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GREEN EMPOWERMENT

TUBULAR BIOGAS DIGESTER MANUAL

This document aims to present a simple method to design a low-cost domestic scale biodigester. It is designed to teach implementers who want to understand the design and implementation of tubular biodigesters. The design guide initially presents concepts that should be taken into account when designing a tubular biogas digester, then goes into design parameters, materials needed for construction, systematic installation and finally design examples.

Various documents have been consulted to make this manual, including:

- Family Biodigesters: Design Guide and Installation Manual Version 1 by Jaime Martí Herrero (Biodigestores Familiares: Guía de Diseño y Manual de Instalación Versión 1 de Jaime Martí Herrero)
- Family Biodigesters: Design Guide and Installation Manual Version 2 by Jaime Martí Herrero (Biodigestores Familiares: Guía de Diseño y Manual de Instalación Versión 2 de Jaime Martí)
- Production of Biogas and its Practical Use-Practical Course of Household Biogas by CIBOGAS (Producción de Biogás y su Aprovechamiento-Curso Práctico de Biodigestores a Escala Doméstica de CIBIOGAS)

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Green Empowerment partners with rural communities and NGOs in developing countries to improve access to affordable and renewable energy, safe drinking water, sanitation systems, and fuel-efficient cookstoves.

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1. Appropriate Biodigester Technology

A biodigester is a natural system that uses the anaerobic digestion (in the absence of oxygen) via naturally occurring bacteria to transform organic waste, typically animal manure, into biogas and fertilizer. Biogas can be used as fuel in kitchens, heating or lighting, and in large installations can be used to power an engine that generates electricity. The fertilizer slurry produced, called biol, has initially been considered a secondary byproduct, but is currently being valued with the same or greater importance than biogas, since it provides families with a natural fertilizer that strongly improves the yield of the crops.

Biodigesters can be installed on the industrial and the domestic level. This manual focuses on low-cost, domestic biodigesters. These digesters are ideal for families that engage in agriculture as they tend to own small amounts of livestock (for example two or three cows) and can therefore use manure to produce their own fuel and improved natural fertilizer. It should be considered that the manure accumulated near the houses can be a cause of contamination, odors and flies will disappear when the manure is being utilized by the biodigester on a daily basis. It is also important to remember the amount of respiratory diseases that families, mainly women, suffer from when inhaling smoke while cooking in closed spaces with firewood or dry dung. The combustion of biogas does not produce visible fumes and its production of ash is infinitely less than the smoke coming from burning wood. Additionally, the biol can be used to improve crop production.

When installing biodigesters on the domestic level, they are typically low cost and designed to meet the needs of the family. There are two types of low-cost, domestic biodigesters: fixed dome biodigesters and tubular biodigesters.

1.1 Fixed Dome Biodigesters

Fixed dome biodigesters are built with cement and brick and have a life of up to 20 years. A skilled mason is needed to construct them and the materials (sand, cement, bricks, etc.) are a large investment. The fixed dome biodigester is usually made with two tanks: one main tank with a completely buried vault and a second, half-buried tank.


Figure 1: Fixed dome biodigester

The first tank is where anaerobic digestion occurs and where the biogas is produced and captured. When buried, the temperature at which anaerobic digestion occurs is similar to the temperature of the soil. The second tank is open and serves as a compensation tank for the biogas. As shown in Figure 2, as the biogas accumulates in the first tank, the pressure of the biogas increases pushing the manure and water mixture into the second tank. When the biogas is consumed, the pressure in the first tank decreases, and the manure and water mixture moves back to the first tank. This movement agitates the mixture and keeps a crust from forming.

These fixed dome biodigesters work very well in tropical and warm climates, but they are limited in cold climates since the soil temperature drops too low and the anaerobic digestion slows down significantly. Two advantages of fixed dome biodigesters are that the biogas pressure can reach one meter of water column (0.7psi) and less water is needed because the organic matter load (normally pig or cow dung) only dilutes 1: 1 with water.

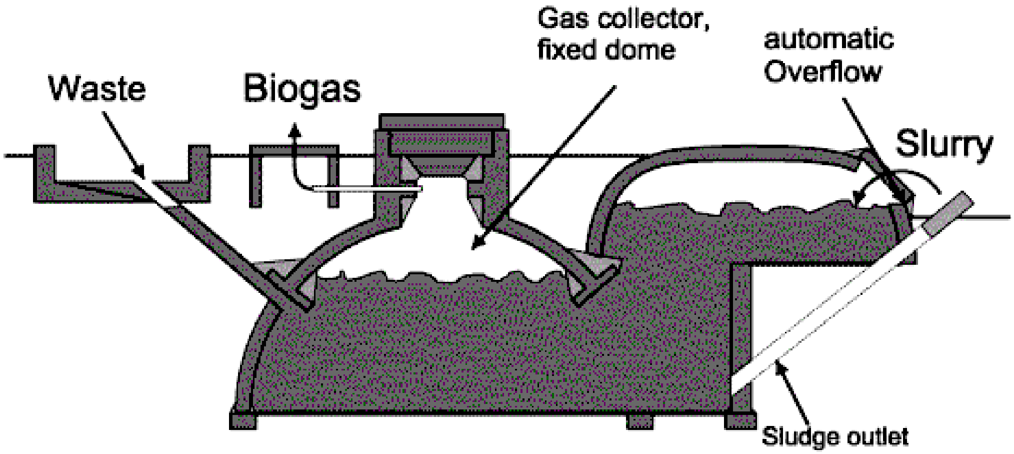


Figure 2: Basic parts of a hard dome biogas digester

1.2 Tubular Biodigesters

The tubular biodigesters are constructed of plastic and usually have cylindrical and elongated forms. They are half-buried, leaving the biogas dome visible. The plastic used to construct these biodigesters is usually greenhouse polyethylene (double layer) in the most economical cases (with durability between 5-7 years if well protected) and geomembranes (with durability of 10 to 15 years). The geomembrane can be PVC or polyethylene, with thicknesses greater than 0.75 mm. The transport of materials is much less than with the fixed dome, and the installation of the system is done in a single day whereas the fixed dome requires skilled labor and takes several days to weeks.

Figure 3: Tubular biogas digester

These biodigesters operate at temperatures similar to soil temperatures because the manure and water mixture is contained in the ditch the biodigester sits in (Figure 4). However, being half-buried, the biogas dome is visible and can be designed to take advantage of solar radiation so the system is heated. In this case, it is necessary to add insulation on the walls and floor of the ditch to not lose heat. If a compact greenhouse is included, which also serves as a protection for the system, it is possible to increase the working temperature of the biodigester, which can make the biodigesters work in extreme climates (temperatures below 0˚C or 32˚F). This makes the tubular biodigesters more versatile in the implementation in different climatic zones.

Tubular biodigesters work at lower pressures of biogas, between 5 cm and 15 cm of water column. The required ratio of manure to water is 1: 3, increases the water usage and the needed volume of the biodigester. If sufficient water is not available, the liquid fertilizer produced can be mixed with fresh manure when loading the biodigester.

