Design of a Lab-scale Anaerobic Biodigester for Renewable Energy from Municipal Solid Waste

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Abstract

The energy sector is in constant search of new clean sources of energy, both to supplement its production, as well as to reduce dependence on fossil fuels and its gradual replacement based on sustainable development methods. In this context, municipal waste is considered as a renewable energy source, since they have a high biomass content (paper, cardboard, food waste, wood, straw, leaves). A renewable source alternative with great prospects for the future is the use and energetic valuation of municipal solid waste. This research aims at the design of a lab-scale biodigester for the energetic industrialization of municipal solid waste, serving as a basis for the construction of a prototype on a pilot scale or a plant for the anaerobic treatment of these generated wastes. In this way, it will be possible to recover the energy contained in them, in order to reduce the flow of the waste destined to the landfills and to provide a production rate for the obtaining of biogas, taking as fundamental basis for the calculations of design and the improvement of laboratory-level production, through co-digestion with other types of organic waste and use of alkaline inoculating substances and determination of the most appropriate anaerobic digestion technology for waste treatment municipal solids.

Keywords
Anaerobic digestion, Biodigester, Biogas, Design, Municipal Solid Waste

1. Introduction
Today, the demand for energy has produced an environmental imbalance, considering that natural resources are only potentially renewable, because of human intervention and population growth, which causes that these resources lose their potential renovation for the growing and unmeasured demand for fossil fuels. From the use of these, air pollution, water and soil pollution, and the phenomenon of global warming are derived. Given that fossil fuel reserves are limited and in the short to medium term, alternative fuel sources are needed, including biologically produced or biofuels. Considering the benefit that can be obtained from the production of energy by means of biodigesters, it is important to learn the design, even more when the raw material is available for its operation. (Balasubramanya, 1988; Chanakya et al., 2012; Le Thi, K. O. et al., 2013).

The development of this research has been oriented towards the use of solid organic waste from fruit, vegetable and food waste, and in this way, the project will be able to serve as a guide for the design of similar biodigesters, posterior uses and applications, with recommendations and practical advice.

Applying this type of technology would represent a radical change to the environment, because with only one family the impact can be considerable if analyzed annually. There are some countries that want to opt for this energy option and there are many companies that have opted for such a big change. In Ecuador there are innumerable implementations of these biodigesters in different provinces such as: Cotopaxi, Tunguragua, Carchi, and more

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specifically Imbabura. Currently anaerobic biodigesters are used at pilot scale, these are in Intag and has had great results.

From the bibliographic analysis carried out, we have concluded the existence of several projects for the generation of biogas from sugarcane and rice husk, among others, which have already demonstrated the viability of the development of this work (Elías et al., 2012; Fernández et al., 2008; Fernandez, 2010; Hansen et al., 2004; Machado et al., 2012). The need to design this prototype was created with the aim of collaborating with the reduction of pollution and taking advantage of the resources generated from the biodegradation process obtained from biogas and biol or biocarbon. The application of biodegradable systems and uses of renewable alternative energies contributes to the conservation of the environment as well; the perspective presented by the research of the biodigester system is to contribute to a technical development for the benefit of society and to promote the industrial sector. The benefits that are obtained with the biogas are presented in the same conditions as the LPG, being able in future to replace it with this cleaner and economical technology (Bolzonella, 2006; Nayono, 2009).

Biogas can be economically manufactured at both small and large scales therefore can be tailored to supply rural and urban gas needs as well as meet regional and nationwide energy demands. It has been used as an alternative and renewable source of energy for wide spread range of applications including among others cooking, lighting, heating in households and most recently in the developed world, biogas technology is in advanced stages and being used as a vehicular fuel and to produce clean electricity (Kigozi et al., 2014). Biogas lies especially in two fundamental aspects: the easy obtaining of the raw material (waste generated from paper, cardboard, food waste, among others) and the low cost of the biodigester, even many of the biodigesters are composed of materials Recycled, especially those that are used for minor purposes like experiments in families or farms, already for those industrial biodigesters the materials can change but it does not become something extremely expensive (Bolzonella, 2006).

