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Using Agricultural Waste for Biogas Production as a Sustainable Energy Supply for Developing Countries

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The paper focuses on the research, development, and application of simple, reliable, efficient, and low-maintenance technology for the production of biogas from local organic agricultural wastes in the Republic of Togo. This technology is intended as a sustainable decentralised energy supply, which should meet the economic and social conditions of developing countries in the West African region. The paper briefly outlines the current state of small-scale biogas production in Africa. Several reviews of the already existing and operated facilities in the mentioned area are named and evaluated. Specific opportunities, limitations, and experience are discussed and the results of the biogas production studies using pineapple waste, carried out at Augsburg University of Applied Sciences and at Brno University of Technology, are presented.

1. Introduction

Togo's recent economic performance has been relatively robust with the gross domestic product growth being, on average, 5.5 % in the last five years. Such economic development requires a stable energy supply; however, the country's electrification ratio remains low and the electricity supply is unreliable. In 2014, about 46 % of the population of Togo (in the rural areas only 16 %) had access to electricity, which was primarily supplied through thermal power plants, imports from Nigeria and Ghana, and some hydropower plants. Although the share of renewable sources in the total energy consumption is relatively high, 72.8 %, this includes over 50 % of traditional solid biomass that is not sustainably used (The World Bank, 2018). Still, the potential of Togo (or other West African countries) in terms of decentralised renewable energy resources is significant. The present research therefore focuses on the development of simple and efficient biogas production technology from pineapple solid wastes, which would represent a sustainable alternative to the conventional energy sources used in Togo such as imported heavy fuel oil or natural gas. The objective is to find the conditions leading to the maximum biogas production and to develop a reliable technology featuring low investment and operating costs, which would be usable in developing countries.

About 100 plants with different digester sizes between 10 m^3 and 30 m^3 were installed in 2011 in Ghana according to Arthur et al. (2011). In these plants, the input material consists of liquid and solid residues of animal farming, human excreta, agricultural residues, and kitchen waste. Arthur et al. also state that, in general, only three main digester types are employed – fixed dome digester, floating drum digester, and Puxin digester – and that the biogas is used mainly for cooking purposes where no gas purification is necessary. The reason for this is that production of electricity, where gas purity is essential (Sakhmetova et al., 2017), biogas upgrading (Miltner et al., 2016), biogas synthesis networks (Čuček et al., 2017), or other, more advanced technologies are often hard to implement in the discussed conditions. As for the bio-slurry on the output side, typically it is used as a fertiliser. What is more, half of the 100 plants mentioned by Arthur et al. have been visited by these authors and they point out that only half of those (i.e., 25) are running entirely without technical issues. The problems and

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causes of the failures of African biogas production facilities are described in detail by Amigun et al. (2008) and are as follows:

- Poor design and construction of digesters, incorrect operation, lack of maintenance.
- Poor dissemination strategy and the lack of project monitoring and follow-up by the promoters.
- Poor ownership responsibility by users.
- Failure by government to support biogas technology through a focused energy policy.

A detailed study regarding drivers and barriers for the dissemination of biogas digesters in Ethiopia was given by Kamp and Bermúdez Forn (2016). In their paper they state that only around 40 % of the 1,000 biogas production plants with digester sizes ranging from 2.5 m^3 to 200 m^3 installed in the last two decades are still being operated. In Uganda, socio-economic, demographic, and political topics related to the adoption of biogas production as a sustainable fuel source for cooking purposes and lighting were surveyed by Walekhwa et al. (2009). This study mentions that family-size digesters, which use mainly cow dung and other organic wastes from agriculture, show high potential but are not as wide-spread as they could be. Such digesters seem to have a more intense application in rural areas of India, Nepal, and China, where the different digester types are named after their local origin or inventors. Literature is available regarding application and optimization of their operation – e.g. Kalia (1988) compared the biogas yield of an advanced biogas plant type and the conventional fixed-dome type without any moving parts that is also known as Janata model. Construction details for the whole system, which comprised a material investment of about 500 US$ in 1988, were given. With an average temperature of less than 20 °C at the location where the discussed study was carried out, the performance in a West African climate would be very interesting.

