Experimental Investigation of Anaerobic Co-Digestion of some Organic Wastes in Madagascar

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***Abstract*— Anaerobic digestion is a technique of treatment and valorization of various organic wastes with several advantages: reduction of environmental harmful effects, production of biogas and organic fertilizer. The present work is an experimental study of the co-digestion of mixture of several organic wastes by using 6 units of metallic digesters. It follows from experimentation results that the amount of produced biogas changes with pH of the co-substrate and the digester temperature. Comparison of the amounts of produced biogas from all digesters allows us inferring that the zebu manure and rice straw mixture substrate is the best one. By means of experimental data curve fitting, a model predicting the amount of produced biogas was suggested as a function of the temperature and pH of the co-substrate. The goodness of the fit was statistically highlighted by computing the coefficient of determination.**

Keywords—Anaerobic co-digestion, organic wastes, substrates, domestic metallic digester.

I. INTRODUCTION

For the last three decades, water, air and soil pollutions by urban, industrial and agricultural wastes have rapidly increased in Madagascar, especially in the capital city of Antananarivo which is the most populated region of this big island. Besides, the endemic fauna and flora of its tropical forests are threatened by a total deforestation due to bush fire and wood consumption. Indeed, according to a survey conducted by the Jariala program [1], the current wood consumption in Madagascar is estimated at over 21 million m^3 per year. Wood constitutes the main energy source of cooking fuel available for the majority of households, especially those with low incomes. Moreover, electricity and gas (including biogas) remain luxury energy sources for cooking for most of the population. This phenomenon should push many actors such as governments, non-governmental organizations, researchers, and industries to look for other effective and cheaper solutions, such as treatment of organic wastes, for reducing the irrefutable wood consumption. One of the best technologies to treat such organic wastes is the technique of anaerobic digestion of organic matter that produces a mixture of methane (CH_4), carbon dioxide (CO_2) and some minor amounts of other gases, called biogas [2], and digestat. Anaerobic digestion is also one of the best ways that can reduce various issues related to climate change.

The use of anaerobic digestion for the treatment of wastewater and biodegradable wastes is not a new technology. It has been used since the nineteenth century. In rural areas of China and India, simple reactor have been used for a long time to treat agricultural and livestock wastes in order to get energy for cooking and lighting [3]. However, it was only in the 70s that this technique has attracted the attention of many scientists in terms of research and technological development. This interest has increased after being conscious of climate change and the degradation of the environment. Furthermore, in the late 80s, the technique of co-digestion, that treats a mixture of different types of waste including livestock waste, agriculture waste and household organic waste, has been widespread in several countries [4].

Nowadays, a large number of anaerobic digestion technologies are used to treat organic wastes.

According to Suh and Roussaux [5], anaerobic digestion is one of the best waste treatment processes that are less dangerous towards the environment. Anaerobic digestion allows a reduction of dry matter of about 50% [6] and a production of biogas mainly composed of methane (55-70%) and carbon dioxide (25-40%) with some elements in traces like hydrogen, water as vapor and hydrogen sulfide [2, 7]. Trably [8] and Moletta [9] stipulated that during the anaerobic digestion, the microorganisms use only about 10 to 15% of the energy from the treated substrate for their growth, the remainder being used to produce biogas. The anaerobic digestion generally consists of four phases [10] which are hydrolysis, acidogenesis, acetogenesis and methanogenesis.

The use of the traditional techniques of anaerobic digestion of wet organic matters suffers from many problems despite of its advantages as it requires suitable organic loading rate or total solids content [11]. A multitude of works have been done and published on anaerobic digestion treating different mixture of organic wastes [12,13]. This technique, in addition to its various advantages compared to the traditional one, gives a higher amount of methane production than that obtained when organic wastes are treated individually [14]. While investigating a mesophilic co-digestion of kitchen waste and pig manure at different ratios of total solids, Hailin et al. [15] found a maximum biodegradability of 85.03% and a methane yield of 409.5mL/gVS with a ratio of wastes of 1:1. They noticed a severe methane inhibition when the kitchen waste content was over 50% due to the accumulation of volatile fatty acids (VFA).

Muhammad et al. [16] co-digested rice husk with food waste under mesophilic conditions to overcome the accumulation of VFA in the digestion of food waste alone. His work was focused on different C/N ratios and the highest specific biogas yield of 584L/kgVS was obtained from substrate with C/N ratio of 20. The increase of rice husk proportion was found to decrease the production of biogas.

