A model of didactic guidelines to train designing and implementation of biodigesters

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Abstract. Biodigesters can be a suitable solution to exploit organic waste, fermenting it into biogas and biofertilizer. The presented type of biodigesters is easy to build, to operate, and to maintain even by nonqualified personal. In this document, guidelines for the design, as well as for the installation and for the operation of a small biodigester in rural areas is presented. The most important components and their function in the process of organic digestion are also described. The calculation is simplified to an iterative process to determine the geomembrane dimensions for a given daily organic waste production.

1. Introduction
In rural areas, waste management is not a very common task. The inadequate residues disposal can cause sanitary problems that burden the environment and people’s health [1]. Nowadays, biodigesters are gaining the attention of the research community due to their low cost and effectivity in transforming the organic residues into a valuable product. In general, a biodigester converts organic material in biogas [2], which can be used, e.g. for cooking or heating applications, and, liquid biofertilizer, which provides suitable nutrients and therefore improves plant growth. The organic material may be human or animal excretes [3], or vegetable waste. The biodigester is a closed, hermetic, and impermeable container, in which the organic material is deposited to ferment (while producing biogas) due to microorganisms [4].

Biogas is a gaseous combustible, formed mainly by methane (CH₄) and carbon dioxide (CO₂). Although, the composition mainly depends on the type of organic residue and the developed microorganisms in the digestion stage, in Table 1 the average composition in percentage by volume of biogas is presented.

| Components                | % in volume |
|---------------------------|-------------|
| Methane (CH₄)             | 55 – 65     |
| Carbon dioxide (CO₂)      | 34 – 45     |
| Nitrogen (N₂)             | 0 – 3       |
| Hydrogen (H₂)             | 0 – 1       |
| Hydrogen sulfide (S₂H)    | 0 – 1       |

A biofertilizer is a liquid material, rich in nitrogen, which contains considerable amounts of potassium, phosphorus, and other elements, essential for plant development. In addition to the low-cost, another advantage of using natural fertilizers is a better absorption of its nutrients than those of the unprocessed organic matter or even chemical fertilizers by the plants [6].
Simultaneously to the production of biogas and biofertilizer, the contaminating potential of the excrement is reduced and therefore the groundwater is protected. The whole process achieves an “upgrading” of the biological waste, while making it a product. Also, an economic impact is accomplished.

In this paper, a step by step design procedure of a biodigester is explained, to produce a meaningful learning of thermodynamic and chemical concepts for engineering students.

2. Methods
To decide which system takes the most advantage of organic residues in rural areas, first of all, the flow type of the organic material needs to be studied. Discontinuous-flow means that all the material to be processed is loaded at the beginning. Once the fermentation process has been carried out, the biofertilizer is extracted and the loading is performed again. There is no biogas production in this type.

The semi-continuous flow implies loading and unloading of the material in small lapses (usually once a day). They are the most used biodigesters in rural areas when they are destined for domestic use. The most popular designs are: Chinese type, Hindu type and Taiwan type [7].

The continuous flow biodigesters are generally implemented in industrial scale for the treatment of wastewater. They are installed with heating devices, agitation and power control, and produce large amounts of gas.

Due to the aforementioned, a semi-continuous flow biodigester is the most common installation in rural areas. Therefore, choosing between the following 3 systems is necessary:

- Chinese: fixed dome biodigester.
- Hindu: floating dome biodigester.
- Taiwan: tubular membrane horizontal biodigester.

In this paper, a Taiwan biodigester will be treated, as shown in Figure 1. The tubular membrane is made out of a completely sealed high-density plastic. The lower 75% of the biodigester volume contains the material, which is being fermented and the upper 25% contains the biogas. The microbial fermentation process is completely anaerobic (no air is included in the process after the starting mechanism).

![Figure 1. Scheme of a Taiwan biodigester [8].](image-url)

The most important factors to guarantee a good operation of the process are temperature, PH, and water content in the dilution. Temperature increase accelerates the degradation of the material and the production of biogas. Three temperature levels of anaerobic digestion occur: syphilitic, mesophilic and...
thermophilic. But even more important than the temperature level, is maintaining it constant since fluctuations negatively affect the bacterial action.

A neutral medium guarantees the survival and reproduction of methanogenic bacteria. Experience shows that the pH must be maintained between 6 and 8.3 during the entire biogas production process.

