids recirculation as a new anaerobic process for the treatment of slaughterhouse waste. *Bioresource Technology* **2013**, *131*, 460–467, doi:10.1016/j.biortech.2012.12.187.
10. Hidalgo, D.; Sastre, E.; Gómez, M.; Nieto, P. Evaluation of pre-treatment processes for increasing biodegradability of agro-food wastes. **2012**, *3330*, doi:10.1080/09593330.2012.665488.
11. Chen, Y.; Cheng, J.J.; Creamer, K.S. Inhibition of anaerobic digestion process : A review. **2008**, *99*, 4044–4064, doi:10.1016/j.biortech.2007.01.057.
12. Fang, W.; Zhang, P.; Zhang, X.; Zhu, X.; van Lier, J.B.; Spanjers, H. White rot fungi pretreatment to advance volatile fatty acid production from solid-state fermentation of solid digestate: Efficiency and mechanisms. *Energy* **2018**, *162*, 534–541, doi:10.1016/j.energy.2018.08.082.
13. Fang, W.; Zhang, X.; Zhang, P.; Carol Morera, X.; van Lier, J.B.; Spanjers, H. Evaluation of white rot fungi pretreatment of mushroom residues for volatile fatty acid production by anaerobic fermentation: Feedstock applicability and fungal function. *Bioresource Technology* **2020**, *297*, 122447, doi:10.1016/j.biortech.2019.122447.
14. Anwar, Z.; Gulfraz, M.; Irshad, M. ScienceDirect Agro-industrial lignocellulosic biomass a key to unlock the future bio-energy : A brief review. *Journal of Radiation Research and Applied Sciences* **2014**, *7*, 163–173, doi:10.1016/j.jrras.2014.02.003.
15. Cesaro, A.; Naddeo, V.; Amodio, V.; Belgiorno, V. Ultrasonics Sonochemistry Enhanced biogas production from anaerobic codigestion of solid waste by sonolysis. *Ultrasonics - Sonochemistry* **2012**, *19*, 596–600, doi:10.1016/j.ultsonch.2011.09.002.

16. Cecchi, F.; Pavanb, P. Anaerobic co-digestion of sewage sludge : application to the macroalgae from the Venice lagoon. *3449*.
17. Godi, N.Y.; Zhengwuvi, L.B.; Adulkadir, S.; Kamtu, P. Effect of cow dung variety on biogas production. **2013**, *5*, 1–4, doi:10.5897/JMER12.014.
18. Hamzawi, N.; Kennedy, K.J.; McLean, D.D. ANAEROBIC DIGESTION OF CO-MINGLED MUNICIPAL SOLID WASTE AND SEWAGE SLUDGE. *Water Science and Technology* **1998**, *38*, 127–132.
19. Chang, H.N. Biochemical methane potential a n d solid state anaerobic digestion of korean food wastes. **1995**, *8524*, 245–253.
20. Kaparaju, P.; Rintala, J. Anaerobic co-digestion of potato tuber and its industrial by-products with pig manure. **2005**, *43*, 175–188, doi:10.1016/j.resconrec.2004.06.001.
21. Callaghan, F.J.; Wase, D.A.J.; Thayanithy, K.; Forster, C.F. Continuous co-digestion of cattle slurry with fruit and vegetable wastes and chicken manure. **2002**, *27*, 71–77.
22. Bothi, K.L. CHARACTERIZATION OF BIOGAS FROM ANAEROBICALLY DIGESTED DAIRY WASTE FOR ENERGY USE, 2007.
23. Corro, G.; Pal, U.; Bañuelos, F.; Rosas, M. Generation of biogas from coffee-pulp and cow-dung co-digestion: Infrared studies of postcombustion emissions. *Energy Conversion and Management* **2013**, *74*, 471–481, doi:10.1016/j.enconman.2013.07.017.
24. Kasisira, L.L.; Muyiiya, N.D. Assessment of the Effect of Mixing Pig and Cow Dung on Biogas Yield. *The CIGR Ejournal* **2009**, *XI*, 1–7.
25. Saludes, R.B.; Iwabuchi, K.; Miyatake, F.; Abe, Y.; Honda, Y. Characterization of dairy cattle manure/wallboard paper compost mixture. *Bioresource Technology* **2008**, *99*, 7285–7290, doi:10.1016/j.biortech.2007.12.080.
26. Martí-Herrero, J.; Alvarez, R.; Cespedes, R.; Rojas, M.R.; Conde, V.; Aliaga, L.; Balboa, M.; Danov, S. Cow, sheep and llama manure at psychrophilic anaerobic co-digestion with low cost tubular digesters in cold climate and high altitude. *Bioresource Technology* **2015**, *181*, 238–246, doi:10.1016/j.biortech.2015.01.063.
27. Hartmann, H.; Ã, B.K.A. Anaerobic digestion of the organic fraction of municipal solid waste : Influence of co-digestion with manure. **2005**, *39*, 1543–1552, doi:10.1016/j.watres.2005.02.001.
28. Macias-corral, M.; Samani, Z.; Hanson, A.; Smith, G.; Funk, P.; Yu, H.; Longworth, J. Bioresource Technology Anaerobic digestion of municipal solid waste and agricultural waste and the effect of co-digestion with dairy cow manure. **2008**, *99*, 8288–8293, doi:10.1016/j.biortech.2008.03.057.
29. Liu, K.; Tang, Y.; Matsui, T.; Morimura, S.; Wu, X.; Kida, K. Thermophilic anaerobic co-digestion of garbage , screened swine and dairy cattle manure. *JBIOSC* **2009**, *107*, 54–60, doi:10.1016/j.jbiosc.2008.09.007.
30. Zhang, L.; Lee, Y.; Jahng, D. Bioresource Technology Anaerobic co-digestion of food waste and piggery wastewater : Focusing on the role of trace elements. *Bioresource Technology* **2011**, *102*, 5048–5059, doi:10.1016/j.biortech.2011.01.082.
31. Wasajja, H.; Lindeboom, R.E.F.; Lier, J.B. Van; Aravind, P. V Techno-economic review of biogas cleaning technologies for small scale off- grid solid oxide fuel cell applications. *Fuel Processing Technology* **2020**, *197*, 106215, doi:10.1016/j.fuproc.2019.106215.
32. Hendriks, A.T.W.M.; van Lier, J.B.; de Kreuk, M.K. Growth media in anaerobic fermentative processes: The underestimated potential of thermophilic fermentation and anaerobic digestion. *Biotechnology Advances* **2018**, *36*, 1–13, doi:10.1016/j.biotechadv.2017.08.004.