Example of a well-running, small-scale biogas production plant in a rural community in India was described by Reddy (2004). The whole community contribute with cow dung and as a reward people get biogas for cooking and lighting at an affordable price, and drinking water, which is provided by an electrical pump. Electricity is generated by a diesel engine with the generator being fuelled by a mixture of diesel and the produced biogas.

Rajendran et al. (2012) presented an overall view of the employed digester types in different regions in the world. Advantages, disadvantages, construction details, and cost estimates were given for each of these types. Possibilities of using the biogas were described and, again, it was emphasized that careful operation of the digester was crucial for successful biogas production. Similarly, Hoo et al. (2017) reviewed successful biogas implementations in Bangladesh, China, India, Malaysia, Thailand, Japan, and some European countries where effective government support policies were in place. As for Malaysia in particular, being the second largest producer of palm oil in the world, Kwee et al. (2017) discussed biogas generation from palm oil mill effluent in the rural areas where it could be effectively used as an alternative source of energy.

In terms of biogas production solely from fruit and vegetable wastes, for example Tahir et al. (2015) showed that a mixed fruit waste provides a 10 % larger biogas yield than a mixed fruit-vegetable waste. The same paper also discussed a scalable method to increase the methane content in the produced biogas to over 70 % using $Ca(OH)_2$ as a way fulfil the Pakistan's energy demands with sustainable management of organic fraction of municipal solid waste.

From all these studies as well as many others available it is clear that the commonly employed techniques are good enough to reach acceptable biogas yields; however, in terms of reliability and maintenance there still is much room for improvement. This is why it is important to develop a low-maintenance technology which would be simple yet reliable and efficient.

2. Biogas production from pineapple wastes

Seasonal processing of pineapples in Togo takes place primarily in decentralised small- and medium-sized enterprises such as the one shown in Figure 1. In 2016 the pineapple production in Togo was 1,908 t (FAOSTAT, 2018). A typical enterprise processes 1–2 t/d of fresh pineapples. The manufactured pineapple products are dried fruits and fruit juice and are mainly exported.

The resulting pineapple waste is about 40 % related to the fresh weight, i.e., typically 400–800 kg/d can be used for biogas production. The biodegradable organic waste comprises peels, cores, stems, crown waste products, and discarded fruits with high moisture content. Since pineapple waste is rich in lignin, cellulose, hemicellulose, and other carbohydrates, it is appropriate to utilise anaerobic digestion. However, these compounds form stable incrustations, essentially complicating the biological decomposition of organic substances by hydrolysis, and therefore a pre-treatment of the waste by crushing before it is fed into the digester is recommended.

Although the produced biogas is primarily intended for utilisation as a decentralised source of renewable energy, it can also be used as a fuel for the process of drying of the fruits. Moreover, biogas generation from the mentioned wastes contributes to improved waste management and, consequently, also to lesser environmental pollution in developing countries. Given the typical African climate, the liquid digestate is used directly, but in

Figure 1: Processing of pineapples in a typical small-sized Togolese enterprise.

terms of developing countries with less dry climates its thickening via various evaporation methods (Vondra et al., 2016) could be beneficial.

The main goal is to make the microbiological conversion of pineapple wastes into energy-rich biogas via hydrolysis, acidogenesis, acetogenesis, and methanogenesis as effective, stable, and safe as possible. The parameters, which influence this process, were discussed e.g. by Baranowski (2017). In order to explore how exactly they affect the performance of biogas production, laboratory-scale experiments were carried out in the first phase of the present research.

3. Materials and methods

All experiments were conducted at a laboratory-scale at temperatures corresponding to the mean ambient temperature in Togo. The influences of different process parameters on quantity and composition of biogas in a semi-batch reactor were investigated.

In total, three test series – A, B, and C – with different substrate compositions have been successfully carried out at Augsburg University of Applied Sciences. Hydraulic retention times of 92 d, 73 d, and 67 d were used for the following analyses. The samples of the substrates evaluated in the laboratories had relatively low dry matter content (less than 8 wt.%) and therefore no pumps were required. Fermentation was carried out in digesters with effective volumes of 1–3 L with inlets for feeding and outlets for biogas and effluent. Because efficient microbiological decomposition of organic substances requires enlargement of the specific surface of the substrate, the pineapple waste was machine-minced into 1–3 mm particles.