2. Materials and methods

Anaerobic digestion, also known as biomethanisation, is a natural process that happens in conditions of absence of oxygen. In this microbiological process the organic matter is fermented transforming by the bacterial action in biogas (composed of CH_4 and CO_2 mainly) and producing a fertilizer rich in mineralized nutrients and therefore in immediate disposition for the plants. Digesters, also known as biodigesters, are closed reactors that facilitate anaerobic digestion by providing an anaerobic atmosphere for the organisms responsible for this process (Balasubramanya, 1988; Chanakya 2009).

Anaerobic fermentation is a biological process in which organic matter is degraded without the presence of atmospheric oxygen to produce water, carbon dioxide and methane. There are specific conditions that are provided to allow the growth of anaerobic bacteria (Melosi, 2008). These conditions can occur in natural environments such as in lakes sediments and in gastrointestinal tracts of animals or can be created in industrial, semi-industrial and rural processes (Khalid et al., 2011).

Biological process

Anaerobic digestion is a multi-stage process and parallel reactions where different types of bacteria degrade organic matter successively. Large bacterial populations are identified, which are developed catalyzing three consecutive processes: hydrolysis, acidogénesis (formation of acids) and methanogenesis (formation of methane) (Bouallagui, 2005; Elías et al., 2012; Yaw et al., 2016).

2.1 Environmental and Control parameters

There are several factors that can affect, improve or inhibit the functioning of the anaerobic digestion process. These factors, described below, are pH, temperature, nutrients, organic load, concentration of solids in the tributary, available nutrients, retention time and organic loading speed, agitation and inhibitory substances (Khalid et al., 2011).

pH

The pH value is an important indicator of the operation of the process within the biodigestor. According to Elías et al. (2012), in each phase, microorganisms show maximum activity in a differentiated pH range (Table 1). The biggest problem is generally to maintain the ph above 6.6, since the organic acids produced as intermediates in the early stages due to an overload or any other imbalance can cause a rapid decrease of the pH and the consequent cessation of methane production. Alkalinity and pH in anaerobic digestion can be adjusted by adding different chemicals to the mixture (sodium and potassium bicarbonate, calcium carbonate, etc.) and also by mixing different residues to be treated in the reactor (codigestion). (Diaz de Basurto, 2013)

Table 1. Optimum ph ranges for different micoorganisms (Elías et al., 2012)

Stage	Type of bacteria	Optimum pH Range
Hydrolysis and Acidogenesis	Hydrolytic acidogenic	7.2 – 7.4
Acetogenesis	Acetogenic and homoacetogenic	7.0 – 7.2
Methanogenesis	Methanogenesis and acetogenesis	6.5 – 7.5

Temperature

Temperature is one of the most important parameters in anaerobic digestion, since it determines the degradation rate of the anaerobic process, mainly those of the hydrolysis and methanogenesis stages. There are three temperature ranges in which anaerobic digestion can be carried out:
Psychrophilic: Below 25 º C
Mesophyll: between 30 and 40 º C
Thermophilic: between 50 and 60 º C

With the increase in the temperature range increases the hydrolysis rate, the speed of growth and thus the speed in the production of biogas. (Elías et al., 2012; Fernández et al., 2008)

Hydraulic retention time and organic load speed

The hydraulic retention time is the measure that describes the average time a substance resides in the reactor. By increasing this time, it increases the degree of degraded organic matter, as well as the production of methane. The organic loading speed is defined as the amount of organic matter fed by volume of biodigestor over a certain period of time. In the absence of inhibitors, high organic loads provide high methane production, but also increases the risk of point overloads that lead to acidification of the reactor causing a decrease in pH and possible failure of the system.