33. Paulo, L.M.; Ramiro-Garcia, J.; van Mourik, S.; Stams, A.J.M.; Sousa, D.Z. Effect of nickel and cobalt on methanogenic enrichment cultures and role of biogenic sulfide in metal toxicity attenuation. *Frontiers in Microbiology* **2017**, *8*, 1–12, doi:10.3389/fmicb.2017.01341.
34. Schmidt, T.; Nelles, M.; Scholwin, F.; Pröter, J. Bioresource Technology Trace element supplementation in the biogas production from wheat stillage – Optimization of metal dosing. *Bioresource Technology* **2014**, *168*, 80–85, doi:10.1016/j.biortech.2014.02.124.
35. Yaw, Y.; Norli, I.; Zuhairi, A.; Firdaus, M. Bioresource Technology Impacts of trace element supplementation on the performance of anaerobic digestion process : A critical review. *Bioresource Technology* **2016**, *209*, 369–379, doi:10.1016/j.biortech.2016.03.028.
36. Agani, I.C.; Suanon, F.; Dimon, B.; Ifon, E.B.; Yovo, F.; Wotto, V.D.; Abass, O.K.; Kumwimba, M.N. Enhancement of Fecal Sludge Conversion Into Biogas Using Iron Powder During Anaerobic Digestion Process To cite this article : **2016**, *5*, 179–186, doi:10.11648/j.ajep.20160506.15.
37. Yadvika; Santosh; Sreekrishnan, T.R.; Kohli, S.; Rana, V. Enhancement of biogas production from solid substrates using different techniques - A review. *Bioresource Technology* **2004**, *95*, 1–10, doi:10.1016/j.biortech.2004.02.010.
38. Kabir, E.; Kim, K.H.; Yoon, H.O. Trace metal contents in barbeque (BBQ) charcoal products. *Journal of Hazardous Materials* **2011**, *185*, 1418–1424, doi:10.1016/j.jhazmat.2010.10.064.
39. Nawrocki, J.; Moir, D.L.; Szczepaniak, W. Trace metal impurities in silica as a cause of strongly interacting silanols. *Chromatographia* **1989**, *28*, 143–147, doi:10.1007/BF02319636.
40. Mao, C.; Feng, Y.; Wang, X.; Ren, G. Review on research achievements of biogas from anaerobic digestion. *Renewable and Sustainable Energy Reviews* **2015**, *45*, 540–555, doi:10.1016/j.rser.2015.02.032.
41. Angelidaki, I.; Ahring, B.K. Effect of the clay mineral bentonite on ammonia inhibition of anaerobic thermophilic reactors degrading animal waste. **1993**, 409–414.
42. Lindeboom, R.E.F.; Ferrer, I.; Weijma, J.; van Lier, J.B. Silicate minerals for CO2 scavenging from biogas in Autogenerative High Pressure Digestion. *Water Research* **2013**, *47*, 3742–3751, doi:10.1016/j.watres.2013.04.028.
43. Thiruselvi, D.; Yuvarani, M.; Amudha, T. Environmental Effects Synthesis of iron nano-catalyst using Acalypha indica leaf extracts for biogas production from mixed liquor volatile suspended solids. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* **2018**, *40*, 772–779, doi:10.1080/15567036.2018.1463308.
44. All, U.T.C. THE TRACE AND MAJOR ELEMENT COMPOSITION OF THE LEAVES OF SOME DECIDUOUS TREES : II . SEASONAL CHANGES Author (s): M . M . GUHA and R . L . MITCHELL Published by : Springer Stable URL : https://www.jstor.org/stable/42932622. **2018**, *24*, 90–112.
45. Christy, P.M.; Gopinath, L.R.; Divya, D. A review on anaerobic decomposition and enhancement of biogas production through enzymes and microorganisms. *Renewable and Sustainable Energy Reviews* **2014**, *34*, 167–173, doi:10.1016/j.rser.2014.03.010.
46. Camp, H.J.M.O. Den; Verhagen, F.J.M.; Kivaisi, A.K.; Windt, F.E. De; Lubberding, H.J.; Gijzen, H.J.; Vogels, G.D. Applied Microbiology Biotechnology Effects of lignin on the anaerobic degradation of (ligno) cellulosic wastes by rumen microorganisms. **1988**, *1988*.
47. Lim, J.W.; Wang, J.Y. Enhanced hydrolysis and methane yield by applying microaeration pretreatment to the anaerobic co-digestion of brown water and food waste. *Waste Management* **2013**, *33*, 813–819, doi:10.1016/j.wasman.2012.11.013.
48. Johansen, J.E.; Bakke, R. Enhancing hydrolysis with microaeration. *Water Science and Technology* **2006**, *53*,