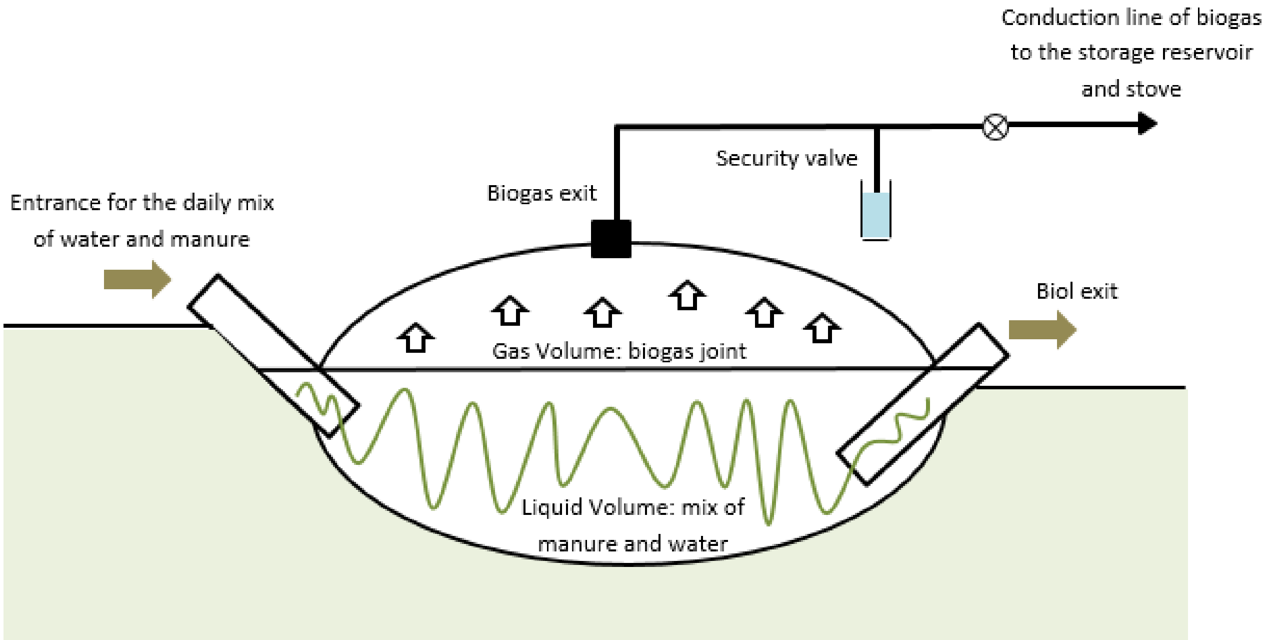


Figure 4: Basic parts of a tubular biogas digester

<table>
<tr><th colspan="4">Table 1: Advantages and Disadvantages of Fixed Dome Biodigesters and Tubular Biodigesters</th></tr>
<tr><th></th><th>Fixed Dome</th><th colspan="2">Tubular</th></tr>
<tr><th rowspan="3">Advantages</th><td rowspan="3">-Has a life expectancy of 20 years
-Uses little water (manure: water 1: 1) with respect to tubular biodigesters
-Does not occupy space on the farm when they are buried and there is no need for a protection system
-Achieves much higher biogas pressures (1 m water column) than tubular biodigesters
-It is a technology widely used in Asia and Africa</td><td colspan="2">-Can be installed in warm and cold regions (colder climates regions require passive solar heating).
-Quick installation (1 or 2 days) after the ditch is dug
-Easy training to become a tubular biodigester installer
-The cost of transporting materials is low because they are lightweight pieces.
-It is a technology widely used in Latin America</td></tr>
<tr><th>Using Plastic</th><th>Using Geomembrane</th></tr>
<tr><td>-The cost / durability ratio (5-7 years) is in line with small agricultural producers
-Materials available at hardware stores in the local market</td><td>-Comes prefabricated
-Can be made in any size
-Lifetime of 15 years
-PVC geomembrane is very easy to repair
-Polyethylene geomembrane is very hard and resistant</td></tr>
<tr><th rowspan="2">Disadvantage</th><td rowspan="2">-Its cost is greater than plastic tubular biodigesters
-They are not adapted to work in cold climates
-The transport of materials to communities can increase costs</td><td colspan="2">-It is necessary to protect the biodigester
-They use more water in the load (manure: water, 1: 3 to 1: 5) than the fixed dome biodigesters
-Achieve lower biogas pressures (up to 15cm of water column) than fixed dome pressures</td></tr>
<tr><th>Using Plastic</th><th>Using Geomembrane</th></tr>
</table>

	-Intense training is required to install biodigesters	-Limiting in terms of size of plastics available -Can repair holes up to 20cm long.	-PVC geomembrane: if it is not reinforced it reaches biogas pressures around 5cm of water column. -Polyethylene geomembrane: repairable up to 20cm hole

2. Concepts of the Tubular Biodigester Design

Tubular biodigesters are low-cost family biodigesters and have been developed and widely implemented in Latin America. These models of family biodigesters, constructed from tubular polyethylene sleeves, are characterized by their low cost, easy installation and maintenance, as well as by requiring only local materials for their construction. Therefore, they are considered an "appropriate technology".

There are several limitations for biodigesters:

- The availability of water to make the mixture with the manure that will be introduced in the biodigester, the amount of livestock that the family owns (2-3 cows are sufficient), the ease of manure collection, and the appropriation of the technology by the family. This is not a portable technology, there must be a permanent presence of the user and is not idea for families who travel significant amounts of time.

- Tubular biodigesters take advantage of the tubular polyethylene or greenhouse plastic to create a chamber or tube several cubic meters long that is sealed completely airtight to maintain an anaerobic environment. This anaerobic environment is essential for the occurrence of anaerobic biological reactions.

- The tubular polyethylene film is tied at both ends to PVC pipes, about six inches in diameter, with recycled strips of the inner tube of the tire of a car. With this system, by conveniently calculating the inclination of these pipes, an airtight tank is obtained. Since the tubular biodigester is flexible, it is necessary to build a 'cradle' or ditch that shelters it, either by digging a ditch or by raising two parallel walls.

As shown in Figure 4, one of the pipes will serve as input of raw material (mixture of manure with water of 1:4 or 1:3 depending on the type of manure) and the other outlet for biol. In the biodigester, a balance of hydraulic level is reached by the amount of manure and water mixture added, and the same amount of fertilizer comes out through the pipe at the other end.

Due to the absence of oxygen inside the airtight chamber, the anaerobic bacteria contained in the manure itself begin to digest it. The gaseous product produced, called biogas, is a mixture of methane (60-80%), carbon dioxide (20-40%), molecular nitrogen (2-3%) and hydrogen sulfide (0.5-2%).

The biogas conduction to the kitchen is done directly, keeping the whole system at the same pressure: between 5 and 15 cm of water column depending on the height and type of stove. This pressure is achieved by incorporating a safety valve built from a 2-liter soda bottle in the gas line. To do this, a 'tee' is included in the line, and off the tee a pipe (5-15 cm) is inserted into the water–filled soda bottle.

Systems adapted for the highlands are placed in buried ditches to take advantage of the thermal inertia of the ground, or two thick walls of adobe in case it cannot be dug. In addition, the biodigesters are enclosed with a roof of greenhouse plastic or other material and supported on the side with adobe walls (40 cm thick). These adobe walls will accumulate the heat of the greenhouse effect, and on cold nights they will keep the biodigester in operation because of its great thermal inertia. In the case of tropical or valley biodigesters, the greenhouse roof is unnecessary but it is necessary to protect the digester from the direct rays of the sun.

2.1 Concepts of the Family Biodigester Design

The design of a biodigester depends directly on several parameters including the average ambient temperature of where the digester is installed. The temperature determines how quickly the bacteria digest the manure; the higher the temperatures the faster it is digested, the lower the temperatures the slower it is digested. If the temperature is lower (18˚C or 64˚F), the manure will quire more time inside the digester, increasing the retention time.

The daily load is another factor to take into account as it determines the amount of biogas produced per day. The daily manure load, together with the retention time (determined by the temperature), will determine the volume of the biodigester.

One benefit of this technology is that it is adaptable to many situations, and its design can consider different criteria:

- Amount of fuel needed
- Environmental needs (when it is desired to treat all manure generated)
- Amount of natural fertilizer needed

A limiting criteria is the amount of manure available. The use of the digester will determine the size of it. It is important to add at this point that a biodigester can also digest organic waste or sewage produced in a latrine or bathroom, but for that, extra factors should be considered such as the limited use of fertilizer due to possible pathogens and the size of the biodigester.

2.2 Anaerobic Digestion

Fresh manure contains bacteria that continue to digest it and produce methane, carbon dioxide and other gases. If this digestion is done in the absence of air, (anaerobic digestion) biogas is produced. This process is done by a chain of different type of bacteria, as shown in Figure 5 below. The white boxes indicate the process or type of bacteria and the green boxes indicate what they are producing.

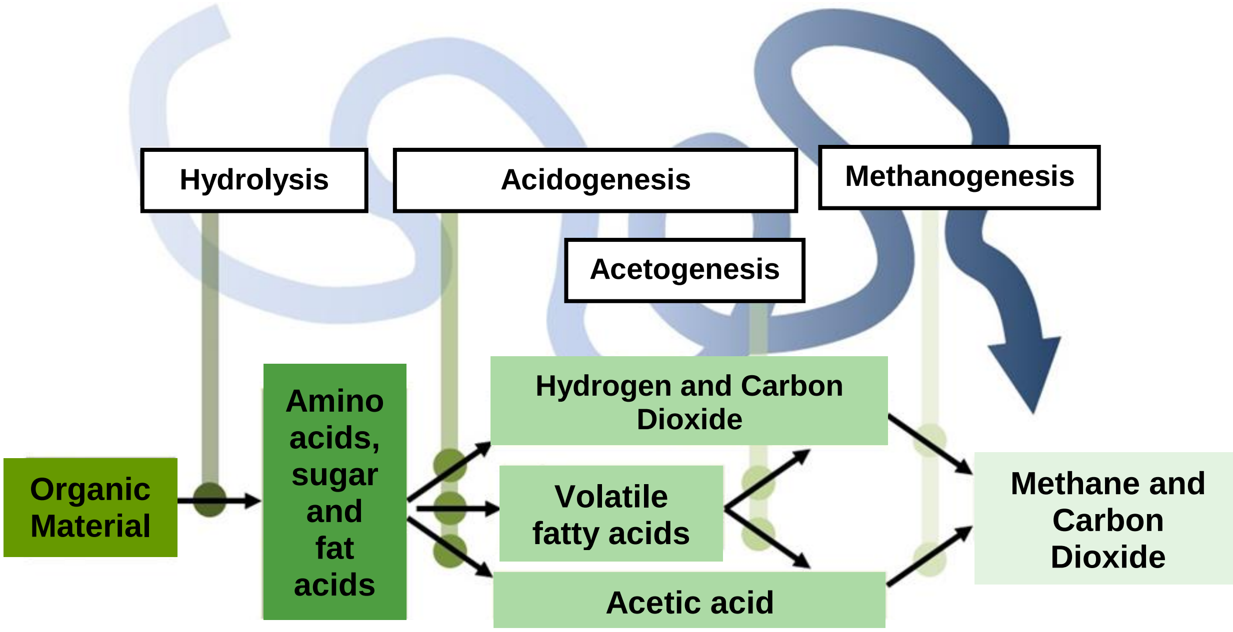


Figure 5: Manure breakdown process by bacteria inside of a biogas digester

2.3 Daily Manure and Manure Available

Daily manure refers to the amount of manure, regardless of whether the animals are stabled or not. This value serves to have an idea of the potential, and be able to estimate how much of that manure will be available to load into the biodigester.

In the case of animals that are not stabled the user must go and collect the manure to load it into the digester. In the event that the animals are stabled at night, or certain hours for milking, there will be an amount of manure available for loading the biodigester (the user can collect from the stable verses the pasture). For animals kept in a pen, the amount of manure produced is the amount being loaded into the digester. The first thing is to know what amount of manure is produced every day on the farm. There are two options: either an on-site measurement is made every day for a week to take averages, or it can be estimated based on average weight.

