CHEMICAL ENGINEERING TRANSACTIONS
VOL. 58, 2017
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Remigio Berruto, Pietro Catania, Mariangela Vallone

ISBN 978-88-95608-52-5; **ISSN** 2283-9216
DOI: 10.3303/CET1758078

Conceptual Design and Functional Modelling of a Portable Thermophilic Biodigester for a High Dry Matter Feedstock

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In years to come, water and energy are two issues of concern for trying to keep a continued and sustainable existence of mankind on earth. Regarding the generation and reliable supply of energy; it is a vital matter, especially for those marginal and inaccessible rural communities, which continually struggle for energy as constantly it is in short supply and their only energy sources at hand are crops and forest biomass. When there is abundant availability of vegetative biomass and crop residues, consequently processing them for biogas generation is a great opportunity for energy diversification which will allow for having a sustainable and readily access to other available energy sources. The objective of this work was to undertake a conceptual engineering design for a portable biodigester by using sheep manure, whereas its performance is modeled for evaluating its descentral operation, especially when it has to handle a previously treated high dry matter substrate. Simultaneously, it has to reduce as much as possible the energy utilized for transporting the residues and the biofertilizer cake, by carefully planning the location for feedstock loading and biofertilizer unloading sites. The biodigester consists of a cylinder with an effective operating capacity of 10 m^3, where a substrate with 39% of total solids is poured, having a retention time of 30 days, and bearing in mind that it should operate within the thermophilic range which is controlled by the container thermal insulation and warm water heated by solar energy. During the simulation performance trials for the biodigester running with residues to generate biogas, the energy balance for the descentral scheme was more efficient as it got an energy saving of 50% when it was compared to a centralized functioning mode.

1. Introduction

Mexico is located between 15 and 22 degrees North latitude, covers an area of about two million sq. km. It has boundaries, with the United States of America on the North, the Gulf of Mexico on the East, the Pacific Ocean on the West, and the Republic of Guatemala on the Southeast. There is a significant geographic mismatch between water resources and population of Mexico; only 12% of the nation’s fresh water is on the central plateau where 60% of the population and 50% of the basic cropland are located.
Two thirds of the Mexican Territory is arid or semiarid region, where human activities in agriculture depends upon low, seasonal and ill-distributed rainfall, falling often in intense storms and the zones are vulnerable to droughts and other adverse climatic variations. Rössel et al. (2013) states that important strategies have to be considered in order to secure safe production of food and fibers to feed the population, moving along a constant interaction between scientific and technical progress, while energy production is in great need and any development has to take into account to highest efficiency and low production costs.
The production of energy at rural level comes from biomass, indirectly using the solar energy stored up by photosynthesis in plants. First perceived inconveniences for developing power plants small enough become big advantages in a shaped structure where energy is descentrally produced. Descentrally supply of energy means that energy is generated and consumed at the same location. This feature makes energy to be straightforwardly consumed by thirsty, marginal and disperse rural communities. Their first bioenergy feedstocks are farming residues while, forest and cellulosic biomass are feasible feedstocks to produce other biofuels which rural

Please cite this article as: Rossel-Kipping E., Ortiz-Laurel H., Gonzalez-Medina E., Amante-Orozco A., 2017, Conceptual design and functional modelling of a portable thermophillic biodigestor for a high dry matter feedstock, Chemical Engineering Transactions, 58, 463-468 DOI: 10.3303/CET1758078

population can use directly, mainly for heating and cooking. Furthermore, those readily available biofuels contribute to alleviate the energy shortage at rural level.

Descentral production of energy allows to fully satisfying energy demands for every isolated location by wisely using the available and low cost energetic resources at hand, while reducing detrimental effects on environment, besides it contributes to diminish energetic losses due to usual transmission and distribution grid processes (Gavilán, 2004). Under this scenario, utilization of biodigesters in rural areas is a strategy for descentral clean energy generation. Biogas can be locally obtained where livestock manure and other farm wastes are readily available. Equally, other renewable energies can be incorporated for aiding to this purpose on the same installation which will improve the energy balance and drastically reduce greenhouse gas emissions. This proposal is a feasible alternative instead of assisting rural population to continue utilization of wood for cooking and heating.

Thus, the objective of this work is to design a prototype biodigester for field use. The main features for such installation are: a) portability, since treatment of organic residues and biogas generation have to be descentral, b) other renewable energies can be readily incorporated up its operation and functionality in order to increase biogas production and higher methane content, c) capacity for a high load of organic matter that includes efficient use of process water. By doing that, there will be a new clean source for energy generation for Mexican highlands and at the same time hands-on a technology that allows to care for the environment.

