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SELECTION OF OPTIMAL ANAEROBIC DIGESTION TECHNOLOGY FOR FAMILY SIZED FARM USE – CASE STUDY OF SOUTHWEST MADAGASCAR

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Abstract

The aim of this work was to evaluate local conditions in Madagascar and their effects on anaerobic digestion process in order to select a suitable technology and design for small-farm biogas production. Climatic conditions, input feedstock properties as well as limitations and possibilities of commonly used designs for anaerobic digestion (AD) are discussed. Mesophile conditions in digester, co-digestion of zebu dung with weed plants and agriculture residues and production of 1m^3 of biogas per day were found as optimal regarding local specifications. Common technologies used in developing countries are considered as inapplicable because of their need of large amount of water for wet type of AD. Dry batch technology is recommended as suitable for the area in southwest Madagascar.

Keywords: biogas; biomass; developing countries; digester; energy

INTRODUCTION

Constantly growing worldwide energy consumption and population expansion in developing countries increase stress and damage to the planet. As the resolution of primary commodities and energy shortage, alternative forms of energy, mainly biomass can be applied. Biomass is traditionally used as a source of energy by almost half of the world population (in developing countries, biomass presents 90% of energy use) (Jumbe et al., 2009). Unfortunately the traditional use of biomass – by burning, not only contributes significantly to environmental pollution and increases concentration of greenhouse gases, but also leads to irreversible changes in native ecosystems (Faaij, 2006). These problems particularly affect the African continent, where most of the population still lives below the poverty line, and where often the only way to survive is to use local natural resources (White et al., 2001). Madagascar, particularly known for a great number of endemic species and one of the largest biodiversity sites in the world, is also one of the poorest countries where two thirds of residents live below the poverty line. The majority of the population is living from agriculture (mainly slash and burn type), livestock and logging. About 80% of the population works in the agricultural sector. This leads to massive deforestation and after dangerous erosion endangering farming itself. A serious problem is the lack of energy. Southwestern Madagascar near the city of Toliara is specific by endemic arid spiny forest and is one of the most endangered places of Madagascar by logging for charcoal production (Scott et al., 2006). Village associations in the village Ranobe (30 km north of Toliara) began three years ago with the program of bush restoration by planting indigenous trees. But the sustainability of the system is subject to availability of an alternative source of energy for small farmers instead of burning wood or charcoal. The solution is utilization of anaerobic digestion, microbial transformation of organic biomass in anaerobic conditions. This type of renewable energy has many advantages, in particular, low initial investment, ease of use, product purity, and large numbers of applications (Faaij, 2006). Products of AD are not only the biogas, methane-rich gas with the net calorific value of 20-23 MJ/m^3 (Motlik and Vana, 2002) that can be used in many appliances, including modified lamps, stoves, refrigerator burners, generators and engines. There is also other product of fermentation, bio-stabilized substrate (digestate) for use as fertilizer. Feasibility of farm-scale AD project, yield of biogas and speed of digestion depend on many factors that will be analyzed in this article to find the optimal technology in the conditions of southwest Madagascar.

MATERIALS AND METHODS

Study area

The research site is in Ranobe village and its surroundings. Ranobe village (GPS point:-23° 0’ 54.48”, +43° 36’ 5.61”) is located about 30 km north from Toliara, capital of Atsimo-Andrefana district in the southwest of Madagascar.

Climatic conditions

TFA 35.1075 Nexus weather station was used for the measuring of average air humidity, temperature, rainfall and wind speed. Surveying of weather was conducted from December 2009 to December 2010 and measurements were made every half hour. Data were processed using Excel tools.

Agriculture practices and energy use

Study area preliminary testing was held in Ranobe village. Seven farmers were interviewed about their agriculture practices and energy use. Unstructured questionnaires were based on the interaction with the informant to elicit information and used as part of observation field work (Punch, 1998).