2.2 Type of Biodigesters

Family-scale biodigestion has been widely disseminated in countries like China or India since the last quarter of the last century and more recently in Nepal (Biogas Support programme), typically in fixed-dome (Chinese type) or floating-dome digesters (type Indian). However, the complexity of its construction and a relatively high cost may be limiting to its implementation. The plastic tubular biodigesters, of simple and economical construction, allow for a greater expansion of this technology (Preston, 2002). Possible materials for its construction are polyethylene and PVC (Geomembrane), being the last more resistant but also more expensive (Pedraza et al., 2002).

Continuous Flow Biodigesters

A continuous-flow reactor is one that has a continuous tributary and effluent. In the continuous-flow reactor there is a mass exchange throughout the operating time. Where it is sought to reach the stationary state by controlling the operating conditions that are the concentration of substrate, pH and temperature.

Discontinuous Flow Biodigesters

The load of all the material to be fermented is done at the beginning of the process and the discharge of the effluent is done at the end of the process; usually they require more labor and a space to store the raw material if it is produced continuously and a gas tank (due to the large variation in the amount of gas produced during the process, having its peak in the middle phase of this) or was sources alternatives to supply it.

Semi-continuous flow biodigesters

The load of the material to be fermented and the discharge of the effluent is carried out in a continuous way or by small potholes (eg once a day, every 12 hours) during the process, which extends indefinitely over time; they usually require less labor, but a more fluid or mechanically mobilized mixture and a gas tank (if this is not fully used continuously). The continuous biodigesters are used to purify water contaminated by different pits.

2.3 Lab-scale biodigester

According to Kim Oanh et al. (2013) in the laboratory-scale study, they used 45-litre cylindrical reactors located inside. These were insulated with polyurethane foam to minimize reactor temperature variations that could affect the anaerobic digestion process. Each reactor was hermetically sealed with rubber tape and a screw cap to ensure anaerobic conditions. The recycled liquid was obtained by filtering the effluent from the digester through a screen to prevent clogging of the pipes and then distributed over the top of the solid waste in the reactor by means of a pump and a sprinkling system of taps. The detailed design of the laboratory-scale biodigestor is shown in Figure 1. This was loaded a mixture of various types of solid organic waste.

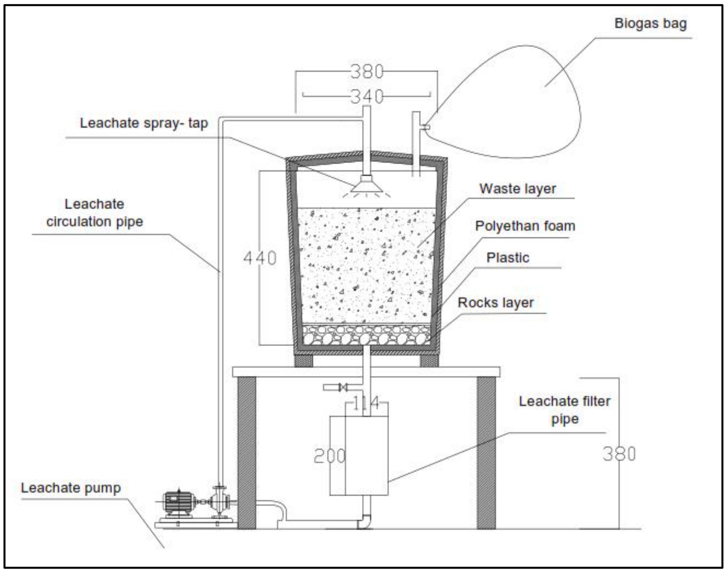

Figure 1. Laboratory-scale anaerobic digestion biodigester (Le Thi, Ko et al., 2013)

The mixture of the best results with respect to the production of biogas and the methane content in the laboratory-scale test was selected for experiments with pilot-scale reactors (Le Thi, K. O. et al., 2013).