To know the daily manure available, use Table 2 below, which shows the amount of daily manure produced per 100 kg of live weight for different types of animals. An example of how to calculate the daily manure produced follows.

Table 2: kg of manure produced daily based on animal type

Animal	kg of manure produced per day per 100kg of live weight (kg/d)
Cow	8
Pig	4
Goat/sheep	4
Rabbit	3
Horse	7
Adult	0.4 kg per adult
Child	0.2 kg per child

Example:

A cow weighing 450kg will produce:

$$\left(\frac{450\ kg}{100\ kg}\right) 8\frac{kg}{d} = 36\ kg\ of\ manure\ per\ day$$

A pig of 100 kg of weight will produce:

$$\left(\frac{100\ kg}{100\ kg}\right) 4\frac{kg}{d} = 4\ kg\ of\ manure\ per\ day$$

A young pig weighing 30 kilos will produce:

$$\left(\frac{30\ kg}{100\ kg}\right) 4\frac{kg}{d} = 1.2\ kg\ of\ manure\ per\ day$$

With these calculations, it is easy to estimate the amount of manure produced by a farm, since the calculation can be done per animal. For example:
A farm with 10 cows weighing 450 kg each will be producing

$$(10\ pigs)\left(\frac{450\ kg}{100\ kg}\right) 8\frac{kg}{d} = 36\ kg\ of\ manure\ per\ day$$

In a farm with 10 pig mothers of 100kg each, 40 young pigs of 30kg each, and 15 piglets of 2 kg each, you can make a table like the following

Pigs	# of animals	Average weight (kg)	Kg of manure produced per daily per 100 kg of live weight (kg)	Live weight (kg)	Daily manure produced (kg)*
Mother	10	100	4	1000	40
Young	40	30	4	1200	48
Piglet	15	2	4	60	2.4
				TOTAL (kg)	90.4
* to make this calculation the total live weight has been taken, it has been divided by 100, and it has been multiplied by the "daily manure kg per 100kg of live weight".					

The farm with 10 mother sows, 40 young pigs and 30 piglets produces 90.4 kg of manure per day.

Using the calculated daily manure available, one can calculate the manure available to enter the digester based on the hours the animals spend in a pen. The available manure will always be less than or equal to the daily manure. Table 3 summarizes how to calculate the available manure from daily manure in different cases.

Table 3: Calculation of manure available	
Case	**Manure Available**
Stabled 24 hours	$= daily\ manure$
Stabled only at night	$= 0.25 \times daily\ manure$
Stabled only a # of hours	$= \left(\frac{\#\ hours\ stabled}{24\ hours}\right) \times daily\ manure$

Example:

In the previous example, with 10 cows of 450 kg each, a total of 360 kg of manure was produced per day. If we only consider that only 25% would be left in the place where they sleep, we would have:

$$360\ kg\ x\ \left(\frac{25}{100}\right) = 90\ kg\ of\ manure\ available\ per\ day\ from\ the\ cows.$$

Another case would be that the cows are on a concrete floor (easy place to clean and collect manure) during the wait and milking about three hours a day. In this case, if there are 10 milking cows weighing 450 kg each, they will continue to produce a total of 360 kg of manure per day, but we can only collect the one from the 3 hours they spend on a concrete floor. This means that they pass $100\ x\ \left(\frac{3}{24}\right) = 12.5\%$ of the time on the concrete floor and we will only have 12.5% of the daily manure available. Therefore, if they produced 360kg of daily manure, the available manure per day will be:

$$360\ kg\ x\ \left(\frac{12.5}{100}\right) = 45\ kg$$

As you can see, 10 milking cows of 450 kg each that spend 3 hours a day on the concrete floor, provide 45 kg of manure per day, similar to the pig farm that has 10 mother sows, 40 young and 15 piglets which provides 45.2 kg of manure per day. This is because, although cows produce much more manure every day, only a fraction is available to add to the biodigester.

A final example would be that of a typical family of 5, with 2 adults and 3 children. In this case the daily manure produced by the adults would be:

$$2\ adults\ x\ 0.4\ \frac{kg}{adult} = 0.8\ kg$$

and of the children:

$$2\ children\ x\ 0.2\ \frac{kg}{child} = 0.6\ kg$$

being a total of (0.8 + 0.6) = 1.4 kg of daily manure.

Some questions to think of: do they all go to the bathroom at home? Or would they also go to the bathroom at school or work? The answer to these questions will vary from case to case, and help determine the amount of manure available.

2.4 Manure to Water Mix Ratio

Once the amount of manure available is known, the manure to water ratio will be calculated to determine the daily load into the biodigester. In the tubular biodigesters, it is necessary that the input load (the mixture of manure and water) has between 3% and 5% of Total Solids (TS). It is possible to have loads with less percentage of TS, however, it is not recommended to have higher values. As a reference, it can be said that cow manure must be mixed 1:3 with water (1 part of manure with 3 parts water), and that of pig 1:4, as shown in Table 4.

Table 4: Mix of water for daily load to biodigester

Manure	Ratio manure: water
Cow	1:3
Pig	1:4
Llama/sheep/guinea pig	1:8-9

Once common concern is what happens if the pen floors are washed that the manure and water mixture goes directly to the biodigester. If the pens or stables are cleaned with water, the daily load will have to be modified to take this into account. It is always advisable to know what the amount of manure available and ideal amount of water to mix with it, in order to know if washing the floors is using too little or too much water.

If less water is used than what is needed, more water should be added to reach the amount required. If too much water is used, it is necessary to consider how to save water or be more efficient with washing practices. One can attach a water gun to the hose, collect the dry manure from the floor with a shovel and then wash the floors with water (with the right amount of water) or any other option that facilitates the reduction of water consumption.

When working with households or communities (especially those that have pig farms), knowing the amount of water consumed per day or per week when washing the pens is essential. In fact, this is the reference to calculate the daily load.

Another concern is if the biodigester is installed in an environment where there is not enough water available to meet the needed ratio. In this case, it may be necessary to recirculate the biol, which is to use the biol that leaves the biodigester replacing part of the water needed to load the digester. The best way to do this is to filter the biol before recirculating the liquid, so that the solids are left out of the biodigester as they could possibly choke the biodigester. This recirculation process will also improve biogas production and the quality of the biol, but reduces the amount of biol available for crops.

2.5 Daily Load to the Biodigester

The daily load is the amount of manure and water mixture that will enter the biodigester every day and is usually expressed as liters of load per day (l/d). An equivalence is made between 1 kg of manure and 1 liter of water, assuming that the manure, whatever it is, has a density of 1 kg/l. With this assumption and the ratio values from Table 4, one can determine the daily load into the biodigester. In the case of cow manure, the daily load will be composed of 25% manure and 75% water, with three liters of water per kg of manure. In the case of pig manure, the daily load will be composed of 20% of pig manure and 80% of water, with four liters of water for each kg of pig manure. It is necessary to keep in mind that the daily load will be the volume that enters the biodigester and is a key parameter for sizing the biodigester as it reflects the amounts of biogas produced.

Example:

Following the previous example with the farm that has 10 cows that are on a concrete slab for 3 hours a day for milking, there are 45 kg of manure available per day, and a 1:3 mixture is required (see Table 4), it will be necessary to add:

$$45\ kg\ manure\ x\ \frac{3\ liters\ of\ water}{1\ kg\ manure} = 135\ liters\ of\ water$$

With the daily load of $45\ kg\ manure + 35\ liters\ of\ water = 180\ liters\ per\ day$

For the farm that had 10 mother pigs, 40 young pigs and 15 piglets, there are 45.2 kg of manure available per day and because it is pig manure, the ideal ratio will be 1:4 (manure: water). With this ratio, it is necessary to add:

$$45.2\ kg\ manure\ x\ \frac{4\ liters\ of\ water}{1\ kg\ manure} = 180.8\ liters\ of\ water$$

With a daily load of $45.2\ kg\ manure + 180.8\ liters\ of\ water = 226\ liters\ per\ day$

2.6 Retention Time and Temperature

The higher the temperature the faster bacteria work to breakdown the manure into biol and produce biogas. Due to this, the working temperature of the biodigester defines the time that the bacterial consortium will need to break down the manure and produce biogas. This time is called Retention Time (RT), which can be understood as the time it takes the daily load to completely cross the biodigester, until it is released through the exit. If this time is less than that required by bacteria, less biogas will be produced or even only carbon dioxide will be produced (with hardly any methane). If the bacteria are given a lot of time, the full biogas potential of the daily load will be extracted, but this will require larger biodigesters, and therefore higher costs. Therefore, it is necessary that the RT be adjusted to the temperature at which the bacteria in the biodigester will work. Table 5 shows the required RT for bacteria working at different temperatures.

To better understand retention time, one can think that it as the time in which the manure will be inside the biodigester. You can also think that it as the time it takes to fill an empty biodigester, if every day we are adding the same daily load.

Table 5: Relationship between ambient temperature and retention time recommended to achieve acceptable biogas production

Temperature		Retention Time (RT)
ºC	ºF	
35	95	25-30 days
30	86	30-40 days
25	77	35-50 days
20	68	50-65 days
15	59	65-90 days
10	50	90-125 days

2.7 Working Temperature of the Biodigester

The working temperature is determined by the temperature at which the bacterial consortium inside the biodigester best performs and is dependent upon its location, average room temperature and the use of passive solar heating (greenhouse) design criteria. For regions with hot climates where the average environmental temperatures are above 20ºC and are below 1,500 m, it is not necessary to incorporate passive solar design criteria, and therefore the biodigesters will work at temperatures very similar to average environmental temperatures. A biodigester located in high valleys (average room temperature of 13 to 17ºC and above 1500m) with an incorporated passive solar design will have optimal production due to the increase temperatures associated with the solar design, raising average ambient temperature to 18 a 22 ºC. Table 6 shows the expected working temperature of a biodigester for different eco-regions and average environmental temperatures, with and without passive solar design criteria.