Biomass feedstock

Three samples of biomass from Ranobe (rice straw, rice husk and corn stalk), *Opuntia ficus-indica* cladodes obtained from Botanical garden of the Faculty of Science Charles University in Prague, human urine and zebu (*Bos indicus*) dung from ZOO Vyškov were studied in the laboratory of CULS in Prague. The water content, ash content, total volatile solid content, C, N, H, S, O, Cl content were measured according to the European standard methods - EN 14774-1:2009, EN 14775:2009, EN 15148:2009, EN 15104:2011, EN 15289:2011 respectively (BSI, 2011) and total solid content, and C/N ration of all samples were calculated (see Table 1).

Methods

To choose the best technology applicable in the specific area, the examination of all determined inputs (local climatic conditions, average family size and energy requirements, available substrate and its parameters) was used. To specify the reactor operational temperature and possibility of use of AD as a source of energy in southwest Madagascar, confrontation of measured information and average values was done. The literature review was conducted to specify functioning of AD at various temperatures and linkage between fluctuation of temperature and microbial activity. Then the average rainfall and its importance for the selection of suitable technology were observed. Study of energy use in developing countries, fuel type research in Ranobe region and average size of families in Madagascar served to define the energy requirements. Field work and questioning led to the knowledge of type of biomass available for AD. The calculations as well as literature review of important properties for stable AD identified the right feedstock description and preparation.

Various types of designs used in technologies for developing countries and their advantages and disadvantages were studied with the consideration of cheap and technologically simple variants suitable for these regions and small farms (An et al., 1997). Availability of construction materials and simplicity of construction and use were discussed. An extensive literature review was done to assess the innovative technology.

RESULTS AND DISCUSSION

Experimental conditions

Temperature

According to the Climate-Charts, in the southwest Madagascar, annual minimum and maximum temperatures range between 15 – 23 °C and 27 – 33 °C, respectively (Climate-Charts, 2008). Our measurements (using TFA 35.1075 Nexus weather station) conducted

Table 1: Testing of feedstock samples for AD available in southwest Madagascar

Material	Use	Availability	Water content %	Ash content %	Total volatile solids % in DM	% DM	C/N ratio
Rice straw	Crop residues	Twice/year	8.04	19.06	79.27	91.96	69.29
Rice husk	Crop residues	Twice/year	7.57	25.97	71.9	92.43	67.96
Corn stalk, cobs	Crop residues	Once/year	15	13.15	77.34	85	68
Opuntia ssp.	Weed plant	All year	91.54	1.93	75.33	8.46	69.26
Zebu dung	Animal waste	All year	71.2	7.59	73.81	28.8	29.12
Human urine	Waste	All year	98.62	0.2	75.66	1.38	0.80

one year varied between 10.4 °C to 41.6 °C with average annual temperature of 23.4 °C. It was found that temperature variation occurs during the day and during the year. As we expected, daily minimal temperatures occurred mostly in early morning hours. Statistics of Climate-Charts about temperature seasonal variations were confirmed and the period from July to August was found as the coolest with average daily minimum temperatures of 14. 7 °C, and average daily maximum temperatures of 27.1 °C.

Naturally, AD can take place in the large range of temperatures, even below 20 °C (known as psychrophilic temperatures) but the digestion is slow and incomplete (Philip and Itodo, 2007). Most reactors operate in mesophilic (20-45 °C) or thermophilic (45-65 °C) conditions. For thermophilic conditions, a heating system has to be provided and the investment costs and the gas consumption for heating affect the viability of small scale system negatively (FAO/CMS, 1996). Between 25-30 °C, the gas production is satisfactory and, moreover, under ambient temperature of 30 °C or less, the inside digester temperature remains about 4 °C above ambient temperature because of a high microbial activity (Philip and Itodo, 2007). Not only the ambient temperature is important, also temperature fluctuations (seasonal or diurnal) affect the performance of a biogas plant. Even small variation of temperature, from 30 °C to 32 °C caused a reduction of biogas production rate (Ward et al., 2008). To ensure the smallest fluctuations in temperature for microbial activity inside the digester, the best way is to provide good insulation of the reactor or to construct an underground digester because the temperature 1m below the ground is almost constant (Philip and Itodo, 2007).