Nurliyana [17] studied the effect of C/N ratios towards co-digestion of palm oil mill effluent (POME) and empty fruit bunches (EFB) in order to evaluate methane production and electricity generated based on the methane produced. His research study shows that methane production increases from 0.17L of CH_4 (without EFB) to 2.03L of CH_4 with a C/N ratio of 45 of the mixed substrate. The maximum of electricity production of 196kWh was calculated with the same C/N ratio and at a proportion of 10 L: 3.1kg of POME: EFB. Evaluation of pH stability, organic removal rate, and biogas production was investigated in a dry anaerobic co-digestion of different mixture of organic waste composed of cattle manure, household organic waste, and residue from agriculture by Tianxue Yang [18]. An enhancement of the biogas production was obtained using the co-digestion of a mixture of organic matter compared to the production from digestion of a single substrate.

Co-digestion of municipal sludge has been experimented in many countries with a large variety of wastes. The experiment co-digesting a mixture of external organic wastes with municipal sludge at various ratios [19] results to a significant increase of biogas production and an additional degradation of the municipal sludge between 1.1 and 30.7%. A large number of anaerobic digestion and co-digestion technology is currently used to treat organic wastes. A recent report on the technique of co-digestion of organic wastes shows that cattle manure, sewage sludge, and organic fraction from municipal solid waste are the most treated co-substrates for biogas production and so draws many researcher's attention and also in industrial applications section [20].

Therefore, this study is focused on the co-digestion of various mixtures of organic wastes such as zebu manure, pig manure, chicken manure, rice straw and water hyacinth with different volume ratios. The main objective is to determine which mixture is able to produce the maximum of biogas yield. Besides, based on experimental data, a model predicting the amount of produced biogas should be established for each kind of mixture substrate.

II. Materials and Methods

A. *Conducting the Experiments*

For conducting the experiments of this survey, six units of metallic digester were used. Each digester unit has a capacity of 420L. Thus 3 types of experiments of anaerobic co-digestion of various mixture of organic waste that are abundant in Madagascar have been achieved.

Experiment 1: Anaerobic co-digestion of the mixture of zebu, chicken and pig manure substrate (ratio 1: 1:1) in a discontinuous digester:

Collecting zebu, chicken and pig manures is not an issue for Malagasy peasants as these domestic animals are abundant in the rural areas of Madagascar. It is then interesting to study the co-digestion of these wastes.

Experiment 2: Anaerobic co-digestion of the mixture of zebu manure and rice straw (ratio 1:1, 1:2 and 1:3) in 3 digesters operating continuously

Collecting rice straw is also easy for Malagasy farmers as it generally serves to feed their livestock especially during period of drought. However, it is interesting to determine the amount of biogas production from this substrate when mixed with zebu manure at different ratio. The anaerobic co-digestion was carried out into 3 digesters D2, D3 and D4.

Experiment 3: Anaerobic co-digestion of mixture of zebu manure and water hyacinth (ratio1:1 and 2:1 in 2 digesters operating continuously

Significant amounts of water hyacinth cause each year big issues of water evacuation in the capital city of Antananarivo especially in summer. No technique of treatment of this kind of vegetation has yet been conducted to solve this problem. Thus, water hyacinth was mixed with zebu manure and treated by anaerobic co-digestion process in order to determine at what mixing ratio we can obtain the maximum amount of biogas. The plant has been dried first then cut in order to get rapid decomposition of the organic matter. The experiment was set into 2 metallic digesters D5 and D6

The characteristics of the treated mixed substrates are shown in the Table I. It should be noted that ratio means, in this paper, the comparison of volumes of the wastes to be mixed to constitute a substrate. For example, ratio 1:2 of mixed cow manure and rice straw means the substrate is made of a volume unit of cow manure and two volume units of rice straw.

For each experiment, each digester was fed up to 75% of its volume with the mixture of substrates and water. All digesters were functioning continuously except the digester D1.

TABLE I. NATURE OF SUBSTRATES USED FOR THE ANAEROBIC CO-DIGESTION EXPERIMENTS

Digester	Substrate
D1	Mixed zebu-chicken and pig manure, ratio 1:1:1
D2	Mixed cow manure and rice straw, ratio 1:1
D3	Mixed cow manure and rice straw, ratio 1:2
D4	Mixed cow manure and rice straw, ratio 1:1
D5	Mixed cow manure and water hyacinth, ratio 1:1
D6	Mixed cow manure and water hyacinth, ratio 2:1

After the loading process was finished, all digesters were left for fermentation process during 13 days and data collection was done. Then a daily measurement of the pH of each substrate, the temperature surrounding the digesters, the temperature of the digesters and the volume and mass of produced biogas was done during the experimentation stage in order to identify how well each substrate produces biogas as function of the pH and the temperature.