> Since the bacteria found naturally in the manure are used in the biodigester and are accustomed to the interior temperature of the animal which is around 35-37ºC, the bacteria's optimal performance can be found at this temperature as well. But, the bacteria can adapt to work at lower temperatures, which will be the typical case of tubular biodigesters. This acclimatization of working at lower temperatures may take a few months and will happen naturally within the biodigester itself.

Table 6: Biodigester working temperature

Eco region (altitude, meters above sea level)	Ambient Temperature		Working Temperature of Biodigester (ºC)				
	ºC	ºF	Biodigester without Passive Solar Design		Biodigester with Passive Solar Design		Criteria
			ºC	ºF	ºC	ºF	
Warm Tropical (<300)	28-32	82-90	28-32	82-90	Solar design not needed		----
Tropical (300-1,000)	23-27	73-81	23-27	73-81	Solar design not needed		----
Valley (1,000-2,000)	18-22	64-72	18-22	64-72	23-27	73-81	Dark color + ditch insulation
High Valley (2,000-3,000)	13-17	55-63	13-17	55-63	18-22	64-72	Dark color + ditch insulation + greenhouse
Highlands (3,000 – 4,500)	8-12	46-54	8-12	46-54	13-17	55-63	Dark color + ditch insulation + greenhouse

2.8 Design of Passive Solar Heating in Biodigesters

In cases where the average room temperature is around 20ºC or lower, it is recommended to consider the passive solar heating design criteria. To increase the temperature of the biodigester to meet the working temperature, follow the three steps listed:

- The biodigester is made of dark colored materials: this is to absorb the solar radiation, which will heat the geomembrane dome (up to 15 and 21ºC) and raise the internal temperature of the biodigester. This option is only recommended if polyethylene geomembrane is used to make the biodigester (it already comes in a black color and absorbs direct solar radiation very well) since direct solar radiation on PVC or plastic geomembrane greatly shortens its useful life. With this technique, the working temperature of the biodigester can be raised between 2ºC and 3ºC. If this is not sufficient, continue to step 2.
- Wall and ditch insulation: By installing a ditch with insulation (usually straw or Styrofoam) the temperature will increase. To utilize ditch insulation, the biodigester must be installed as described in criteria 1 (utilizing solar radiation and black polyethylene geomembrane to naturally raise the internal temperature of the biodigester). With this technique (insulation plus dark color) the working temperature of the biodigester can be increased between 4 and 6ºC. If this is not sufficient, continue to step 3.
- Greenhouse: A greenhouse can be utilized as a passive solar heating element but also as protection. The greenhouse can have walls of adobe, brick or the greenhouse itself. For this system to work it is necessary to include criteria 1 and 2 (dark colored polyethylene geomembrane and insulated walls and ditches). With this technique you can increase the temperature of the biodigester to 6-10ºC, achieving temperatures similar to the maximum environmental temperatures.

Figure 6: Tubular biogas digester with a greenhouse

Besides increasing the internal temperature of a biodigester, one needs to think about protecting it from animals and people. For all household biodigester installations, it is highly recommended to install protective walls or a fence around the biodigester. There have been many incidences when this was not done and dogs, cows, horses, cats or other animals have walked on the biodigester and ruptured it. It is also highly recommended to install a roof above the biodigester to keep branches or other materials from falling on it and causing it to rip. When thinking of a protective design, make sure to think of the installation steps as well. When installing a wall or fence, make sure there is enough space to walk around and access the biodigester. Most roofs should be installed high enough not to touch the biodigester when it is completely inflated and should be installed prebiodigester installation if nails or other sharp materials are being used as they can puncture the biodigester.

2.9 Production of Biogas, Temperature and Retention Time

The production of biogas from manure depends on what temperature the bacterial consortium is working and the retention time required to produce biogas. Each manure has a potential for biogas production and, for the same working temperature, some manures can produce the biogas more quickly than others. This implies that we must differentiate from when working with cow dung or pig (pig manure is faster at producing biogas than cow manure). Table 7 shows this variation.

Table 7: Retention time and Biogas Production based on Working Temperature of Biodigester

Working Temperature of Biodigester		**Fresh Cow Manure**		**Fresh Pig Manure**	
ºC	**ºF**	**Retention Time (days)**	**Biogas* (l/kg)**	**Retention Time (days)**	**Biogas* (l/kg)**
33-37	91-99	30	39	25	71
28-32	82-90	40	38	30	67
23-27	73-81	50	35	35	61
18-22	64-72	65	33	50	59
13-17	55-63	90	31	65	54
8-12	46-54	125	29	90	50

*The biogas is expressed for 25ºC and 1 atmosphere of pressure, assuming 65% methane content (CH4). The biogas produced per kilogram of fresh manure is referential, and really should apply a range of +/- 10%, to be able to consider the different factors that can affect it (moisture of manure and animal diet).

As you can see, it is recommended that pig manure at a working temperature of 23-27ºC has a retention time of 35 days and will produce around 61 liters of biogas. Cow dung under the same conditions requires 50 days of retention time and will produce around 35 liters of biogas.

2.10 Consumption of Biogas from Different Equipment

Another important aspect to know for the design of a biodigester is the use of the biogas being produced. The most efficient use of biogas is to use it as fuel in the kitchen or for heating water or spaces (such as stables for piglets). The next most efficient use of biogas is in mechanical applications (pasture choppers or water pumps) and finally in the production of electricity. Table 8 shows some energy equivalents of biogas with other fuels or thermal energy or utility connections.

Table 8: Energy equivalents to biogas

1000 liters ($1m^3$) of biogas is equivalent to:	
5,647 kcal	Energy (65% CH_4)
6,056 kWh	Energy (65% CH_4)
1.6 kg	Wood
1.2 kg	Dry Manure
1.1 liters	Alcohol
0.75 liters	Gasoline
0.65 liters	Gas-oil
0.76 m3	Natural Oil

0.7 kg	Carbon
3.3 kWh_t	Heat (65% CH_4; 50% performance)
2 kWh_e	Electrical (65% CH_4; 30% performance)

Table 9 shows typical values of biogas consumption per hour of different elements.

Table 9: Biogas consumption per hour based on use

Biogas Use	Consumption of Biogas (l/h)
Domestic stove	300
Industrial stove	450
Pig heater	300
Lamp (equivalent to 60W)	120
Rice cooker (2L)	140
Water boiler (14 kW)	2,500
Water boiler (26 kW)	5,000
Refrigerator (100L)	30 (in a cold zone)
	75 (in a hot zone)
Motor < 5hp (per 1hp)	400
Motor > 5hp (per 1hp)	250
Milking machine (15hp)	2,500
Generator (1.2 kW)	600
Generator (3 kW)	2,100
1kWh electricity (5 - 20 kW)	1,600

2.11 Volume of a Biodigester, Daily Load and Retention Time

The volume of the biodigester can be divided between the part that occupies the liquid phase (manure and water together with the bacterial consortium) and the part that occupies the gas phase (where the generated biogas accumulates). The liquid volume of the biodigester is related to the daily load and the retention time. If we imagine a biodigester initially empty and start loading it daily with the same amount (daily load), it will take as many days as the retention time has been considered, to be filled. So, the day "retention time +1 day" is when the digester will overflow, expelling the load of the first day already digested. Therefore, the liquid volume of a biodigester will be the retention time multiplied by daily load. This would indicate to us how many days it would take to fill the biodigester with that amount of daily load. The liquid volume with respect to the retention time and the daily load is shown in Equation 1 below.

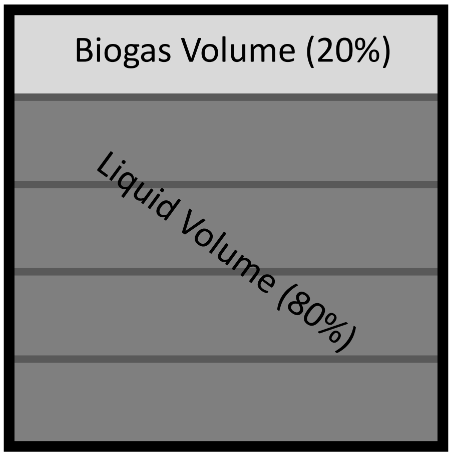
In a biodigester already built, if the daily load is increased, the retention time will be reduced (since it would take less days to fill) and if the daily load is reduced, the retention time is increased (it would take longer in filling the biodigester by reducing the daily load).

Equation 1 $$V_L = RT \; x \; DL$$

V_L = liquid volume (m^3 o L)
RT= retention time (days)
DL=Daily load (m^3/d o L/d)

The liquid volume (V_L) is the volume that must be considered in the calculations for the retention time, and not the total volume. The total volume (V_T) of the biodigester will be the sum of the liquid volume and volume of biogas (V_B).

Equation 2 $$V_T = V_L + V_B$$ V_T= total volume (m^3 o L)
V_B= biogas volume (m^3 o L)



Total Volume (100%)

Figure 7: Biogas and volume distribution in a tubular biogas digester

The volume of the biogas dome can be made larger or smaller during the design phase. This does not determine the space occupied by the bacteria and therefore does not depend on the retention time or the place or climate where the biodigester is installed. The biogas volume of the biodigester may be desired to be large (such as to store 1 or 2 days of daily biogas production and require an external biogas reservoir) or very small (a few liters of volume). As a reference, in plastic tubular biodigesters it is usually considered that the volume of the biogas will be 20% of the total volume, and the liquid volume will be 80% of the total volume. That is, the total volume of the biodigester will have one part of biogas and four parts of liquid, or the volume of the liquid will be four times the volume of the biogas. Using these values:

Equation 3 $$V_L = 4 \times V_B$$

Equation 4 $$V_T = 5 \times V_B = \frac{5}{4} V_L$$

2.12 Tubular Biodigesters

The volume of the biodigester must be given a form, which is determined by the dimensions of the biodigester. We must consider that the most important part is the liquid volume, which is associated with the daily load and the retention time. The volume of the biogas only tells us how much biogas we can store and does not influence the anaerobic digestion.