Rainfall

The area around Ranobe village is very dry. The average annual rainfall is about 400mm (Climate-Charts, 2008) and according to our research, most of the rain comes from December to February. Poor precipitation does not affect the process of anaerobic digestion directly like the variations of the temperature do. However, water scarcity influences the composition as well as the moisture content of substrates used for the digestion. Low precipitation generally leads to less intensive systems of animal husbandry and less dung is available. Moreover, in dry climate regions, the agricultural residues and other available phytomass have to be drought-resistant or have the concentration of total solids much more important. This leads to further need of water for sufficient mixture of the substrate mainly for wet AD (Kossmann et al., 1999).

Plant design and fermentation system

For the design of anaerobic digester, it is necessary to know some important information about future technology. First, it is the size of the family and its daily energy (cooking and lighting) requirements; next the availability and the amount of feedstock and water. Using this information, the type of digester and the required digester volume can be determined.

Energy requirements

The average number of persons per Malagasy household is 4. 9 (INSTAT, 1998). Based on our research on energy use, cooking is the largest energy-consuming purpose. It accounts for 90-100% of energy consumption. It was found that in Madagascar about 94% of the households rely on biomass as cooking fuel because agricultural residues, cow-dung and wood are available in their living area and is cheap, too. In Ranobe area, only sometimes charcoal is used (more often in urban areas), (World bank, 2000). According to the observations, wood for cooking is collected by women and children and it takes 3-4 hours/day.

As found in the literature, on average 26 l of gas are required to boil 1 liter of water and 200 liters of biogas (with about 60% of methane) is required for cooking 3 meals for one person per day (An et al., 1997; Kristoferson and Bokalders, 1991). This implies that 1 m^3 of biogas is needed for average Malagasy family per day only for the meal preparation. It is clear that the consumption depends on the type of meal cooked and efficiency of stove and pots used; we used the average value.

Characteristics of substrates

As mentioned previously, the characteristics of substrate feedstock plays an important role in AD process. The feedstock for the good bacterial activity depends on many factors, some of which may be adjusted by right choice of biomass (C/N ratio, available nutrients content, substrate dry matter, and particle size). Our observations made in the study area, interviews and bibliographic research led to the identification of the phytomass and other available waste (see Table 1), low in cost that could be suitable for biogas production in southwest Madagascar.

Based on our research, the phytomass present in Ranobe region could be divided into two categories – agriculture waste or weed plant. The most important agriculture product in Madagascar is rice. For this reason, rice husk and straw are abundant materials present in study area which are unfortunately wasted and burned directly on the field or near the mills. In Ranobe area, rice is harvested twice a year and average yield stated by farmers in the village is 2.5 t/ha. Within the maize cultivation, usually 13.3 t/ha of corn are produced and only a part of residues could be used as feed for the cattle. Residues are commonly burned even before harvesting. The farmers mentioned growing some other crops such as sugar cane, manioc or bananas but only in small quantities. They do not use fertilizers.

Invasive plants belonging to *Opuntia* ssp. (*Opuntia ficus-indica* (L.) Miller, *Opuntia monacantha* Haw.) present the efficient weed biomass which is omnipresent in the southwest Madagascar (Binggeli, 2003). As for animal husbandry, many zebus are owned by the farmers. They are used for transportation and farming. They move throughout the village and are generally kept in the spiny forest (a few hundred meters from village). For this reason, cattle (zebu) dung is easily available as a good substrate for AD. The last material which could be possibly used is human urine.

All these organic materials have different chemical characteristics and also the potential to produce the biogas. One of these significant characteristics is Carbon/Nitrogen (C/N) ratio. Most of the literature recommends the C/N ration range of 20 to 30, the optimum is 25-32:1 (Hills and Roberts, 1981). If the C/N ration is much higher, the accumulation of volatile fatty acids will take place in the digester. On the other hand, with the smaller ratio, high amount of nitrogen will be liberated and accumulated in the form of ammonia (NH_4) and pH will increase drastically. In both cases, methanogen activity and biogas formation will decrease (Li et al., 2011). In practice, the ideal C/N ratio is achieved by mixing of different substrates, as it happens also in our case study because C/N ration for all single substrates except zebu dung is far from the optimal range (see Table 1).