Cow dung was used as inoculation material and co-substrate at the ratios from 1:2.4 to 1:4 based on weight. The compositions of the substrates are listed in Tables 1–3. Dry matter fraction and moisture content of the substrates were determined via drying in an oven at 105 °C until a constant weight was obtained. For the determination of organic dry matter (ODM) fraction, the dried solid samples were combusted at 220 °C for 30 min and thereafter at 550 °C for 2 h. Fermentation took place at the temperature of (31.0–32.4) ± 2.0 °C and pH values between 6 and 8. The pH value was regulated through the addition of sodium hydrogen carbonate to ensure stability of the digestion process. Twice a day the substrate was carefully homogenized by manual stirring. Fermentation liquid was checked for pH value using a pH meter even though for plant control purposes the ratio of volatile organic acids to total inorganic carbon (VOA/TIC) is more suitable. The VOA/TIC value was determined by endpoint titration using dilute sulfuric acid. During experiments, gas samples were taken from the sampling ports for analysis at regular intervals. The actual gas compositions were identified using gas chromatography mass spectrometry. Temperature, pH value, and biogas and methane productions during fermentation were determined.

Table 1: Properties of a substrate digested in the digester with effective volume of 3 L and hydraulic retention time of 92 d (test series A)

Substrate	Weight [g]	Mass fraction [%]	Dry matter [wt.%]	Organic dry matter [wt.%]
Pineapple waste	438.2	11.26	1.61	60.10
Cow dung	1040.5	26.74	3.84	119.68
Water	2413.0	62.00	0	0
Total	3463.7	100.00	5.45	179.78

Table 2: Properties of a substrate digested in the digester with effective volume of 1 L and hydraulic retention time of 73 d (test series B)

Substrate	Weight [g]	Mass fraction [%]	Dry matter [wt.%]	Organic dry matter [wt.%]
Pineapple waste	80.0	6.90	0.99	10.97
Cow dung	319.7	27.57	3.96	36.77
Water	760.0	65.53	0	0
Total	1,159.7	100.00	4.95	47.74

Table 3: Properties of a substrate digested in the digester with effective volume of 2 L and hydraulic retention time of 67 d (test series C)

Substrate	Weight [g]	Mass fraction [%]	Dry matter [wt.%]	Organic dry matter [wt.%]
Pineapple waste	203.3	8.38	1.20	27.88
Cow dung	508.3	20.96	3.01	58.47
Water	1,713.6	70.66	0	0
Total	2,425.2	100.00	4.21	86.35

4. Results and discussion

It was found that pineapple waste can be used successfully for biogas generation under anaerobic conditions. The produced raw biogas contained 41.0–70.5 vol.% of methane, 7.0–55.9 vol.% of carbon dioxide, as well as water vapor, oxygen, nitrogen, and other components. The performance evaluation of anaerobic digestion in terms of all the performed test series A, B, and C can be made on the basis of methane yield related to the organic dry matter content as shown in Figure 2. In test series A, which used the digesting substrate according to Table 1, the highest methane yield of around 113.8 L/kg ODM after 92 d was achieved due to the larger digester volume, while methane yields in test series B and C taking 73 d and 67 d remained significantly lower. Furthermore, the rates of methane formation vary greatly. In the test series A, the pineapple wastes were mixed with fresh cow dung as inoculation material and fed into the digester. In contrast, in the other two cases, B and C, cow dung had been stored for a few days before being mixed with pineapple wastes so that the growth of methanogenic microorganisms had already started and, subsequently, the increase rates of methane formation were higher. As for the adjustment carbon to nitrogen ratio (C/N), values between 25.8:1 and 31.8:1 were found to be suitable for biogas generation from the various substrates examined in this study.