The measurement of the volume of the daily produced biogas was done by using a plastic tubular bag of 26.7cm of diameter which is connected to each digester by some PVC pieces of 25cm of diameter. The mass of biogas inside the plastic tubular bag was measured every 2 hours (from 6 am to 6 pm) using a scale of 2000g±0.1. The daily measure of the pH was done with a pH-thermometer HI98127. The temperature of the surrounding environment of the digesters and the temperature of the digesters were measured with a HI98127 and with a Polder-make digital thermometer (0 to 200°C).

B. Mathematical Formulation

The simplest equation developed to determine the amount of produced biogas is possibly that proposed by Boshoff [21]

$$M = M_t(1 - e^{-kt}) \tag{1}$$

where M is the weight (g) of produced biogas to be predicted at a chosen time t (d), M_t denotes the possible total weight (g) of produced biogas, k is the reaction velocity constant which is also defined as the reciprocal of the time it takes to achieve 63% of the total biogas production (d^{-1}).

In the present survey, the experimental data curves of the amount of produced biogas related to each substrate was fitted as a power law function of the pH of the substrate and the temperature of the reactor where the anaerobic co-digestion is carried out. In case the so-obtained model cannot fit well the experimental data curves, it means there are other parameters that also influence the biogas production. To overcome this issue, the time variable is adjoined to the two aforementioned parameters for the experimental model fitting.

Equation (2) is hence chosen to predict the amount of biogas production M_{D1} (g) from the batch digester D1

$$M_{D1} = aT^b(pH)^c|sin(\omega\, t + \varphi)| \tag{2}$$

where T is the digester temperature (K), pH denotes the pH of the substrate inside the digester D1, t is time variable (d), a, b, c, ω and φ are constants to be determined by non-linear regression method.

As for the other continuous reactors D2, D3, D4, D5 and D6, formula given by (3) is adopted to predict the amount of daily produced biogas from each of them.

$$M_{Dj,j=2,3,4,5,6} = aT^b(pH)_{Sj}^c \tag{3}$$

where M_{Dj} represents the quantity of produced biogas by substrate from digester Dj, (j = 2,3,…,6), T denotes the digester temperature (K), $(pH)_{Sj}$ the pH of the substrate inside Dj, a, b and c have the same nomenclature as in (2).

The goodness of the fit of the models is assessed with the value of the coefficient of determination R^2. Equation (4) was used to compute this statistical parameter [22].

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(y_{exp,i} - \hat{y}_{pre,i})^2}{\sum_{i=1}^{N}(\bar{y}_{exp} - \hat{y}_{pre,i})^2} \tag{4}$$

where y_{exp}, $\hat{y}_{pre}$ and $\bar{y}_{exp}$ denote the experimental, the predicted, and the experimental mean values of the surveyed variable y respectively while N over which is done the summation is the number of data points.

III. RESULTS AND DISCUSSION

A. Total Amount of Biogas Produced During the 17 Days of Experimentation

Based on (1), the evolution of the daily amount of biogas that can be produced during the 17 days of experimentation is shown in Fig.1. This graph shows that the maximum amount of biogas production is obtained from digester D2 corresponding to a substrate with a mixture of zebu manure and rice straw (ratio 1:1) while the lowest production is that from D1 corresponding to a mixture of zebu, chicken and pig manures (ratio1:1:1). The quantity of biogas produced from digesters D3 (rice straw-zebu manure, (ratio 1:2)) and D5 (water hyacinth-zebu manure, (ratio 2:1)) seems to be in competition.

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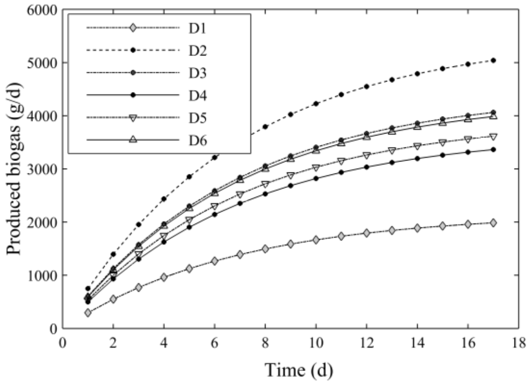

Fig. 1. *Total biogas yield from each substrate*

From these results, Table II gives the total quantity of produced biogas from each substrate during the 17 days of experimentation.