Next parameter of biomass feedstock is available nutrient content. Our testing for content of C, N, H, S, O, Cl in samples of biomass confirmed adequate amounts of these elements common for substrates such as agricultural residues. Other characteristic that is really important in the process of AD is the content of volatile solids. This means portions of the solids actually available for bioconversion (biogas production). One kg of VS produces 0.5 cubic meter of methane (Hills and Roberts, 1981), but only about half the VS added to a digester could be digested. Last characteristic that may be affected by the choice of substrate is the dry matter of feedstock. As shown in Table 1, dry matter of selected feedstock varies from 1.38% to 92.43% and plays an important role in substrate preparation and also in design and technology selection as will be discussed below.

Preparation of substrate

Preparation of feedstock for AD can increase biogas production and reduction of volatile solids. It includes pre-treatment or reduction of feedstock particle size. The use of pre-treatments is particularly useful in the digestion of biomass rich in cellulose or lignin. Pre-treatment can break down these polymers, but it could increase the price for technology. As for the low cost treatment, only size reduction and water maceration can be used. Particle size can affect the yield of AD as it affects the availability of a substrate surface for anaerobic reactions. Maceration reduces the size of fibers and was found to increase biogas production (Ward et al., 2008).

Design and fermentation system

AD processes are classified by critical operating parameters and reactor design such as continuity (batch or continuous), number of stages (one or multiple), operating temperature (psychrophilic, mesophilic and thermophilic), reactor design, and solid content (wet or dry). In batch digesters, the digester is loaded once with raw feedstock (inoculated with digestate) and then left until complete degradation has occurred. It is particularly advantageous when using more digester with different startup times to guarantee a continuous yield of biogas. On the contrary, in continuous digesters, the substrate is regularly and continuously fed (Nizami and Murphy, 2010). One-stage dry batch systems typically employ a system whereby high solids content feedstock is entered into a vessel without initial dilution. Recirculation of leachate is employed and no mixing takes place, and as such energy demand is very low (Nizami and Murphy, 2010). A special type of AD, the co-digestion is the simultaneous digestion of a homogenous mixture of two or more substrates. It provides improved nutrient balance from a variety of substrates which helps to maintain a stable and reliable digestion performance (Jingura and Matengaifa, 2009). Concerning number of stages, in one-stage digestion all the microbiological phases occur in one tank, however, in two-stage digestion different microbial phases can be separated. Generally multi-stage digesters are found to have a higher performance than single-stage digesters, but are more expensive to build and maintain (Ward et al., 2008). Wet AD handles feedstock with solid concentrations between 0.5% and 15%; in contrast the dry digestion can be characterized by the high solid content of the feedstock to be digested, which is typically greater than 15% (Li et al., 2011). Some advantages of dry AD include smaller reactor capacity requirements. Moreover, due to the lower water content, the digestate is much easier to handle. However, these systems also

Table 2: Characteristics of various digesters and their applicability in the study area

Parameters Area characteristics	**Plastic bag**	**Fixed dome**	**Floating drum**	**Plug flow**	**Deenbandhu**	**New design**
Temperature (inside) 27- 28°C	+	+	+	+	+	+
Climate Dry, lack of water	-	-	-	-	-	+
Substrate Dung, agro-residues, opuntia, urine	dung, water	dung, water	dung, water	dung, water	dung, water	+
Dry mass of feedstock						
Wet AD - 5-10%	+	+	+	+	+	-
Dry AD- 10-40%	-	-	-	-	-	+
Simplicity to build	+	-	-	+	-	+
Available construction material	+	+	+	+	+	+
Easy to use	+	+	-	+	+	+
Lifetime	-	+	+/-	-	+	+
Price	+	-	-	+	+	+

Source: FAO/CMS (1996), Kossmann et al. (1999), Faaij (2006)

have disadvantages such as larger amounts of required inocula and much longer retention time (Li et al., 2011). Currently, one-stage dry batch digesters are relatively new and innovative digesters used for bio-waste and grass silage. Their use is expected to increase. In comparison of all technologies, one stage, dry and batch digesters are seen as less expensive or cost-effective (Nizami and Murphy, 2010).