2. Materials and Methods

This study was undertaken in the municipality of Salinas, San Luis Potosi, Mexico. Salinas is geographically located between coordinate: 23° 11' North and 22º 28’ South latitude North, and 101º 19' East and 101º 57' West longitude West, and with a height above sea level of 2099 m (INEGI, 2009).

Climate in this region is dry medium cold with summer rainfall season and winter precipitation ranking from 300 to 500 mm annual (INEGI, 2009). Farming and livestock rising take over around 23% of municipal land surface, where main crops are kidney beans, maize, onions and red hot pepper. While animal production is mainly concentrated on ovine and caprine herds and much less on bovine and porcine heads (INEGI, 2007).

2.1 Considerations for the conceptual design for the biodigester

Some aspects were crucial to define the biodigester: transport optimization and safe storage, climatic issues, general and effective dimensions of the biofermenter, procedures for functioning, biogas storage, energy potential uses and to identify its final destination.

Design of the portable biodigester should fulfill the following features:

a. Portability which will aid to transport the device from one storage site to the next. There are less costs and energy expenditure when the biodigester is moved from one site to the next, instead of transporting the organic residues close to a fixed biofermenter.
b. Energy consumption. Installation for the biodigester will accommodate other renewable energy devices for its operation and functioning (thermophillic process), which will aid to optimize energy balances and drastically reduce the greenhouse gas emissions.
c. Should operate with much less water for the process, as sheep manure has a high concentration of dry matter.

2.2 Selection of organic wastes

One condition for choosing the organic waste was high manure availability in Salinas. Therefore, by using information from SINIIGA (2015) allowed to locate communities where sheep are grow. Daily manure production in each community was calculated by estimating an average weight per animal of 30 kg, that according to Cruz (1986) each generates about 0.7 kg of manure per day.

2.3 Transport optimization and wastes storage

For optimization of manure transportation, it was utilized the method applied for a continuous model suggested by Rössel et al. (2013). This method is utilized to determine the best location for the establishment of the store (*D*) within a certain region where there are manure production places. The method finds out the best place for manure storage, a place where energy expenditure to transport manure from production sites is minimum.

The calculation requires a system of Cartesian coordinate by dividing (North to South and East to West) the entire municipality area, where the separation distance can be made at random. While, at each middle point of every chosen manure producing areas (A_i) it is attached a respective x_i and y_i coordinate. Also, it is estimated the average production of organic wastes on each producing area (a_i). The distance between the middle point of A_i and D is determined by using the Eq(1).

$$e_i = \sqrt{(x_D - x_i)^2 + (y_D - y_i)^2} \tag{1}$$

Hence, this is an iterative computation where m is the number of manure production sites included in the calculation and the selection of site *D*, is carried out under the condition that organic wastes transportation has minimum cost, which can be determined by Eq(2).

$$\sum_{i=1}^{m} a_i \cdot e_i \rightarrow \text{Minimum!} \tag{2}$$

When solving Eq(2), each calculated figure sets up an anticipated minimum, which is confirmed when coordinate for x_d and y_d that marks the site for the storage are calculated by Eqs(3) and (4) respectively.

$$x_D = \frac{\sum_i x_i \cdot a_i}{\sum_i a_i}; \tag{3}$$

$$y_D = \frac{\sum_i y_i \cdot a_i}{\sum_i a_i} \tag{4}$$

3. Results and Discussion

Using data from SINIIGA (2015) were determined sheep manure production sites in the municipality of Salinas (Figure 1). For each site it was calculated the coordinate x and y, while at the same time, was estimated its daily manure production. By utilizing those data was calculated the best location for placing the store, under the condition that energy use for manure transportation to the site was the minimum (Table 1).

Since the biodigester has to be portable by considering the handy available resources of farmers, it was defined that such device was to be transported over a trailer. This restriction jeopardizes its size and capacity for a safe movement on the rural roads. Therefore, a suitable capacity for the fermenter device was established as 10 m^3.

However, the usage of a digester of this capacity is not enough to treat around 12.5 tons of daily sheep manure produced (Table 1). This restriction can be solved by installing the adequate number of biodigesters required to treat that particular amount of manure. It was considered that retention time for the substrate inside the biofermenter to be 30 days, so 12 changes of substrate can be realized in a year. Since a 10 m^3 effective capacity biodigester can treat around 220 tons/year, assuming that maximum load of total solids inside the substrate is to be less than 50 %. Thus, the amount of manure moisture content does not affect, as one kilogram of sheep manure poured inside the digester has on average 44% of total solids, so added water for the process is much less..