TABLE II. TOTAL AMOUNT OF BIOGAS GENERATED FROM EACH DIGESTER D_J (J = 1,2,…,6)

Digester	Weight of yield biogas (kg)
D1	1,98
D2	5,04
D3	4.06
D4	3,36
D5	3.62
D6	3,98

B. Evolution of the Production of Biogas from Each Substrate with Temperature

Biogas production depends directly on the temperature of the digester [2]. As can be seen from Fig. 2 to Fig. 4, bacteria from mesophilic and thermophilic dominate the process of methanogenesis.

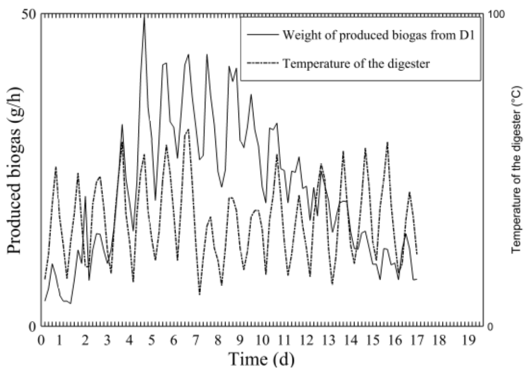

Fig.2. *Evolution of the amount of biogas production inside the batch digester D1 and the surrounding temperature*

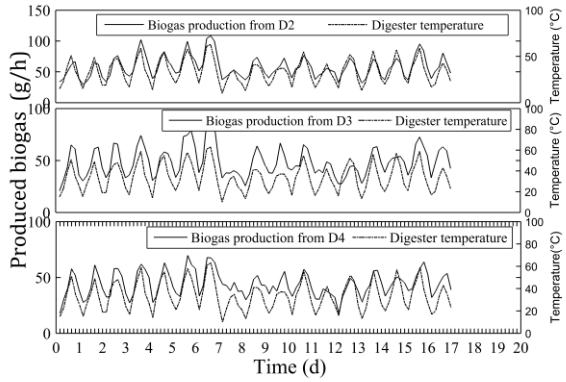

Fig.3. *Evolution of the amount of biogas production inside the continuous digesters D2, D3 and D4 with the temperature*

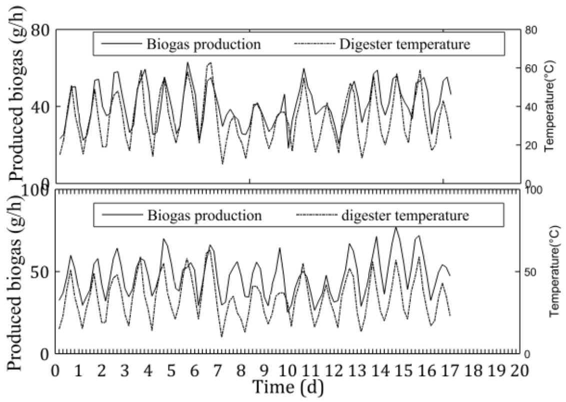

Fig.4. *Evolution of biogas production inside the digesters D5 and D6 with the temperature*

C. Evolution of the Production of Biogas and Substrate pH

pH plays an important role in the growth of microorganisms through the process of anaerobic co-digestion. It is preferable that its value remains as close as possible to the neutrality of a solution since its decrease under 6.5 results in inhibition of the methanization process [2]. The results of the evolution of the biogas production and of the pH of each treated substrate are shown from Fig. 5 to Fig. 7. It is highlighted that the pH value of each substrate fits well the process of the anaerobic co-digestion except sometimes with the substrate from the digester D1 whose value fell to 6.3 in the late experimental measurements (Fig. 5). The reason should be due to the degradation of the organic matter and the batch nature of the generator D1. The variation of this parameter is dependent on the evolution of the decomposition of organic matter. Its decrease is due to the production of VFA during the acidogenesis phase. Nevertheless, a study of the characteristics of the mixture of zebu, chicken and pig manures should be deepened to understand this rapid fall of pH and the slowness of the production of biogas.