Most important factors influencing the system and design selection are simplicity, economics, durability, suitability for the feedstock type and also use of local materials (FAO/CMS, 1996). A put over of the alternative technology is economically limited especially in developing countries. Economic situation in Madagascar and our object (useful family-size technology) allow closer focus only on simple low-cost digesters. Five basic designs of digesters used in developing countries can be distinguished: the floating-drum, the fixed-dome, the Deenbandhu, the plug-flow and the bag digester. Characteristics of all these digesters and potential use in Madagascar are shown in Table 2. All these digesters are commonly used for wet type digestion with dry matter of feedstock of maximum 10%. Normally dung is mixed with a large amount of water and fed to the digester. However, the use of wet type of fermentation can be debatable in the dry conditions of Madagascar. Moreover, it is possible that good working technologies in Asia may not necessarily work well in Africa. Omer and Fadalla (2003) stated that small-scale biogas plants are located all over the Africa but very few of them are operational. In most African countries, biogas is produced using the Chinese fixed-dome digester and the Indian floating-drum digester, which are not reliable and have poor performance in most cases. Most of the plants have only operated for a short period due to poor technical quality (Mshandete and Parawira, 2009). As a solution to simplify installation and operation, the polyethylene digester technology was invented. Its advantage is reduction of the production cost by using local, low-cost materials (An et al., 1997) but this technology is based only on use of animal manure as feedstock. As can be seen, there is a great need for biogas technology development aimed at enhancement of biogas process using efficient cost-effective high rate bioreactors and appropriate biogas feed stocks other than conventionally used animal manure.

According to the new technology characterization in Table 2, this new technology should be based on mesophilic temperature range (27-28 °C), dry, co-digestion concept. As for the low cost requirements, the one-stage batch system could be used. This batch dry digestion has a significant advantage; the simplicity. Few moving part and not diluted feedstock make this technology suitable for our use. As for biogas production, it starts from zero, increases, peaks and decreases. For this reason a set of batch digesters is required. The retention time is normally longer than 30 days (Nizami and Murphy, 2010). In developing countries, dry batch digesters are not commonly used, in contrast there are used widely in Europe for dry solids content up to 50%. In this digester type, the leachate is recirculated and sprayed back on to the feedstock. This could be done through the use of a manual pump. After completion of digestion, the digester is reopened, unloaded and less than half of the feedstock is left as inoculum (Nizami and Murphy, 2010). In Ranobe village, material suitable for the construction of this simple digester (1-5 m^3 plastic water tank) is not available, but could be transported from Toliara (30 km).

CONCLUSION

Anaerobic digesters can play a vital role in farming systems by adding value to agricultural waste and livestock excreta. However, the adoption of the technology and successful results depend on aspects such as location and the way in which the technology is introduced, adapted and improved according to local conditions and attitudes of technicians.

The dry farm tank digester technology could be a cheap and simple way to produce energy for cooking and at the same time to save a woodland everyday. Firewood consumption could be reduced and a gradual regeneration of spiny forests would be possible. Moreover, *Opuntia* ssp. as a perennial problem in Madagascar could be used as a co-substrate in anaerobic digestion and be converted from a weed to an energy source. Its benefits become more apparent because these crops grow on fallow land or in marginal areas not normally used for food production. In this manner, small farming AD technology could be resource- and energy-efficient, cost-effective and have maximized environmental benefits.

More research in terms of durability and other limitations should be done to prove the sustainability of the new biogas technology and to finally show the potential to overcome energy poverty, a constant barrier to economic development in Africa.

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