43–50, doi:10.2166/wst.2006.234.
49. Botheju, D.; Lie, B.; Bakke, R. Oxygen effects in anaerobic digestion - II. *Modeling, Identification and Control* **2010**, *31*, 55–65, doi:10.4173/mic.2010.2.2.
50. Díaz, I.; Pérez, S.I.; Ferrero, E.M.; Fdz-Polanco, M. Effect of oxygen dosing point and mixing on the microaerobic removal of hydrogen sulphide in sludge digesters. *Bioresource Technology* **2011**, *102*, 3768–3775, doi:10.1016/j.biortech.2010.12.016.
51. Kato, M.T.; Field, J.A.; Lettinga, G. Anaerobe tolerance to oxygen and the potentials of anaerobic and aerobic cocultures for wastewater treatment. *Brazilian Journal of Chemical Engineering* **1997**, *14*, 395–407, doi:10.1590/S0104-66321997000400015.
52. Kato, M.T.; Field, J.A.; Lettinga, G. High tolerance of methanogens in granular sludge to oxygen. *Biotechnology and Bioengineering* **1993**, *42*, 1360–1366, doi:10.1002/bit.260421113.
53. Brioukhanov, A.L.; Thauer, R.K.; Netrusov, A.I. 532_Brioukhanov. 2002. Catalase and superoxide dismutase in the cells of stricktly anaerobic microorganisms. Microbiology. *Microbiology* **2002**, *71*, 281–285.
54. Jenicek, P.; Koubova, J.; Bindzar, J.; Zabranska, J. Advantages of anaerobic digestion of sludge in microaerobic conditions. *Water Science and Technology* **2010**, *62*, 427–434, doi:10.2166/wst.2010.305.
55. Jenicek, P.; Keclik, F.; Maca, J.; Bindzar, J. Use of microaerobic conditions for the improvement of anaerobic digestion of solid wastes. *Water Science and Technology* **2008**, *58*, 1491–1496, doi:10.2166/wst.2008.493.
56. Jenicek, P.; Celis, C.A.; Koubova, J.; Ruzickova, I. Change of the digested sludge quality at microaerobic digestion. *Journal of Residuals Science and Technology* **2011**, *8*, 39–44.
57. Jenicek, P.; Celis, C.A.; Krayzelova, L.; Anferova, N.; Pokorna, D. Improving products of anaerobic sludge digestion by microaeration. *Water Science and Technology* **2014**, *69*, 803–809, doi:10.2166/wst.2013.779.
58. Krayzelova, L.; Bartacek, J.; Díaz, I.; Jeison, D.; Volcke, E.I.P.; Jenicek, P. Microaeration for hydrogen sulfide removal during anaerobic treatment: a review. *Reviews in Environmental Science and Biotechnology* **2015**, *14*, 703–725, doi:10.1007/s11157-015-9386-2.
59. Mulbry, W.; Selmer, K.; Lansing, S. Effect of liquid surface area on hydrogen sulfide oxidation during micro-aeration in dairy manure digesters. *PLoS ONE* **2017**, *12*, 1–12, doi:10.1371/journal.pone.0185738.
60. Van Lier, J.B. High-rate anaerobic wastewater treatment: Diversifying from end-of-the-pipe treatment to resource-oriented conversion techniques. *Water Science and Technology* **2008**, *57*, 1137–1148, doi:10.2166/wst.2008.040.
61. Li, Y.; Wang, Y.; Zhang, X.; Mi, Z. Thermodynamic analysis of autothermal steam and CO 2 reforming of methane. *International Journal of Hydrogen Energy* **2008**, *33*, 2507–2514, doi:10.1016/j.ijhydene.2008.02.051.
62. Girona, K.; Laurencin, J.; Fouletier, J.; Lefebvre-Joud, F. Carbon deposition in CH4/CO2operated SOFC: Simulation and experimentation studies. *Journal of Power Sources* **2012**, *210*, 381–391, doi:10.1016/j.jpowsour.2011.12.005.
63. Ginsburg, J.M.; Piña, J.; El Solh, T.; De Lasa, H.I. Coke formation over a nickel catalyst under methane dry reforming conditions: Thermodynamic and kinetic models. *Industrial and Engineering Chemistry Research* **2005**, *44*, 4846–4854, doi:10.1021/ie0496333.
64. Garfí, M.; Martí-Herrero, J.; Garwood, A.; Ferrer, I. Household anaerobic digesters for biogas production in Latin America: A review. *Renewable and Sustainable Energy Reviews* **2016**, *60*, 599–614,