Therefore, the key is to give adequate biodigester dimensions so it has the desired liquid volume. When working with biodigesters built with flexible materials (greenhouse plastic, PVC or polyethylene geomembrane) it is necessary to give a container to the biodigester that contains that volume, and that container is the ditch. The dimensions of the ditch are what determine the final volume of the digester, because in the end, the liquid volume must be contained in the ditch.

The tubular biodigesters are those that have a tubular shape (cylinder, sleeve, pipe, intestine, etc.). Originally, this tubular shape was utilized because the greenhouse plastic was available in the form of a sleeve. Other materials are available, such as the PVC or polyethylene geomembrane, which is supplied in sheets and have to be welded to form a tube. There are biodigesters that also have a more spherical shape or are built in concrete ditches with the geomembrane acting as the lid or dome top. The spherical shape is advantageous as it uses less material but the tubular digesters allows for the entrance and exit of the biodigester (placed at the ends of the sleeve) to be far enough away, and therefore ensures that the daily load will have to travel the entire length of the biodigester before leaving. This tubular shape resembles the intestine of a digestive system, which is what we are actually trying to replicate.

When taking the length to diameter ratio of a tubular biodigester there is a certain range that must be met to consider it tubular and get optimal performance. The length to diameter ratio of a tubular biodigester must between 5 and 10. If it is outside of this range, it is no longer considered tubular.

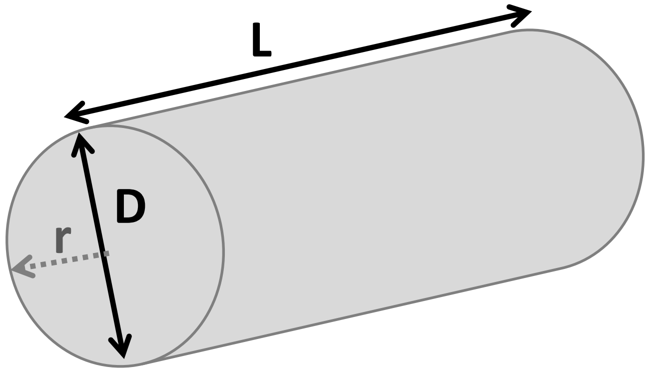


Figure 8 Length to diameter ratio of a tubular biodigester

Equation 5 $$\frac{L}{D} = (5\ a\ 10)$$ L= length

D= diameter

A diameter where L / D <5 will have too short a form and the entrance and exit will be insufficiently distanced apart, not allowing sufficient retention time to properly treat the manure.

If a biodigester has L / D> 10, it will have an elongated shape (more spaghetti-like then sausage). Although this does ensure that the entrance and exit sufficiently distanced apart, it may cause sludge accumulation problems towards the middle of the biodigester. In shorter biodigesters, the daily load produces a turbulence inside the biodigester, keeping the solids suspended. However, with the longer biodigesters the turbulence produced by the daily load does not reach the middle of the digester causing the solids to settle and accumulate.

The optimum ratio between the length and diameter for a biodigester will be 7.5.

Equation 6 $$\frac{L}{D} optimum = 7.5$$

For tubular biodigester, the circumference (C) of the cylinder is:

Equation 7 $$C = 2 \times \pi \times r$$ π = 3.14
r= radius

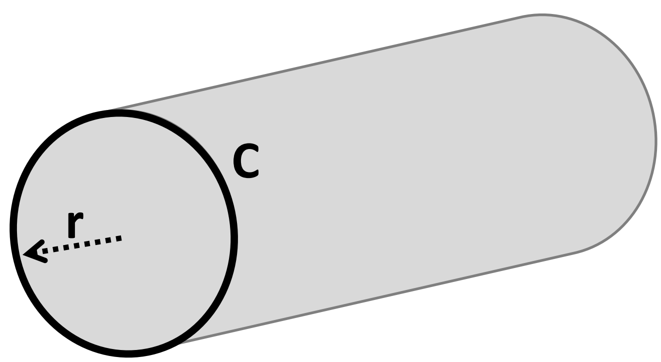


Figure 9: Radius and circumference of a tubular biodigester

The diameter (D) is twice the radius

Equation 8 $$D = 2 \times r$$

The following example shows how to determine the minimum, maximum and optimum biodigester length.

Example:

Greenhouse plastic is typically sold in rolls 2 meters wide in tubular form, and opens to 4 m. This means that the plastic sleeve, when the side is cut, opens to a sheet of 4 meters. These 4 meters correspond to the circumference, and the 2 meters are half the circumference (do not confuse these two meters with the diameter). In this case, if the circumference is 4 meters:

$$C = 2 \times \pi \times r$$
$$4 = 2 \times 3.14 \times r$$
$$r = 0.64;\ diameter = 1.27\ m$$

From this, we can calculate the acceptable lengths of a biodigester that have a 4 m circumference. The shortest length will be the one that maintains an L / D = 5 ratio. To determine the minimum length using a circumference of 4:

$$\frac{L}{1.27\ m} = 5$$
$$L = 6.36\ m$$

The largest length will be:

$$\frac{L}{1.27\ m} = 10$$
$$L = 12.7\ m$$

The optimal length will be:

$$\frac{L}{1.27\ m} = 10$$
$$L = 9.55\ m$$

Table 10 shows the minimum, maximum and optimum lengths of tubular biodigesters according to typical circumferences of plastics that can be found in the market.

Table 10: Biodigester lengths based on circumference

Circumference (m)	Roll Width (m)	Radius (m)	Diameter (m)	Longitude of Tubular Biodigester		
				Minimum (m)	Maximum (m)	Optimum (m)
2	1	0.32	0.64	3.2	6.4	4.8
3	1.5	0.48	0.95	4.8	9.5	7.2
4	2	0.64	1.27	6.4	12.7	9.5
5	2.5	0.80	1.59	8.0	15.9	11.9
6	3	0.95	1.91	9.5	19.1	14.3
7	3.5	1.11	2.23	11.1	22.3	16.7
8	4	1.27	2.55	12.7	25.5	19.1
9	4.5	1.43	2.86	14.3	28.6	21.5
10	5	1.59	3.18	15.9	31.8	23.9
14	7	2.23	4.46	22.3	44.6	33.4

2.13 Dimensions of the Tubular Biodigesters

The dimensions of a tubular biodigester are determined by the dimensions of a trapezoidal ditch (with sloping walls) as it contains the liquid phase of the biodigester.

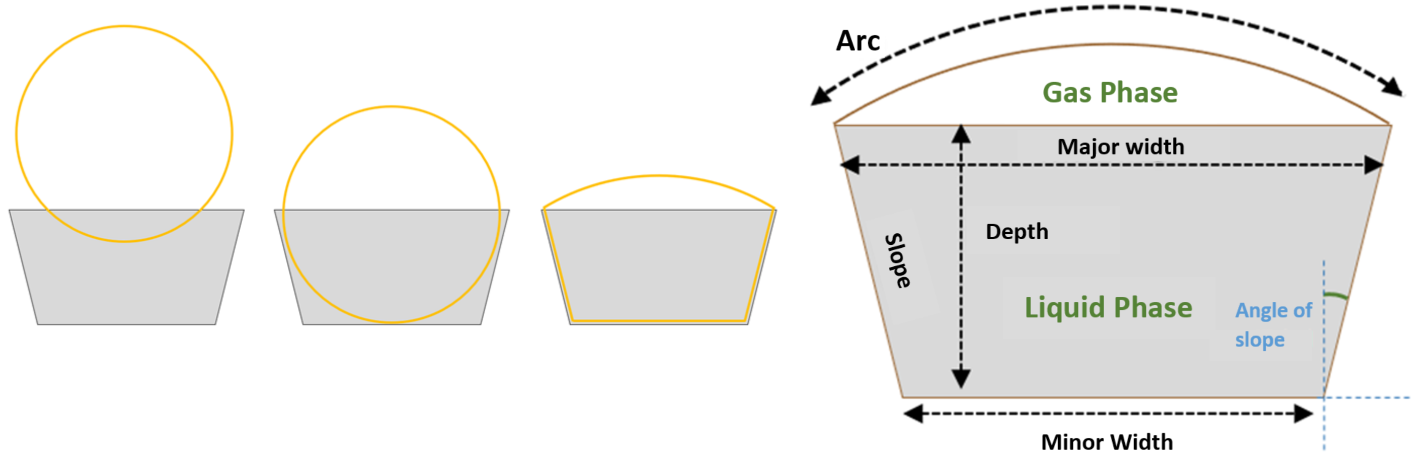


Figure 10 The biodigester will take the shape of the ditch and the ditch will determine the liquid volume of the biodigester

A trapezoid is determined by its lower width (a), upper width (b) and depth (p). When projecting this trapeze, we have the ditch with a length L.