As a basis of our prototype conceptualization, the design and scaling from the laboratory type will be carried out, as a departure for the pilot scale design. This will be carried out according to estimations of residues quantification and previous characterization studies in the area, for the conceptualization and development of the biodigestor. In contrast to the design proposed by Le Thi, K. O. et al. (2013) calculations will be made for sizing, considering the quantity of waste generated and the energy potential to produce biogas to be obtained. Having an accuracy of the laboratory-scale generation, so there will be a period of settlement of waste to determine the methane production potential to be generated, as well as the dimensions of each part and component of the prototype to design.

2.4 Methane Production Potential of Organic Solid Waste

Fruit and vegetable residues present an energetic potential if they become biologically converted into methane (Gunaseelan, 2004). These residues, and in general all organic, can be characterized by their potential biochemical methane (PBM). The PBM test provides a measure of anaerobic degradability of a given residue, in addition, it is a fast and economical method.

Due to the worldwide increase in the application of anaerobic digestion technology, a large number of studies and research has been carried out in recent years to determine the potential for the production of methane from organic solid waste. The different protocols raised differ according to the purpose of the measurement, the type of samples, the complexity of the equipment proposed in each work and even the units of the variables presented, making the comparison of the data of biodegradability in literature is very difficult (Angelidaki et al., 2009).

Hansen et al. (2004) propose a more comprehensive and easy-to-operate protocol for the determination of the methane production potential of organic solid waste and is expressed in terms of volume of methane (mL) under standard conditions of pressure and temperature per gram of organic residue. Biomass has to be a waste to take into account in anaerobic digestion technology, since the potential of methane production of this, is at least, double than animal excrement, or plants (Jagadish et al., 2008). Qiao et al. (2011) evaluate, in their study, the potential for methane production of cow and pork excrement, mud and remnants of fruit, vegetables and food.

3. Results

There are different types of digesters in the industry and rural areas. The design of the digester depends on the operating conditions, the type of raw material, the cost of operation, among others.

Anaerobic digesters can be classified according to the frequency of feed, temperature, degree of mixing, configuration and construction materials. The simplest digester is the batch digester, more complex reactors are the anaerobic contact reactor, multi-stage digester, anaerobic digester of ascending mud mantle and continuous expansion digester, among the most important.

Structure of the Biodigester

There are many variations in the design of the biodigestor. Some elements that are commonly incorporated are:

- *Fermentation chamber:* The space where biomass is stored during the decomposition process.
- *Gas storage chamber:* The space where the biogas accumulates before being extracted.
- *Load stack:* The input where the biomass is placed.
- *Discharge Battery:* The output, is used to remove waste that is spent, and it is no longer useful for biogas, but can be used as a fertilizer (biofertilizer).
- *Agitator:* Displaces the wastes that are in the bottom upwards of the biodigestor to take advantage of all biomass.
- *Gas pipeline:* The biogas output. It can be connected directly to a stove or it can be transported by means of the same pipe to its place of use.

Construction Aspects

The digester can be made with different construction materials, and it can be buried or above ground level, it can be vertical or horizontal. The gas storage bell, called gasometer, which can be mobile and floating, cover the digester and can be constructed of metal, plastics, ferrocement or fixed of masonry, in other cases this moving bell can be separated from the digester, the function of this bell is to store the gas that is produced in the digester, also puts pressure on the gas for consummetion. It has a loading tank where the mixture of the raw material is prepared, with water and through a duct is deposited at the bottom of the digester. The capacity of this must be equal to the volume of the material to digest, which requires the digester daily; in addition, it is possible to place a storage tank of the residue (manure) that leaves the digester and must be placed at 180 degrees of the loading tank, minimum 90 degrees, to complement a biogas project.

Dimensioning

Retention time is a parameter that is only exact in batch-type reactors. For continuous-operating plants, an approximate value will be the one obtained from dividing the reactor volume by the daily feed volume of substrate. The design factors, the geometry of the digester, the mixing etc. can vary this parameter in a notable way for some specific contents of the substrate. Thus, the minimum retention time to be applied will depend on the working temperature and the nature of the substrate.