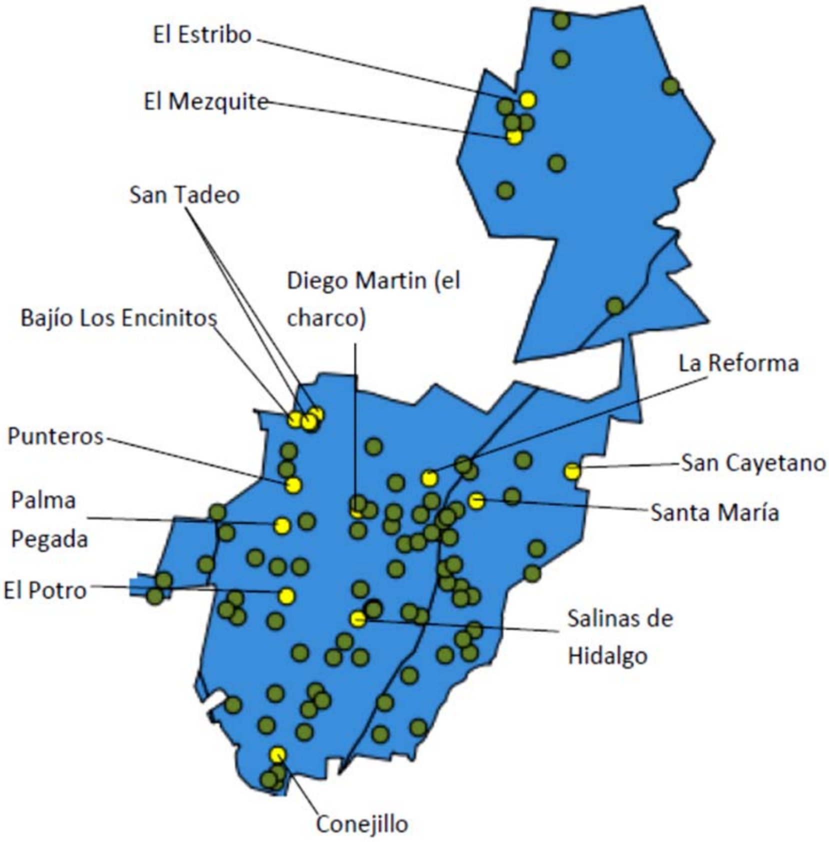

Figure 1: Communities that generate sheep manure in the municipality of Salinas, SLP (yellow color spots)

Table 1: Communities with sheep herds in the municipality of Salinas, SLP including calculations for determination of coordinate xD and yD to find out the storage location

Community A_i	**Sheep (heads)**	**Coordinate** x_i	y_i	**Daily manure production (kg)** a_i	$x_i * a_i$	$y_i * a_i$
Bajío los Encinos	35	12.7	12.8	24.5	311	314
Conejillo	2388	13.0	5.5	1671.6	21731	9194
Diego Martín	41	11.2	10.9	28.7	321	313
El Estribo	39	7.0	20.3	27.3	191	554
El Mezquite	36	7.4	19.5	25.2	186	491
Palma Pegada	4481	13.0	10.1	3136.7	40777	31681
El Potro	1192	12.8	9.1	834.4	10680	7593
Punteros	52	12.7	11.5	36.4	462	419
La Reforma	1173	9.5	11.7	821.1	7800	9607
Salinas	8112	11.0	8.5	5678.4	62462	48266
San Cayetano	138	6.2	11.9	96.6	599	1150
San Tadeo	41	12.0	13.0	28.7	344	373
Santa María	82	8.4	11.1	57.4	482	637
Total	**17810**			**12467.0**	**146349**	**110591**