With these dimensions, the volume of the ditch will determine the volume of the biodigester. For this, it is necessary to first know the area of the trapezoid and then multiply it by the length. The area of the trapeze (ditch) is half the sum of the lower width and the upper width multiplied by the depth, as it appears in the Equation 9 below:

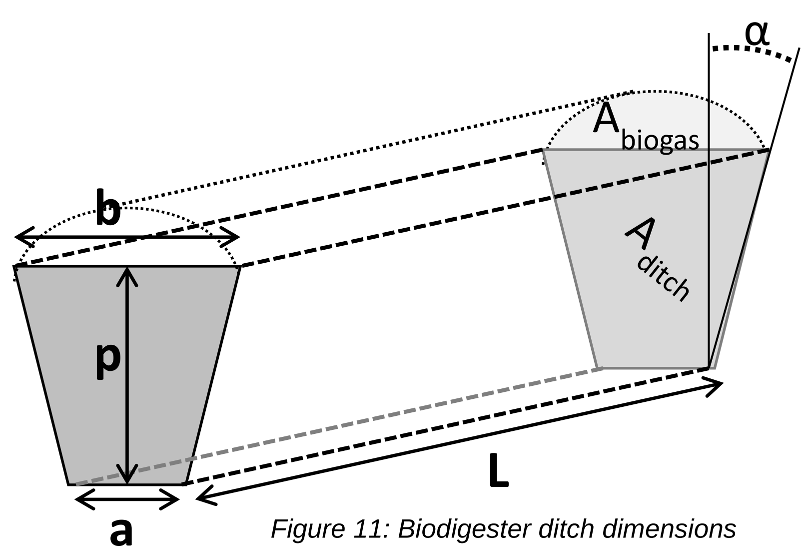


Figure 11: Biodigester ditch dimensions

Equation 9

$$A_{ditch} = p \times \frac{(a+b)}{2}$$

A_{ditch}=area of ditch

p=depth of trapezoid
a=lower width
B=upper width

The key is therefore to give values appropriate to the dimensions of the ditch (a, b and p) and that are consistent with the circumference of the plastic that is going to be used to make the tubular biodigester. The perimeter of the trapezoidal area of the ditch should always be less than the circumference of the plastic, as shown in Equation 10, since the water and manure load will have to travel the entire perimeter and have a surplus to form the biogas dome.

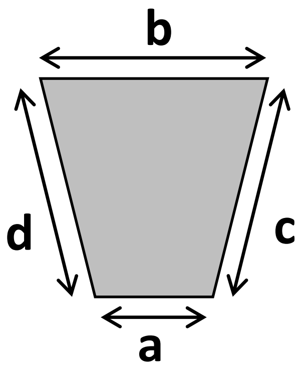


Figure 12: Perimeter of the biodigester ditch (trapezoid

Equation 10
$$\textit{trapezoid perimeter} < \textit{circumference of plastic}$$
$$a + b + c + d < 2\,\pi\, r$$

In general terms, it is recommended that a tubular biodigester have 20% of the total volume occupied by biogas and 80% occupied by the liquid phase, and strong, inclined ditch walls are preferred (angles of 7.5° from the vertical). Table 11 gives the trapezoidal ditch dimensions based on biodigester circumference, which are standard values.

Table 11: Trapezoidal ditch dimensions based on biodigester circumference

Biodigester Tube		Trapezoidal Ditch			A_{ditch} (m^2)	A_{biogas} (m^2)	A_{total} (m^2)
C (m)	r (m)	a (m)	b (m)	p (m)			
2	0.32	0.40	0.50	0.50	0.225	0.056	0.28
3	0.48	0.60	0.80	0.75	0.525	0.131	0.66
4	0.64	0.80	1.05	1.00	0.925	0.231	1.16
5	0.80	1.00	1.30	1.25	1.436	0.359	1.79
6	0.95	1.15	1.60	1.45	1.994	0.498	2.49
7	1.11	1.35	1.80	1.70	2.678	0.669	3.35
8	1.27	1.55	2.10	1.95	3.559	0.890	4.45
9	1.43	1.75	2.35	2.20	4.510	1.128	5.64
10	1.59	1.95	2.60	2.45	5.576	1.394	6.97
14	2.23	2.75	3.65	3.45	11.040	2.760	13.80

The volume of the ditch (V_{ditch}) will be the liquid volume of the biodigester (V_L) and is calculated by multiplying the area of the ditch (A_{ditch}) by its length (L), as expressed below.

Equation 11
$$\boldsymbol{V_{ditch} = V_L = A_{ditch} \times L} \qquad \mathrm{V_{ditch}} = \text{volume of ditch}$$
$$\mathrm{V_L} = \text{liquid volume of biodigester}$$

To know more:

To use the available plastic as efficiently as possible, softer angles are required for the ditch walls and the proportion of volume of biogas to liquid changes (it is no longer 20% and 80%). The relationship between the plastic radius to be used and the dimensions of the ditch will change, as shown in the table below:

α (angle from the vertical)	% V_L	%V_B	a (m)	b (m)	p (m)	A_{ditch} (m^2)	A_{biogas}(m^2)	A_{total}(m^2)
7.5	80	20	1.23 x r	1.63 x r	1.54 x r	2.20 x r^2	0.55 x r^2	2.75 x r^2

15	76	24	1.02 x r	1.82 x r	1.49 x r	2.12 x r^2	0.67 x r^2	2.78 x r^2
30	75	25	0.72 x r	2.26 x r	1.33 x r	1.98 x r^2	0.66 x r^2	2.64 x r^2
45	65	35	0.43 x r	2.57 x r	1.07 x r	1.61 x r^2	0.86 x r^2	2.47 x r^2

If you want to work with ditch walls at 30° angles from the vertical you must know the optimal dimensions of the ditch. To do this multiply the radius of the plastic sleeve (r) by:

- 0.72 to obtain the lower width (a)
- 2.26 to obtain the upper width (b)
- 1.33 to calculate the depth (p) of the ditch

With these calculations for 30° angles, regardless of the radius (r) used, biodigesters will always have a 75% liquid phase and a 25% gas phase.

Following with the case of a ditch of 30° inclination of the walls, to know the vertical area of the A_{ditch}, we will have to multiply 1.98 by the square of the radius. With the A_{ditch} it will be possible to estimate the volume of the same V_{ditch}, that is, the liquid volume of the biodigester (V_L), multiplying it by the length (L), as shown the equation below:

$$V_{ditch} = V_L = A_{ditch} \times L$$

3. <u>Selecting Geomembrane Material</u>

There are different types of materials that can be utilized to construct the tubular biodigester. This section covers the different types of materials, their characteristics, advantages and disadvantages, and how they are used. We will also discuss the different formats in which flexible biodigesters are found in the market, and some examples of known commercial options, in order to expose relevant aspects to interpret and analyze these options to make purchasing decisions.

3.1 Types of Materials

A geomembrane is a synthetic material with very low permeability that is used as a physical barrier to control or contain liquids or gases from different projects, such as landfills (containing leachates and methane gas). These same geomembranes have been used to manufacture biodigesters, due to their low permeability characteristics. Table 12 below contains a list of possible tubular biodigester material:

Table 12: Possible tubular biogas digester material

Material	Durability	Cost	Glue/Weld	Comments
PVC	High	Low	Can be glued with PVC glue, holes can be patched with PVC glue and patches	-Sensitive to UV rays so must be protected by a roof -Some have “memory”, can be stretched out and then returned to original shape -Commonly used for tubular biodigesters
HDPE (high density polyethylene)	High	Medium	Welded with a hot wedge or roller, patches must be	-Compared to LDPE is harder, has a higher chemical resistance and can withstand higher temperatures

			done with welder or hot wedge was well	-Very resistant to weather -Many prefabricated biodigester come in this material
LDPE (low density polyethylene)	High	Medium	Welded with a hot wedge or roller, patches must be done with welder or hot wedge was well	-Compared to HDPE, is softer, more flexible and melts at a lower temperature -Very resistant to weather
Greenhouse plastic	Medium	Low	Comes in a tubular shape, if ripped it cannot be patched	-Installed double lined (one sheet inside another) to increase the material strength

3.2 How to Interpret a Technical Sheet

A technical sheet for geomembrane provides the mechanical and chemical characteristics of the material. It gives properties such as: what percentage should be stretched before it breaks ("elongation to rupture"), or what force should be applied to make a hole ("puncture resistance").

There are standard methods performed by the manufacturer in controlled, laboratory conditions to test these properties and the results are reported in the technical data sheet. It is important to remember some test methods may be different, for example Solmax uses method ASTM D-6693 to report stress resistance where as Filmtex uses method ASTM D882. Other technical sheets do not even present their methods or units. Table 13 presents a summary of characteristics of the most commonly used geomembranes for biodigesters in Latin America, with their respective specifications. This table serves to compare and make decisions when looking to purchase geomembrane, however not all geomembrane will meet these criteria and but will still work.

Table 13: Typical tubular biogas digester specifications

Plastic Type	HDPE	PVC	LDPE	Greenhouse HDPE	fPP	EPDM	
Manufacturer	Solmax	Filmtex	Raven	RPC	Raven	Firestone	
Commercial Name	HDPE Smooth	Perma flex	Rufco 4000B	Dura Film	HydraFlex PP40	GeoGard	
Caliber/Thickness (mm)	1,5[a]	1[d]	1[a]	0,15[b]	1	1,1	
Tensile strenth to break (N/mm)	42[c]	17[e]	32[c]	-	15,9[c]	9*	ISO R527
Elongation at break (%)	700[c]	430[e]	800[c]	430[e]	900[c]	300	ISO R527
Tear resistance (N)	187[f]	44[f]	98[f]	10,2[i]	62[f]	33	D 624 (Die C)
Puncture Resistance (N)	540[g]	210[g]	267[g]	-	200[g]	700	EN ISO122 36
Dimensional Stability (% change)	2%[h]	3%[h]	<2%[h]	-	-	-	-

Stadards or testing method: a) ASTMD-5199, b) AT Method, c) ASTM D-6693, d) DIN53370, e) ASTMD882, f) ASTM D-1004, g) ASTM D-4833, h) ASTM D-1204, i) ASTM D 1922
*N/mm^2

The caliber is a way of saying the thickness of the geomembrane. For example, some companies use 4-gauge, referencing "4 thousandths of an inch," or about 0.1 mm, which is equivalent to 100 microns in thickness. Table 14 below is an approximation for interpreting the thickness or gauge of a geomembrane in different units.