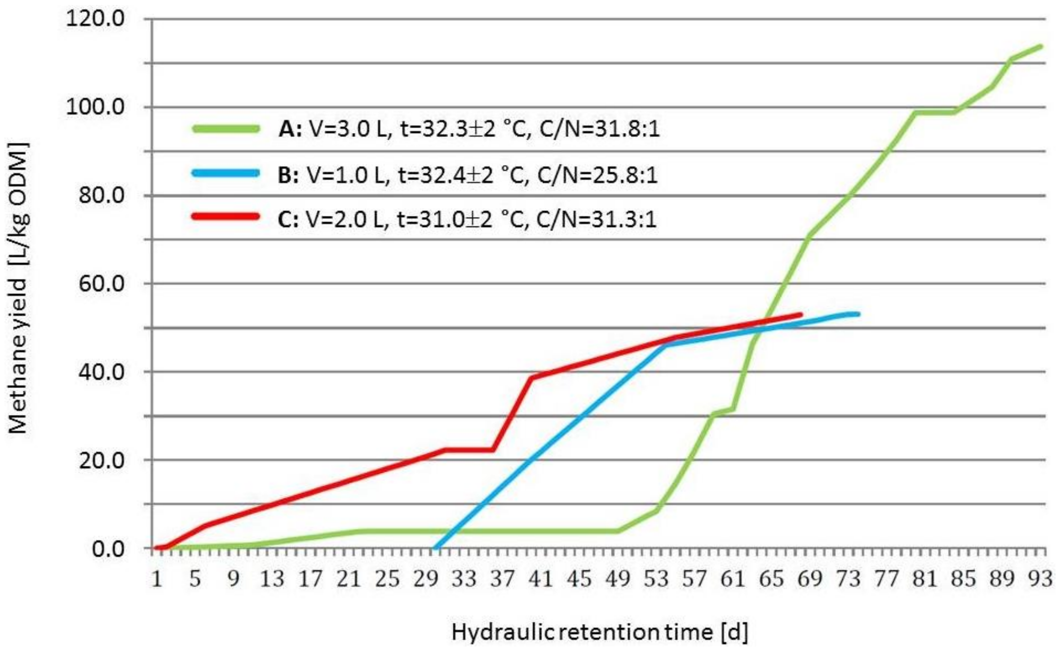

Figure 2: Effects of digester volume, V, temperature, t, and carbon to nitrogen ratio (C/N) on methane yield based on organic dry matter (ODM).

As for the temperature and pH value profiles, these were similar in all the three tests series. In terms of e.g. the test series A, the profiles are shown in Figure 3. Here, the substrate temperature was 32.3 ± 2.0 °C during the entire experimental period. This corresponds to the mesophilic operating conditions for which the reaction rate is slow but more robust and stable than biogas production at thermophilic conditions (Schnürer and Jarvis, 2009). Considering the pH, according to Rao et al. (2010) the optimal efficiency of the methanogens is reached within the pH range of 6.5–8.0, while in case of acetogens the respective range is 5.0 – 8.5. Korres and Nizami (2013), on the other hand, reported that the optimum operating pH range for anaerobic digesters should be between 7.0 and 8.5. Because the pH value fell sharply due to hydrolysis and acidification at the beginning of the tests, a total of 32 g of sodium hydrogen carbonate were added to adjust the pH value between 6.0 and 7.6 in the course of the first 6 d. The formation of methane started after 48 d and took place mainly at the pH around 7.3 (see also Figure 4). Apart from that, Figure 4 also shows for the test series A the corresponding cumulative biogas and methane productions depending on the hydraulic retention time. It can be seen that virtually no methane was formed within the first 48 d (the generated biogas consisted almost exclusively of carbon dioxide and hydrogen). The fluctuating rate of methane formation in the following 44 d was caused by repeated gas sampling. The gas formation period ended after 92 d, during which 49.00 L of biogas and 20.46 L of methane were formed. This corresponds to the methane concentration of 41.7 vol.%.