doi:10.1016/j.rser.2016.01.071.

65. Sheridan, C.; Petersen, J.; Rohwer, J. On modifying the arrhenius equation to compensate for temperature changes for reactions within biological systems. *Water SA* **2012**, *38*, 149–151, doi:10.4314/wsa.v38i1.18.
66. Chae, K.J.; Jang, A.; Yim, S.K.; Kim, I.S. The effects of digestion temperature and temperature shock on the biogas yields from the mesophilic anaerobic digestion of swine manure. **2008**, *99*, 1–6, doi:10.1016/j.biortech.2006.11.063.
67. de Lemos Chernicharo, C.A. Principles of Anaerobic Digestion. *Anaerobic Reactors* **2007**, 7–8.
68. Kanko-Buhwezi, B.; Mwesigye, A.; Arineitwe, J.; Colonna, G.P. *Challenges to the Sustainability of Small Scale Biogas Technologies in Uganda, Second international Conference on Advances in Engineering and Technology*; Entebbe, 2011;
69. Jegede, A.O.; Zeeman, G.; Bruning, H. A review of mixing, design and loading conditions in household anaerobic digesters. *Critical Reviews in Environmental Science and Technology* **2019**, *49*, 2117–2153, doi:10.1080/10643389.2019.1607441.
70. Adeyanju, A.A. Effect of seeding of wood-ash on biogas production using pig waste and cassava peels. *Journal of Engineering and Applied Sciences* **2008**.
71. Misra, M.K.; Ragland, K.W.; Baker, A.J. Wood ash composition as a function of furnace temperature. *Biomass and Bioenergy* **1993**, *4*, 103–116, doi:10.1016/0961-9534(93)90032-Y.
72. Martí-Herrero, J.; Ceron, M.; Garcia, R.; Pracejus, L.; Alvarez, R.; Cipriano, X. The influence of users' behavior on biogas production from low cost tubular digesters: A technical and socio-cultural field analysis. *Energy for Sustainable Development* **2015**, *27*, 73–83, doi:10.1016/j.esd.2015.05.003.
73. Martí-Herrero, J. Reduced hydraulic retention times in low-cost tubular digesters: Two issues. *Biomass and Bioenergy* **2011**, *35*, 4481–4484, doi:10.1016/j.biombioe.2011.07.020.
74. Martí-Herrero, J.; Cipriano, J. Design methodology for low cost tubular digesters. *Bioresource Technology* **2012**, *108*, 21–27, doi:10.1016/j.biortech.2011.12.117.
75. Krishna, G.; Hun, S.; Ill, K. Bioresource Technology Ensiling of fish industry waste for biogas production : A lab scale evaluation of biochemical methane potential (BMP) and kinetics. *BIORESOURCE TECHNOLOGY* **2013**, *127*, 326–336, doi:10.1016/j.biortech.2012.09.032.
76. Kalia, V.C.; Kumar, A.; Jain, S.R.; Joshi, A.E. Biomethanation of Plant Materials. **1992**, *41*, 209–212.
77. Qiao, W.; Yan, X.; Ye, J.; Sun, Y.; Wang, W.; Zhang, Z. Evaluation of biogas production from different biomass wastes with / without hydrothermal pretreatment. *Renewable Energy* **2011**, *36*, 3313–3318, doi:10.1016/j.renene.2011.05.002.
78. Pastor, L.; Ruiz, L.; Pascual, A.; Ruiz, B. Co-digestion of used oils and urban landfill leachates with sewage sludge and the effect on the biogas production. *Applied Energy* **2013**, *107*, 438–445, doi:10.1016/j.apenergy.2013.02.055.
79. Otero, M.; Mor, A. Anaerobic digestion of solid slaughterhouse waste (SHW) at laboratory scale : Influence of co-digestion with the organic fraction of municipal solid waste (OFMSW). **2008**, *40*, 99–106, doi:10.1016/j.bej.2007.11.019.
80. Peu, P.; Sassi, J.; Girault, R.; Picard, S.; Saint-cast, P.; Béline, F.; Dabert, P. Bioresource Technology Sulphur fate and anaerobic biodegradation potential during co-digestion of seaweed biomass (Ulva sp .) with pig slurry. *Bioresource Technology* **2011**, *102*, 10794–10802, doi:10.1016/j.biortech.2011.08.096.
81. Rasi, S. *Biogas Composition and Upgrading to Biomethane Saija Rasi Biogas Composition and Upgrading to Biomethane*; 2009; ISBN 9789513936181.