The size of the digester depends on the quantity, quality and type of biomass available, as well as the working temperature. For the calculation of biogas plants can be from two different analyses:

1. That they know the exact quantities of the organic materials that we want to process and from these calculate all the biogas and fertilizer, as well as the appropriate size of the digester for the treatment of the desired material.
2. They know the amount of biogas energy and fertilizer that is required to supply and from these values, calculate the required organic matter and its corresponding digester.

Volume of the Biodigester

The volume of the digester (Vd) is determined from the hydraulic retention time (TR) and the amount of daily substrate introduced (Vcd) as well:

$$\mathrm{Vd}\ (\mathrm{m}^3) = \mathrm{TR}\ (\mathrm{days}) * \mathrm{Vcd}\ \left(\frac{\mathrm{m}^3}{\mathrm{day}}\right) \quad (1)$$

For a simple plant, the minimum retention time will be in about 30 days. Still, experience has shown that plants with TR of 60-80 days, and up to 100 days work, and with a longer retention time is achieved a higher production of gas, reaching productions of up to 40% more. (Appels, 2008; Ramirez and Yaguana, 2015)

The volume of the substrate introduced depends on the amount of water that is added to reach the adequate solid proportion of 4-8%.

Biodigester volume calculation

TR = 30 days   Retention Time

$Vdv = \frac{Vd}{1000}$ Cylinder volume in m^3 (2)

$0{,}045\ m^3 = \frac{Vd}{1000}$

Vd = 45 L   Litres of Compost   (3)

$Vdv = Vcd * TR$

$45\ L = Vcd * 30$

Vcd = 1,5 kg   Mix per day   (4)

Vcd = 3 Ecd

Ecd = 0,5 kg   Amount of Compost per day   (5)

Calculation of biogas production per day

Production 0.125 L per kg of compost to day = 0.000125 m^3

$SD = Ecd * 0{,}000125\ m^3$

$SD = 0{,}00000625\ m^3$ Biogas production per day   (6)

Safety Factor: 10%

$SDt = SD + SD * 0{,}1\ m^3$

$SDt = 0{,}00006875\ m^3$ Biogas per day   (7)

Biogas storage capacity in the bell

$V_{bell} = \frac{SDt}{2}$ (8)

$V_{bell} = 0{,}0000347\ m^3$

Bell Height

$h_1 = Vbell * 4$ (9)

$h_1 = 0{,}000314\ m$

These parameters are shown below in the representation of Figure 2.