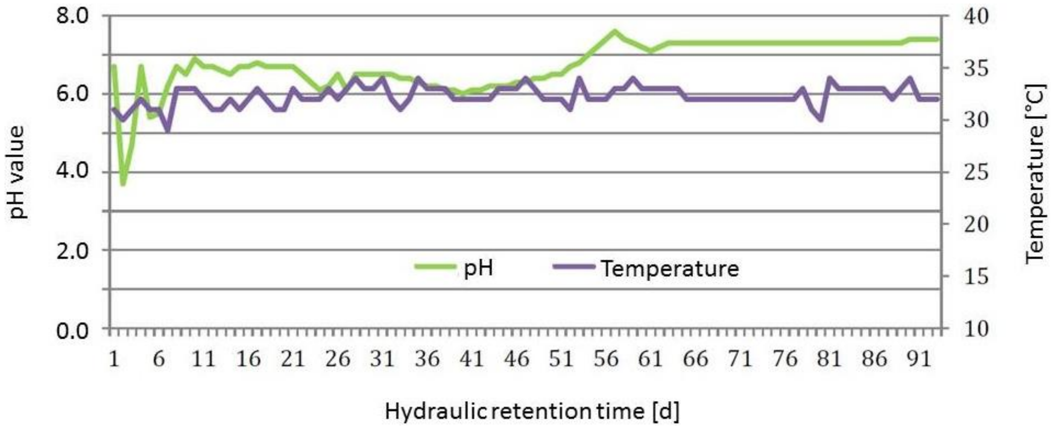

Figure 3: Profiles of temperature and pH value during fermentation of the substrate according to Table 1 (test series A).

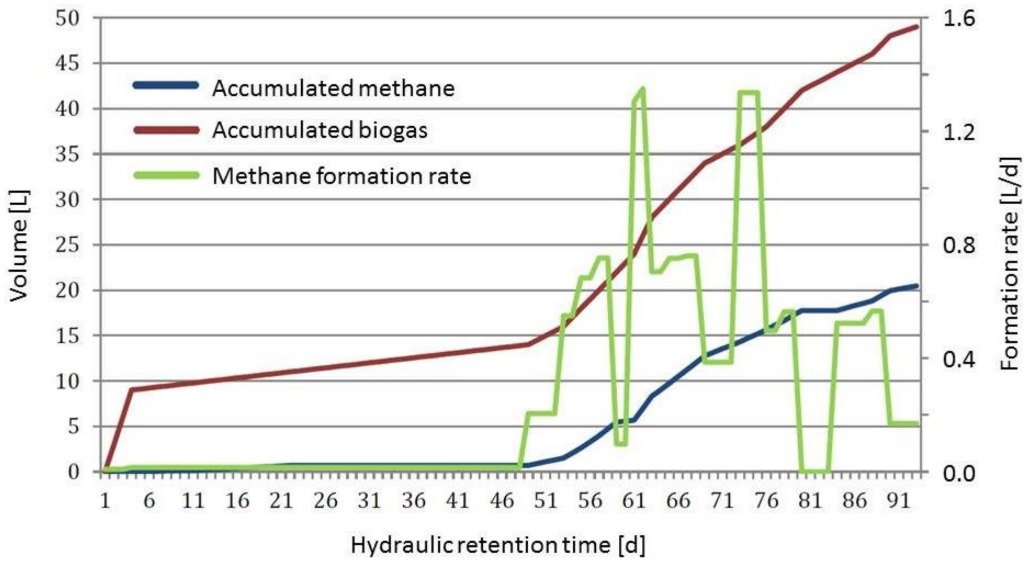

Figure 4: Cumulative biogas and methane production and methane formation rate from the substrate according to Table 1 (test series A).

5. Conclusions

In this study, the conversion of pineapple solid wastes into energy-rich biogas by means of laboratory-scale anaerobic digestion was investigated. It was found that pineapple waste has a high potential for biogas production. The process parameters significantly influencing the quantity and quality of biogas formation using a semi-batch process were identified. The goal was to obtain the highest possible methane yield from the available pineapple waste, which was achieved using a digester having the effective volume of 3 L and a pineapple waste to cow dung ratio of 1:2.4. The resulting methane yield was 113.8 L/kg ODM after the hydraulic retention time of 92 d. The methane content of the produced biogas ranged from 41.0 vol.% to 70.5 vol.%. As for the feasibility of biogas technology in Togo, the next steps are the scale-up of the obtained laboratory results and the construction of a pilot plant. This low-cost plant has already been manufactured and is equipped with a 60 L digester able to treat substrate volumes of 50 – 55 L.

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