82. Shin, H.C.; Park, J.W.; Park, K.; Song, H.C. Removal characteristics of trace compounds of landfill gas by activated carbon adsorption. *Environmental Pollution* **2002**, *119*, 227–236, doi:10.1016/S0269-7491(01)00331-1.

83. Lutaaya, F. QUALITY AND USAGE OF BIOGAS DIGESTERS IN UGANDA Submitted in partial fulfillment of the requirements for the of the degree Of Master of Science in Mechanical Engineering with a specialization in Sustainable Energy Engineering Msc . Thesis Report Departmen, 2013.

84. Case, A. Biogas Quality across Small-Scale Biogas Plants : **2018**, 1–12, doi:10.3390/en11071794.

85. Lansing, S.; Martin, J.F. *Waste treatment and biogas quality in small-scale agricultural digesters*; 2008; Vol. 99;.

86. Pipatmanomai, S.; Kaewluan, S.; Vitidsant, T. Economic assessment of biogas-to-electricity generation system with H2S removal by activated carbon in small pig farm. *Applied Energy* **2009**, *86*, 669–674, doi:10.1016/j.apenergy.2008.07.007.

87. Farooq, M.; Chaudhry, I.A.; Hussain, S.; Ramzan, N.; Ahmed, M. BIOGAS UP GRADATION FOR POWER GENERATION APPLICATIONS IN PAKISTAN 1) INTRODUCTION. **2012**, *VIII*, 107–118.

88. Sevimoĝlu, O.; Tansel, B. Effect of persistent trace compounds in landfill gas on engine performance during energy recovery: A case study. *Waste Management* **2013**, *33*, 74–80, doi:10.1016/j.wasman.2012.08.016.

89. Mccord, A.I.; Stefanos, S.A.; Tumwesige, V.; Lsoto, D.; Adong, A.H.M.A.; Larson, J.J.S.R.A. The impact of biogas and fuelwood use on institutional kitchen air quality in Kampala , Uganda. **2017**, 1067–1081, doi:10.1111/ina.12390.

90. Schieder, D.; Quicker, P.; Schneider, R.; Winter, H.; Prechtl, S.; Faulstich, M. Microbiological removal of hydrogen sulfide from biogas by means of a separate biofilter system : experience with technical operation. **2018**, 209–212.

91. Kumar, S. *Biogas*; InTech: Janeza Trdine 9, 51000 Rijeka, Croatia, 2012;