Lastly, the dilution percentage of the organic material is an important factor, since bacteria and other microorganisms are unable to function effectively for low water content in the mix. Due to the high-water content of excrements, a proportion between the mixture and water of 1:1 is selected. The dilution of the mix can be adjusted depending on the necessity of establishing a flow to the biodigester.

3. Results (guidelines)
A guideline with the most important steps to follow for realizing a biodigester system will be presented.

3.1. Collection of information
The biodigester is basically formed by a tubular flexible geomembrane, an excavated ditch for geomembrane position, and a safety valve to limit system pressure.

Inside the flexible geomembrane, a displacement of the mixture from the inlet to outlet occurs, while its transformation into fertilizer and biogas take place. Each new part of the diluted mix, that is added to the biodigester, pushes the next part and so on, displacing the mass towards the other end until the completely processed material reaches the biodigester outlet. The remaining volume within the geomembrane will be reserved for storing the produced biogas (see Figure 2). The whole dimension of the process depends on the quality of available organic material, not on the necessity of biogas nor fertilizer. To dimension the system some data is required: the amount of daily excrement, type of excrement, and the average temperature of the location. In Table 2 the percentage of produced biogas depending on material type and days of fermentation is shown.

3.2. Design of the biodigester
With the provided information, the values of volumetric fluid, retention time, and required liquid volume are calculated [7]. The volumetric flow per day $\dot{V}$ is determined by Equation (1), where $Q_{\text{excre}}$ is the flow rate of organic material in a day, obtained from collected information in the location, and $Q_{\text{water}}$ the flow rate of the amount of water (proportion about 1:1 is recommended).

$$\dot{V} = Q_{\text{excre}} + Q_{\text{water}}$$ (1)

The retention time ($t_r$) is the required time to degrade the organic material and it is directly related to the ambient temperature and the type of used material. A retention time range of a few to 40 days is recommended. Under optimal conditions, around 30°C, retention time should be about 20 days but due to varying temperatures, i.e. decreasing values with respect to the optimal, retention time will increase in a range between 30 to 45 days or longer. Therefore, when a more retention time is assumed means a

| Table 2. Days of fermentation and percentage of produced biogas depending on material at 30°C [10]. |
|---------------------------------------------------------|---------------------------------|-------------------------------------------------|-------------------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Days of fermentation | 10  | 20  | 30  | 40  | 50  | 60  | 70  | 80  | 90  | 100 |
| Material desperate of | | | | | | | | | | |
| Human excrements | 40.7 | 81.5 | 94.1 | 98.2 | 98.7 | 100 | 0.478 | | | |
| Pig excrements | 46 | 78.1 | 93.9 | 97.5 | 99.1 | 100 | 0.405 | | | |
| Cow excrements | 34.4 | 74.6 | 86.2 | 92.7 | 97.3 | 100 | 0.3 | | | |
| Green grass | | | | | | | | | 98.2 | 100 | 0.41 |
| Wheat straws | 8.8 | 30.8 | 53.7 | 78.3 | 88.7 | 93.2 | 96.7 | 98.7 | 100 | 0.435 |
more conservative design, i.e. a more possibility to complete processing of the waste. The required liquid volume \( V_{\text{req}} \) results in Equation (2).

\[
V_{\text{req}} = \dot{V} \ast t_r \tag{2}
\]

Figure 2(b) shows the recommended shape of the perimeter of trench and geomembrane. The transversal perimeter is given by Equation (3). Out of stability matters, the relation of \( \frac{x}{h} = 0.3 \). \( a \) is the distance between the walls of the biodigester and is defined in Equation (4), in the same way another geometric variables are shown in Equations (5) and (6).

\[
2\pi r = b + 2\sqrt{h^2 + x^2 + \theta r} \tag{3}
\]

\[
a = rv\sqrt{2 - 2\cos\theta} \tag{4}
\]

\[
A_{\text{liq}} = \frac{b+a}{2} h \tag{5}
\]

\[
A_{\text{gas}} = \frac{r^2}{2} (\theta - \sin\theta) \tag{6}
\]