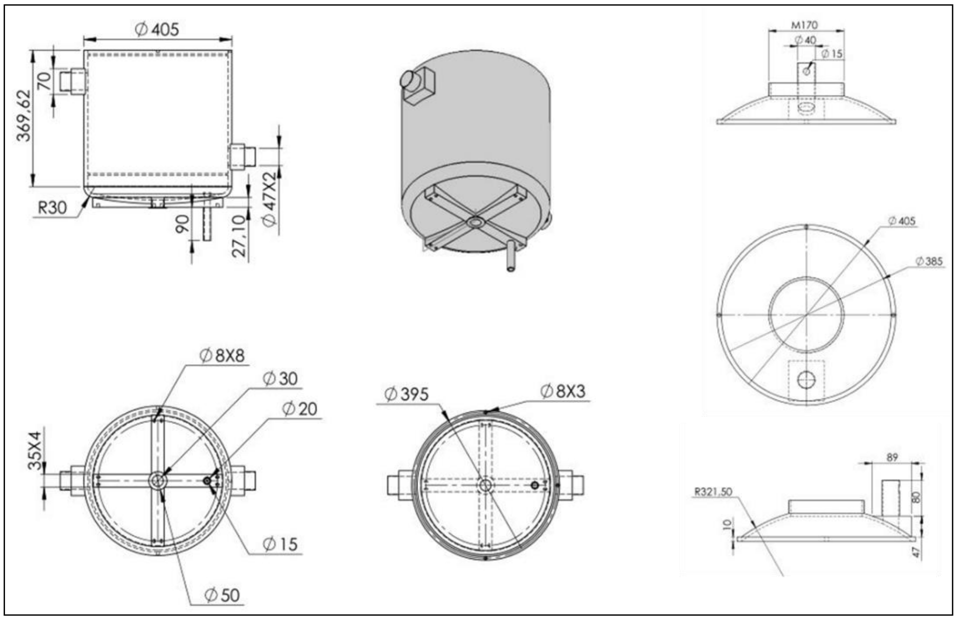

Figure 2. Biodigester Dimensioning

Biodigester Design

Based on the volume of the digester calculated above, we must know the rest of dimensions, for which we consider the following methodology: Generally, the digestors are cylindrical, because this geometric form is very consistent, requires less amount of construction materials, and remove edges or corners of walls that can allow gas leakage. Knowing the volume, we calculate the depth (vertical type) considering that it is a vertical cylindrical biodigestor of diameter (d) equal to the depth (h). See Table 2 and Figure 3.

Biodigester Volume

$d = h$
$V = 0{,}045\ m^3$

Biodigester Inside diameter

$$V = \frac{\pi d^2}{4} * h \quad (10)$$

$$d = \sqrt[3]{\frac{V*4}{\pi}}$$

$d = 0{,}386$ m

Height of the Biodigester

$h = d = 0{,}386$ m

Table 2. Biodigester dimensions

Vd (m^3)	d (m)	H (m)	V_{bell} (m^3)	h_1 (m)
0.045	0.386	0.386	0.0000347	0.000314

With the development of this anaerobic biodigestor at laboratory-scale, it will be possible to carry out research and at the time, to quantify the energetic potential of the municipal solid waste generated in the study area and the most suitable form for its exploitation and use. As well as laying the foundation for the start-up of a laboratory-scale biodigestor and a plant, to recover the energy contained in these wastes and use it as a renewal of electric energy, LPG, and gradually avoid the contamination it generates the environment.

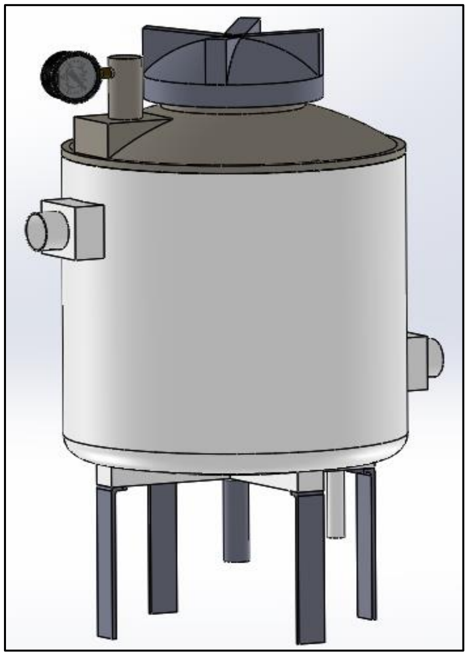

Figure 3. Biodigester

4. Conclusions

With the use of the laboratory-scale digester, the energy contained in municipal solid wastes can be recovered to reduce the flow to landfills and to provide a production rate for obtaining biogas. The digester was designed and scaled based on reliable estimates of waste quantification and characterisation studies conducted at the study area. Obtaining the production of biogas, from the waste generated and as a result, it is deduced that it is possible to reduce dependence on fossil fuels, achieving their gradual replacement with the use of sustainable development methods. The laboratory-scale biodigestor design for the energetic industrialization of municipal solid waste is the basis for the conceptualization, design and construction of a pilot-scale prototype or a plant for the anaerobic treatment of these wastes.

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