Good stability for the combination of biodigester plus trailer and the motorized vehicle travelling over rural roads was a priority, therefore, it was decided to have a height/area ratio equals to 1:3. Because of the available trailer characteristics, it was accepted to have two 5 m^3 effective capacity cylindrical containers for the substrate under fermentation plus an additional one third of this volume for containing the biogas. Thus, considering that the trailer has to have an effective legal width of 2.5 m, diameter for each container was

chosen as 2.2 m, thus the effective calculated container height is 1.31 m and the free height for containing the biogas is 0.42 m. Therefore, the total cylindrical height for each fermenter reaches 1.73 m.
When organic matter has low concentration of total solids it is necessary to add a large amount of water in order to successfully fulfill an adequate fermentation process, as soon as concentration of dry matter increases, there is a reduction of quantity of added water.
According to Figure 2, for an organic waste with low dry matter content, water required for the process is high - less saving, while at high concentration of total solids the saving of water is high, i.e. less consumption of water. Mandujano and Hernandez, 2001 state that there are advantages for an anaerobic digestion process when there is high concentration of solids. Low requirements of water and a high rate of gas generation per unit of volume from the biodigester. According to Varnero-Moreno (2011) for a satisfactory operation of an anaerobic reactor, the amount of total solid content should not be more than 10%.

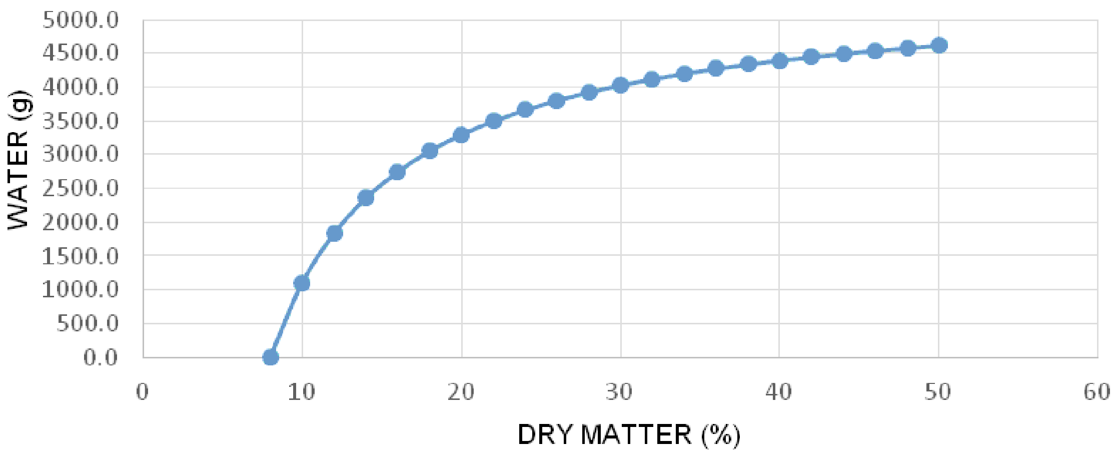

Figure 2: Calculation for conserving process water against percentage of total solids.

Although dry manure holds larger amount of water than wet manure, when fermentation process starts, additional water is sprinkled over the substrate until pore saturation, then excess water starts coming out and sent back. For a successful fermentation process for the entire mass, it is important to achieve a constant and complete mix inside the biodigester as high dry matter concentration complicates movement of substrate. Therefore, we solved this issue by modelling hot water (>70°C) spraying inside the biofermenter. This procedure creates different temperature spaces which generate a natural mass/liquid movement. In this way there is an energy saving because motors and pumps are not used for the mixing.
Authors Weiland (2001); Postel et al. (2008); Eder & Schulz (2007) state the energetic expenditure according to different devices for mixing substrates inside biodigesters. For mechanical mixing data is from 2 to 35 kW according to the type and quality of substrate. For pneumatic mixing, energy required is from 0.5 kW to any range necessary according to the arranged substrate. On the other hand, hydraulic flow for mixing ranges is from 2 to 30 m^3/min. For example, it requires 3 kW for a flow of 2 m^3/min.

4. Conclusions

By utilizing optimization methods for manure transportation and storage it is possible to precisely locate adequate capacity storage sites, which minimize energy use and transportation costs for feedstock inside a defined region. By dividing a defined waste producing area into same size smaller partial areas, where each one will hold a partial manure store will allow to treat these organic wastes inside a portable biodigester. At the end, we generate fuel biogas in a descentral way and a valuable biofertilizer as a result from the fermented waste cake.
Increasing the quantity of high dry matter feedstock contributes to save process water. Also, careful sprinkling of hot water for wetting the manure inside the biodigester aids to energy saving, as there is no device or energy supplied for the substrate mixing. Gravity helps to mix and warm water has lower viscosity so the process is more efficient.
Integration of additional renewable energy devices for the operation and safe functioning of the biodigester allows to a more efficient energy balance, saving up to 50% for the descentral scheme, compared to the central energy generation, for the whole process. There is also a reduction of the greenhouse gas emission.

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