Where \( A_{\text{gas}} \) is the gas-filled area and \( A_{\text{liq}} \) the mix-filled area. The relation of \( A_{\text{liq}}/A_{\text{gas}} = 3 \) is applied, as earlier mentioned. The length of the geomembrane is calculated by Equation (8). In order to simplify the calculation at the design stage, distance \( x \) is assumed as zero and using the relation in areas between \( A_{\text{gas}} \) and \( A_{\text{total}} \) which is being written as

\[
\frac{A_{\text{gas}}}{A_{\text{total}}} = 0.25 = \frac{1}{2\pi} (\theta - \sin\theta) \tag{7}
\]

With \( \theta \) as a unique variable. Now, an iterative process is accomplished in Equation (7) to determine \( \theta \) which is approximately 132.45°. Thus, replacing \( \theta \) in Equations (4) and (6) to obtain \( c \) and \( A_{\text{gas}} \), expressed as a function of \( r \) and given by \( a \approx 1.83r \) and \( A_{\text{gas}} \approx 0.78r^2 \). Then, knowing that \( A_{\text{liq}} \approx A_{\text{total}} - A_{\text{gas}} \approx 2.35r^2 \), where \( A_{\text{liq}} \) is assumed occupying a rectangular space with \( c \) and \( h \) as width and height respectively, it is also possible to express \( h \) in function of \( r \) as \( h \approx 1.28r = A_{\text{liq}}/c \). The estimated biodigester length is calculated by the total volume relationship given as.

\[
V_{\text{total}} = \frac{V_{\text{liq}}}{0.75} = \left(A_{\text{liq}} + A_{\text{gas}}\right)L_{\text{geo}} \tag{8}
\]

Recalling that \( V_{\text{liq}} = V_{\text{req}} \) and replacing the total area in Equation (8), \( L_{\text{geo}} \) can be written as the Equation (9).

\[
L_{\text{geo}} = \frac{V_{\text{req}}}{0.75(\pi r^2)} \tag{9}
\]

In the calculation process, \( r \) is assumed to estimate \( L_{\text{geo}} \), which is validated using the Equation (10).

\[
10 > L_{\text{geo}}/2r > 5 \tag{10}
\]
Equation (10) is recommended by economic consideration (the smaller the superficial area of the geomembrane, the lower the cost) and operational aspects [7]. In summary, all the information given, is used initially to estimate the unknowns \((r, L_{geo})\). Next, the dimensioning process of the trench \((a,b,x,h)\) is completed.

![Figure 2. Transversal profile of the geomembrane, (a) tubular flexible membrane, (b) trench mounted flexible membrane, (c) distribution of areas.](image)

As a calculation example: biodigester load \(V_{req} = 60 l\), (mixture of organic material and water), assuming a retention time of 50 days and a radius of 0.45m, produce a \(L_{geo}\) of 5.09m, Equation (9), which satisfied the Equation (11). Thus, the data for implementation is shown in Table 3:

| Variable | Expression | Value [m] |
|----------|------------|-----------|
| \(L_{geo}\) | Eqs (9-10) | 5.09 |
| \(r\) | Assumed | 0.45 |
| \(h\) | 1.28 \(r\) | 0.652 |
| \(a\) | 1.83 \(r\) | 0.822 |
| \(x\) | 0.3 \(h\) | 0.196 |
| \(b\) | \(a - 2x\) | 0.431 |

### 3.3. Implementation and installation
The system needs two tanks: the first is utilized to mix the organic material with the appropriate amount of water, this tank will be connected by PVC tubes to the loading port flange of the geomembrane; the second tank is used to collect the produced liquid biofertilizer in the geomembrane outlet port. The tank size needs to be at least of the size of the biofertilizer production of one day. The loading tank needs a wire netting to impede blockades. In the following, the security devices, which should be included in an installation, are shown:

#### 3.3.1. Relief valve.
this device relieves biogas to the surroundings if the biodigester internal pressure is above of a determined pressure. A low-cost relief valve is proposed based on a plastic T-piece and a pet bottle (0.5 l). The biodigester internal pressure is adjusted by the water column in the bottle, a 0.15 m of water column can be enough to control the internal pressure in the system.