Table 14: Thickness conversions of geomembrane

Caliber	mm	Microns
4	0,1	10
8	0,2	20
12	0,3	30
16	0,4	40
24	0,6	60
32	0,8	80
40	1	100
60	1,5	150
80	2	200

Some material features are not reported in this data sheet but are still important to be noted, for example, "flexibility". EPDM and PVC are very flexible, which makes them very easy to handle, pack and move, while HDPE is more rigid and can crack more easily (for example during packing and export or mobilization to the install site). The most important thing to consult with the manufacturer is to ask how much they have used the geomembrane for tubular biodigesters before, and make sure that there are several units already operating for several years to ensure the geomembrane is adequate. Also, consider that not all geomembranes or materials are readily available in all countries, and the ideal is to use what is locally available.

What is clear is that the geomembrane must have:

- Resistance to different chemicals: the biodigester contains acid gases and volatile organic acids in the solution.
- Resistance to puncture: it is typical for animals to walk near or on the biodigester, it must have some puncture resistance.
- Low permeability: the geomembrane must demonstrate the ability to retain the biogas.
- Excellent durability: biodigesters are installed outdoors and the geomembrane must resist the weather, mainly changes in temperature and UV rays.

Figure 13: Tubular biodigesters need to be protected from animals as they can easily puncture the material

4. Design of Tubular Biodigesters

Now that the theory behind tubular biodigester design has been discussed, the steps to optimally designing a functioning tubular biodigester will be covered.

The biodigester design can be divided into two parts:

- Determining the volume of the biodigester based on daily load and retention time (this part is common to any type of biodigester, whether tubular or not).

- Determining the dimensions of the tubular biodigester based on material size and ditch area (this part is already specific to tubular biodigesters).

Figure 14 below shows the flow of this process:

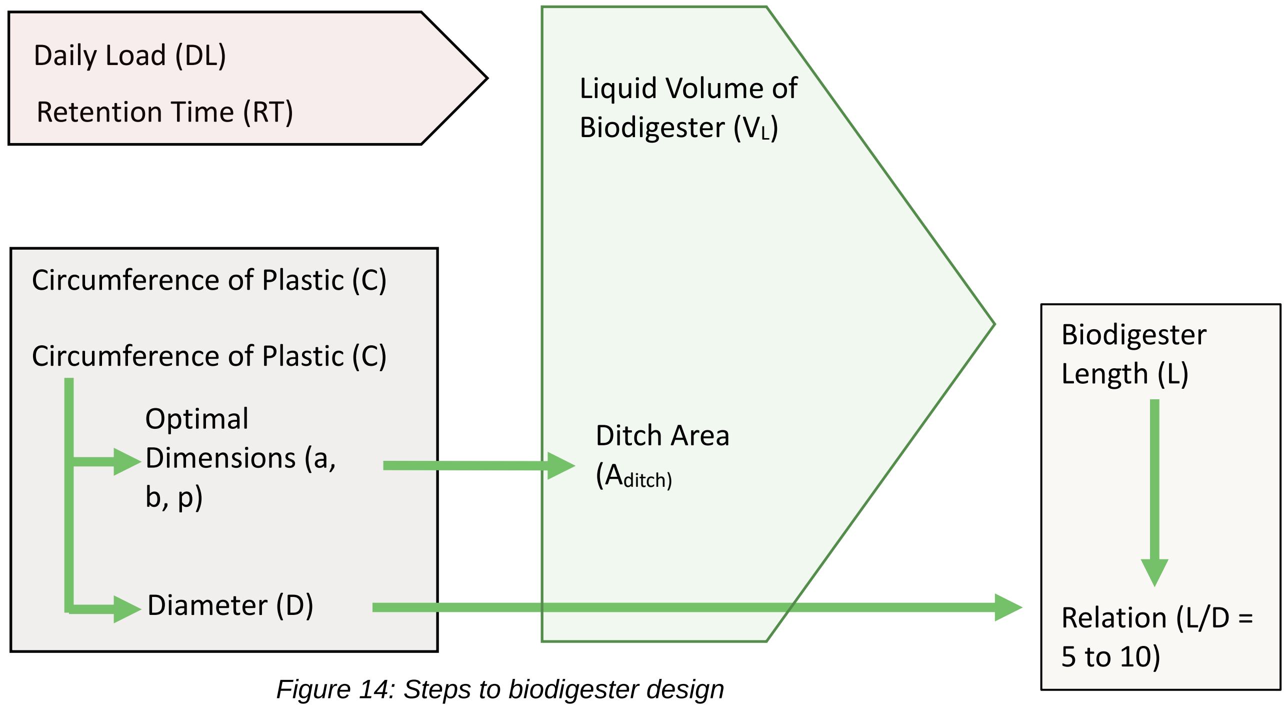


Figure 14: Steps to biodigester design

4.1 Determining the Volume of the Biodigester

The volume of the biodigester is determined by the daily load (mixture of manure and water) and the retention time (RT). In turn, the RT is determined by the climate and passive solar heating (if needed).

The daily load may be based on the amount of manure available, but may also be conditioned by wanting to produce a certain amount of biogas or to produce a certain amount of biol per day or week. Each objective is explained in more detail below:

In a biodigester that is already built, if the daily load is increased, the retention time will be reduced (since it would take less days to fill) and if the daily load is reduced, on the contrary, the retention time is increased (it would take longer in filling the biodigester by reducing the daily load).

- Optimum biol production: When the production of biol prevails, remember that in a tubular biodigester everything moves by gravity, and if it is loaded with a certain amount of manure and water through the inlet, it will overflow/release the same amount of biol through the exit. Therefore, if you want to produce a certain amount of biol per day or week, the biodigester should have a daily or weekly load equal to the amount of biol desired.
- Optimal biogas production: In the case where you want to use a specific amount of biogas, you have to calculate how much biogas is required per day for the selected uses (see Table 9). Once the amount of biogas required is known, using Table 7 one can estimate how much manure is needed to produce the specified amount of biogas. It is also necessary to define at what working temperature the biogas will be and the retention time.

Once the amount of daily manure needed is known to produce the identified amount of biogas, the manure: water mixture (Table 3) can be calculated. This mix will determine the daily load into the biodigester

- Environmental objective: When the objective is to treat all available manure, it is usually either because there is not a lot of manure or a waste treatment system is needed. In this case, you have to think about what will be done with the amount of biol and biogas produced. In general, the daily load to the digester will be calculated by estimating the amount of manure and water available.

Example:

To provide enough fuel for a family kitchen, a minimum of 1000 liters of biogas per day is necessary. If you also want to have a biogas lamp lit 3 hours a night, you will need (120 l / h) x (3 h) = 360 liters more each day, making a total of 1360 liters of biogas per day. Knowing the amount of biogas desired, you can know how much manure is needed to produce it using Table 9.

If the biodigester temperature is going to be at 23-27°C, and you have cow dung, 50 days will be the proper retention time and about 35 liters of biogas will be produced for each kilogram of fresh cow dung.

In this case, to produce the 1360 liters of biogas will require (1360 l) / (35 l / kg) = 38.9 kg of cow manure. Considering that a 1: 3 mixture of manure with water is necessary (see Table 4) it will be necessary to add 117 liters of water, giving a daily load of 156 liters (39 kg of cow manure plus 117 liters of water).

For the same biodigester, if the working temperature is 23-27 °C but pig manure is used instead of cow manure, 35 days will be the required retention time and each kilogram of manure will produce 61 liters of biogas. Therefore, to produce 1360 liters of biogas, it will be necessary to have (1360 l) / (61 (l / kg) = 22.3 kg of pig manure. It is necessary that the 23 kg of pig manure be mixed at a 1:4 manure to water ratio, thus 92 liters of water will be added, giving a daily load of 115 liters.

Once the daily load is calculated, the amount of biogas and boil produced can be determined using Table 7.

Once the daily load (DL) and working temperature are known, the retention time can be determined using Table 7. The liquid volume (V_L) can then be calculated using Equation 1.

Example:

Continuing with the previous example, 1,360 liters of biogas will be produced from cow dung. The daily load of 117 liters and the retention time of 50 days has been calculated using Table 7. With this information and using Equation 1, the required liquid volume will be:

$$117\frac{l}{d}\ X\ 50\ d = 5850\ liters\ or\ 5.85\ m^3$$

If pig manure is being utilized to produce 360 liters of biogas, the estimated daily load is 115 liters with 35 days of retention time. With these values, a biodigester with a liquid volume of 4,025 liters is needed.

$$115\frac{l}{d}\ X\ 35\ d = 4025\ liters\ or\ 4.03\ m^3$$

4.2 Determining the Dimensions of the Biodigester

Once you know the required liquid volume of the biodigester, it is necessary to give it a form, which is determined by the ditch. Using the circumference (C) available based on the material being used, determine the trapezoidal ditch dimensions using Table 11. Knowing the trapezoidal ditch dimensions also gives the liquid volume (Equation 11) of the biodigester and ditch area. Using these values, calculate the necessary ditch length:

Equation 12 $$\boldsymbol{L = \frac{V_L\ m^3}{A_{zanja}}}$$

Using this value, confirm this length meets the L/D ratio (minimum 5, maximum 10). Because several circumferences may be considered, choose the circumference that gives you a ratio closer to 7.5. Also, remember to consider installation space available when determining the final biodigester size.