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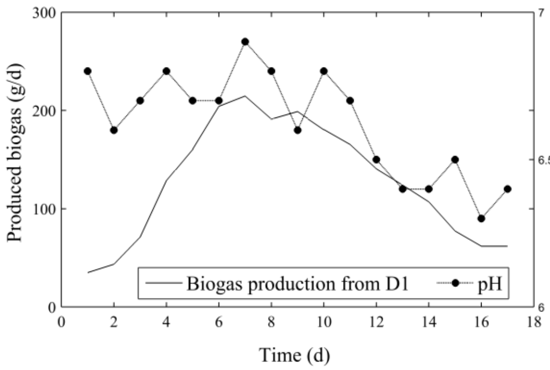


Fig.5. *Evolution of the biogas production and the pH of substrate from digester D1*

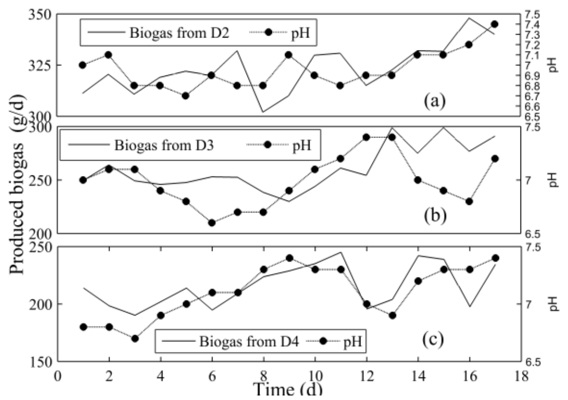


Fig.6. *Evolution of the biogas production and the pH of substrates from digesters: (a) D2, (b) D3 and (c) D4*

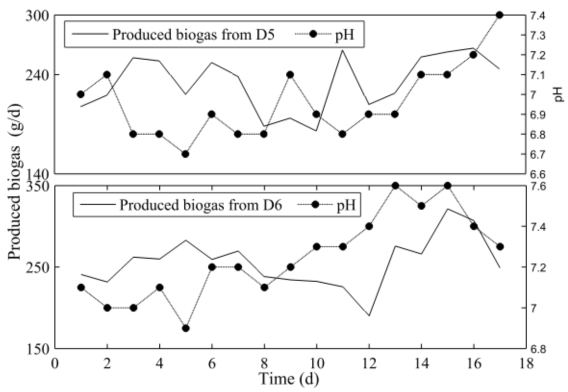
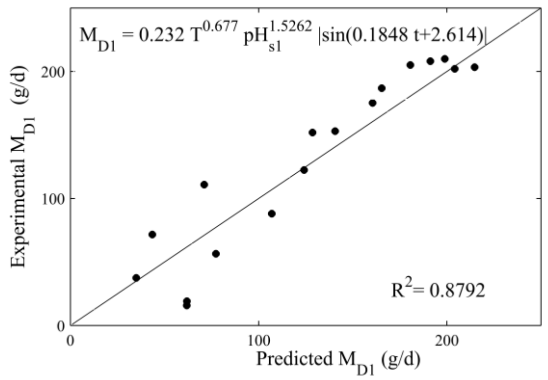


Fig.7. *Evolution of the biogas production and the pH (digesters D5 and D6)*

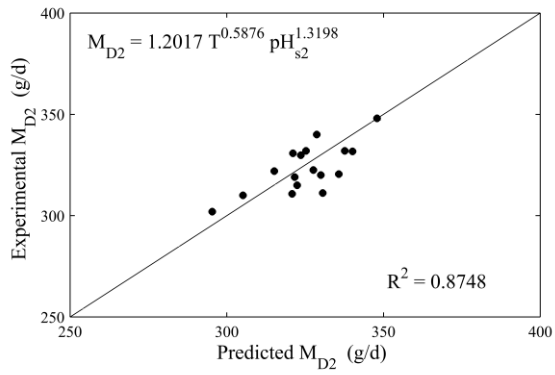
Values of regression coefficients a, b, c, ω and φ, that are obtained from experimental model fittings of (2) and (3) for digesters D1 to D6, are listed in Table III. As can be seen from Fig. 8, the values of R^2 generally turn around 0.9; that is acceptable as other parameters that can influence the anaerobic co-digestion process were not considered during the experimentation.