#### 3.3.2. Hydrogen sulphide filter.
Hydrogen sulphide is a highly corrosive compound present in the biogas. Therefore, it needs to be withdrawn by a filter installed in the transport line of biogas. For a home-size system, a filter is implemented using a pipe portion of a diameter at least one inches bigger than the size of the transportation line and filling this tube with steel wool. A 0.1 m of length pipe is in most of the cases adequate to remove of the stream this compound.
3.3.3. *Carbon dioxide filter*. The elimination of carbon dioxide improves biogas quality. For this type of biodigesters, which are operating at very low pressures, filters of receptacles, plastic or glass bottles are recommended. It is filled with an alkaline solution (water + calcium hydroxide): 2g of calcium hydroxide per 1l of water. The filter is normally installed between the biodigester and the hydrogen sulphide filter in a fixed place, hermetically sealed (see Figure 3).

![Figure 3. Carbon dioxide filter.](image)

3.3.4. *Water trap*. Normally, the biogas is a wet gas with a very low vapor pressure, thus at room temperatures, the condensation can be produced. In order to avoid blockages due to condensation, a water trap is required to be installed at the lowest point of the pipeline. The water trap is a water-filled tube, to avoid escape of biogas, as shown in Figure 4.

![Figure 4. Installation of water trap[13].](image)

3.4. *Biodigester start-up*

Before the biodigester reaches the steady-state operation, some steps have to be performed. First, the geomembrane needs to get inflated, next the geomembranes feeding, and outlet flanges need to be locked. Later, it will get filled with water, allowing the escape of air through the safety valve, until reaching the hydraulic seal [14]. (Add: From this phase, biogas and biofertilizer can be taken and brought to a laboratory. Inhibitors as shown in ¡Error! No se encuentra el origen de la referencia. need to be avoided).

3.5. *Operation*
Finally, to combust the biogas an adjusting process in the burner is required. Thus, the nozzle diameter of the injection valve in the stove is increased step by step until the flame presents similar characteristics to the obtained by LPG or NG by a trial and error process.

4. Conclusions
A biodigester exploits organic waste and produces biogas and biofertilizer while reducing the possible contamination of groundwater due to excrements filtration. In this document, basic equations and general information is provided, thus a functional biodigester can be designed, installed, tested and put in operation by nonqualified personal.

References
[1] Hernández Embate A J. 2013 El potencial de los biodigestores como técnica sostenible para la producción de biogás en la comunidad indígena Nuevo San Juan Parangaricutiro, Michoacán (Michoacan: Universidad Autonoma del Estado de México)
[2] Severiche C A, Acevedo R L2013 Biogás a partir de residuos orgánicos y su apuesta como combustibles de segunda generación Ingenium - Revista de la Facultad Ingeniería 28 6–15
[3] Reuss N, Busso M 2000 Diseño de un biodigestor para obtener metano utilizando excremento de vacas y cerdos en una escuela agrotécnica de la UNNE Consulted on: http://exa.unne.edu.ar/investigacion/energia_solar/PUBLICACIONES/Biogas.pdf
[4] Filippin C Follari J and Vigil J 1979 Diseño de un biodigestor para obtener gas metano y fertilizantes a partir de la fermentación de excrementos de vacas lecheras en la facultad de agronomía de la Universidad Nacional de la Pampa Consulted on: http://www.produccion-animal.com.ar/Biodigestores/02-Biodigestor.pdf
[5] Stamatelatou K, Antonopoulou G, lyberatos G 2010 12. Production of biogas via anaerobic digestion EDS. Luque R, Camelo J and Clark J Handbook of Biofuels Production (Sawston: Woodhead Publishing)
[6] Canepa J R L, Olivier J A S, Moguel K C C, Snachez L J and Olivares J F 2011 Diseño, construcción y operación de un biodigestor anaerobio tipo cúpula a escala real para la obtención de biogás Hacia la sustentabilidad: Los residuos sólidos como fuente energía y materia prima. 2(21) 612–616
[7] Walsh J, Ross C, Smith M, Harper S, Wilkins A 1988 Handbook on biogas utilization (Georgia: Georgia Tech Research Institute)
[8] Guardado C 2007 Diseño y construcción de plantas de biogás sencillas (La habana: Cubasolar)
[9] Botero R, Preston T R 1978 Biodigestor de bajo costo para la producción de combustible y fertilizante a partir de excretas (Cali: Centro Internacional de Agricultura Tropical)
[10] Guevara Vera A 1996 Fundamentos básicos para el diseño de biodigestores anaeróbicos rurales. Produccion de gas y saneamiento de efluentes (Lima: CEPIS)