TABLE III. VALUES OF REGRESSION COEFFICIENTS OF (2) AND (3)

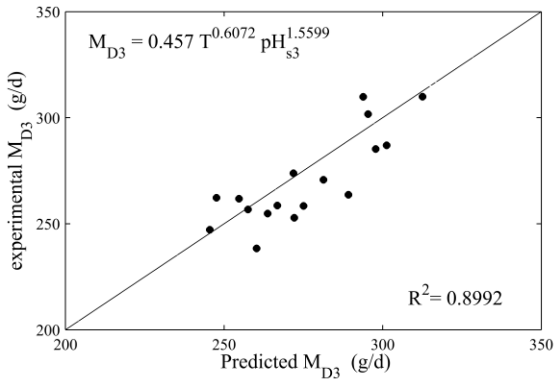
Digester	**Constants**				
	a	***b***	***c***	***ω***	***φ***
D1	0.2320	0.6770	1.5262	0.1848	2.614
D2	1.2017	0.5876	1.3198	-	-
D3	0.4570	0.6072	1.5599	-	-
D4	3.3086	0.1007	1.268	-	-
D5	0.4253	0.8374	0.8075	-	-
D6	2.3556	0.3775	0.8094	-	-



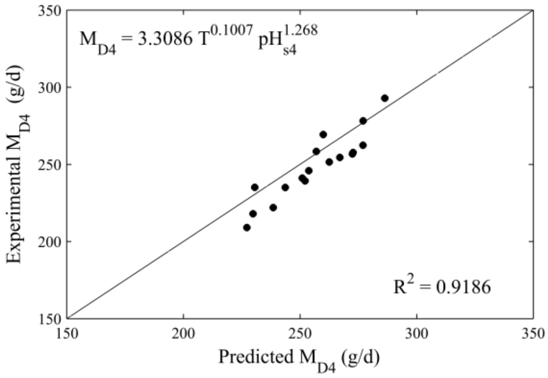
(a)



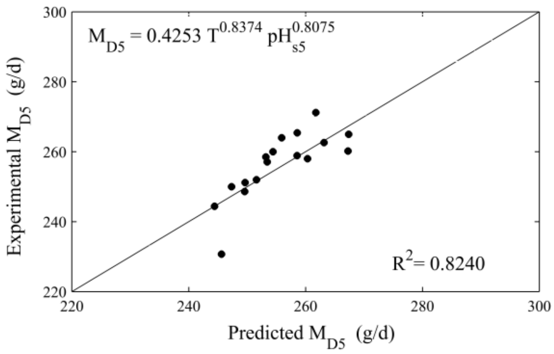
(b)



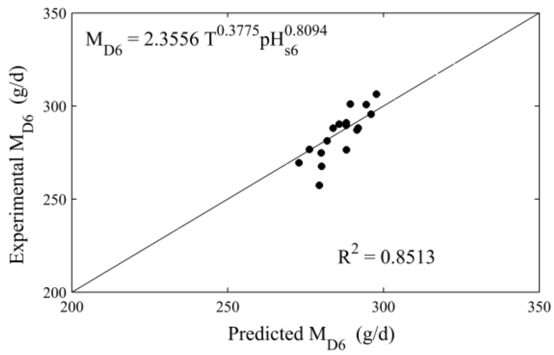
(c)



(d)



(e)



(f)

Fig.8. *Comparison of predicted and experimental values of the amount of produced biogas from each studied digester: (a) D1, (b) D2, (c) D3, (d) D4, (e) D5, (f) D6.*

IV. Conclusion

Given the current context of waste production increase and galloping deforestation in Madagascar, anaerobic co-digestion appears as an alternative solution for treating wastes to boost sustainable development in this big island. The present work aimed at conducting an experimental investigation of biogas production from various mixtures of organic wastes.

Results of this work can be summarized as follows:

- The anaerobic co-digestion of mixed waste substrates considered in this study is related to mesophilic and thermophilic bacteria and has pH values ranging from 6.8 to 7.5, that is, around neutrality.

- The comparison of the produced biogas from each treated substrate allowed to infer that the best substrate is that of the digester D2, consisting of a mixture of zebu and rice straw (ratio 1:1), with a total production of 5.041 (kg) during the 17 days of experimentation.

- Based on experimental data, mathematical models depending on the temperature and pH were fitted for predicting the amount of produced biogas from each studied substrate. The goodness of the fit was statistically proven to be acceptable. However, one should consider other parameters such as the Volatile Fatty Acid (VFA), the rate of volatile solids, the dry matter, the organic matter, in order to get a better fit.

Although anaerobic co-digestion process is in relation with the temperature increase, a study of the thermal behavior of the domestic metallic digester should be carried out as an example of extension of this work. Characterizing the co-digestion of other kinds of mixtures of organic wastes would be an interesting continuation of this survey as well.

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