A table such as the one below can be used to easily compare values based on different circumference sizes. C, r, a, b, p, and A_{ditch} are standardized values that can be found in Table 15.

Table 15: Comparison of optimum digester measurements based on circumference

C (m)	r (m)	a (m)	b (m)	p (m)	A_{dich} (m^2)	L (m)	D (m)	L/D
...	...	...	...	...	...	V_L/ A_{ditch}	2 x r	L/D
...	...	...	...	...	...	V_L/ A_{ditch}	2 x r	L/D

Example:

Using the previous examples where a biodigester of 5.85 m^3 fed with cow manure and a biodigester of 4.03 m^3 fed with pig manure had been designed, the biodigester dimensions will be calculated.

Starting with the 5.85 m^3 cow biodigester and considering the tubular plastics available are 1.5, 2 and 2.5 m roll widths (which open at 3, 4 and 5 m), create a table similar to Table 15 using the values from Table 11.

C (m)	r (m)	a (m)	b (m)	p (m)	A_{ditch} (m^2)	L (m)	D (m)	L/D
3	0.48	0.60	0.80	0.75	0.525	11.1	0.95	11.7
4	0.64	0.8	1.05	1	0.925	6.3	1.27	5
5	0.80	1	1.30	1.25	1.438	4.1	1.59	2.6

In this case the plastic of circumference of 4 m is the only one that gives a L / D between 5 and 10, but with a value of 5 it really is in the limit of not being considered a tubular biodigester. In this case, since the required length is 6.3 m, one option is to extend this length a little to 7 m, so that the L / D increases to 5.5. By increasing the length of the biodigester, the liquid volume will increase to 0.925 (m^2) x 7 (m) = 6.48 m3. With a daily load of 117 l/d, the retention time increases to 6480 liters / 117 liters per day = 55.4 days.

For the biodigester fed with 4.03 m^3 of pig manure and the same tubular plastics available:

C (m)	r (m)	a (m)	b (m)	p (m)	A_{ditch} (m^2)	L (m)	D (m)	L/D
3	0.48	0.60	0.80	0.75	0.525	7.7	0.95	8
4	0.64	0.8	1.05	1	0.925	4.4	1.27	3.4
5	0.80	1	1.30	1.25	1.438	2.8	1.59	1.8

Using the values from this table, the biodigester circumference of 3 m and length of 7.7 m will be used since this is the only one that the L / D ratio is between 5 and 10.

4.3 Finalizing the Biodigester Size

In addition to the volume of the biodigester, the depth of the ditch and the length of the inlet and outlet ties must be taken into account when determining the final length of the biodigester material (remember the working volume and ditch will remain the same). This formula is typically used:

Equation 12 $$\boldsymbol{Length\ of\ ditch + 1\ m + depth\ of\ ditch}$$

For example, if a biodigester is going to be 10 meters, and the ditch depth is 1 meter. Two extra meters will be used to install the inlet and outlet pipes (1/2 meter each) and to accommodate the ditch at the ends (1 meter).

More design examples of tubular biodigesters can be found in Section 11.

5. <u>Tubular Biodigester Install</u>

After the design of the digester is complete (volume, ditch dimensions, circumference of plastic, etc.) the next step is to install it. It is important to remember that during installation problems may occur where the design needs to be changed, such as inability to excavate and the digester has to be installed as two digesters instead of one, or more backfill material needs to be added because of the slope of the terrain, and this is okay.

5.1 Materials Needed

Making a complete list of materials is always difficult because each biodigester install is different. Even so, a list of materials that facilitate building the biodigester, creating a biogas connection with a relief valve and hydrogen sulfide filter, and installing a cooking connection is useful. Table 16 below lists the materials needed for a biodigester install, but remember this varies between projects.

Table 16: Material list

Material	Comment	Quantity
Ditch		
Plastic sheeting	To lay the biodigester on during construction	2 meters longer than the length of the biodigester
Old plastic sacks	Can use old food sacks, used to make sandbags to give the ditch the proper shape if needed.	Number necessary
Old plastics, tarpaulins or sacks	The ditch can be lined with these materials to protect the biodigester.	Number necessary
Biodigester		
Tubular sleeve	It can be tubular greenhouse plastic (in this case a double layer will be used), or polyethylene geomembrane (that may need to be welded into a tubular form), or a prefabricated biodigester made of PVC geomembrane or polyethylene geomembrane.	This is based on the design and the type of material being used.
PVC drainage pipe	It can be 4 "or 6". 4" is recommended when working with loads that are liquid or manures and 6" is recommended with less liquid or kitchen waste. The 6" also allows a better tie with the tubular plastic.	3 meters (Cut into two, 1.5-meter pieces).
Tire tube	Sometimes the tire tube comes pre-cut. If not, you can cut the new or used tire tube (if used make sure it is still flexible and not dry) with a width of 4-5 cm. The longer you can the piece the better. To do this, you can cut it in a spiral (like peeling an orange).	Two ring tubes of 14 or 16 m or 30 to 40 m meters pre-cut tire tubing.
Flange or tank adapter	Typically, ½" or ¾" in size and easily found in hardware stores. If not found, can use the flanges used on plastic water storage tanks.	1 piece
PVC pipe (water)	Usually a ½" or ¾", depending on flange purchased. Used to connect the biogas outlet to the relieve valve.	3 metros
Rope	A plastic rope	2.5 times the length of the biodigester
Water jug/milk jug	Filled with water and tied to the plastic rope to help mix the biodigester	1 jug
Relief Valve		
Tee	Normally a ½" or ¾" pipe works (same as the flange)	1 tee

2-liter empty soda bottle	Is filled with water and creates the backpressure	1 2-liter bottle
Ball valve	Normally a ½" or ¾" pipe works (same as the flange)	1 ball valve
Wire	To tie the 2 liter bottle to the tee	2 feet
Biogas Conduction		
Gas line	Normally a ½" or ¾" pipe works (same as the flange). It can be a rigid PVC pipe (bondable) or polyethylene (threaded). Flexible tubing can also be used but requires pressure fittings (flex) that require a clamp at each joint.	As many meters as it takes to get the biogas from the biodigester to the point of consumption
Ball valves	Normally a ½" or ¾" pipe works (same as the flange), installed after the relief valve and before the stove inlet	Minimum of 2
Tee	Normally a ½" or ¾" pipe works (same as the flange	Minimum of 1, depends on design
Elbow	Normally a ½" or ¾" pipe works (same as the flange	Minimum of 1, depends on design
Universal union	Normally a ½" or ¾" pipe works (same as the flange, goes before and after the hydrogen sulfide filter	2 unions
Iron wool	Used to remove the hydrogen sulfide smell	1 pack
Vinegar	To oxidize the iron wool	1 bottle
Stove	Any kitchen can be adapted by reducing the amount of air mixed in and widening or removing the gas outlet.	2 stoves or burners are recommended
General		
PVC teflon tape	Recommended to use Teflon tape (10 turns) on the thread of the tank adapter.	1 roll
PVC glue	To glue the gas line together	1 bottle

Biodigester installation only requires a few tools:

For the ditch:
- Pickaxe
- Shovel
- Sacks

For biodigester installation:
- Scissors or razor cutter
- Metal saw
- Stillson wrench (socket wrench)
- Permanent marker

Conduction Line
- Pipe threader (if you are going to use polyethylene or PVC threaded irrigation pipes)

- PVC glue (if going to use pipe that can be glued)
- Screwdriver

5.2 Installation Plan

The installation of a biodigester has several stages that are described below. Prior to installation, site visits must be conducted to discuss the project with the future user, determine digester design, install location and finalize the material list.

1. Location and digging of ditch: first determine where the biodigester will be located and start digging the ditch according to the established design. Dig time can vary depending on size of the ditch and if excavation is being done using an excavator or by hand.
2. Installation of the biodigester to the relief valve: once the ditch is dug and lined with sacks or plastic, install the biodigester and the relieve valve. With two experienced installers the construction and installation of the biodigester and relief valve usually takes half a day. If installing protection around the biodigester site such as fencing, a wall or a roof, it is highly recommended to do this before the biodigester is installed and could take half a day to a couple of days depending on how sophisticated it is.
3. Installation of biogas conduction to point of consumption: from the relief valve, the biogas conduction and hydrogen sulfide trap are installed and connected to the kitchen or point of consumption. This is usually done when the digester is already producing biogas (between 2 and 6 weeks after installation) or while waiting for biogas to be produced. This usually takes a couple of days.

5.3 Installation Process

The first step is to determine where the biodigester will be installed. There are a few simple criteria:

- Close to where the manure is produced (either a close walk to the biodigester or can be washed into the loading end of the biodigester via gravity).
- In a sunny area (select the area with the least amount of shade throughout the day, considering the sun paths as well).
- Avoid highly trafficked area or close to a public road (do not put the biodigester in places where people and animals often walk as they can damage the biodigester or by a public road to protect it from vandalism).
- Avoid high flood areas (the biodigester can easily be swept away by a strong current or will float and not be placed back in the ditch correctly once the water recedes).

The second step is to dig the ditch

- First mark the major, minor and long width using lime, chalk or paint.
- Begin excavating with either machinery or a shovel, starting with the smaller width to the indicated depth and then make the respective slopes.
- The floor of the ditch does not need to be inclined as the pressure from adding new manure and water agitate the biodigester contents enough to push it along.

The images below show step-by-step how to dig a ditch for a biodigester:

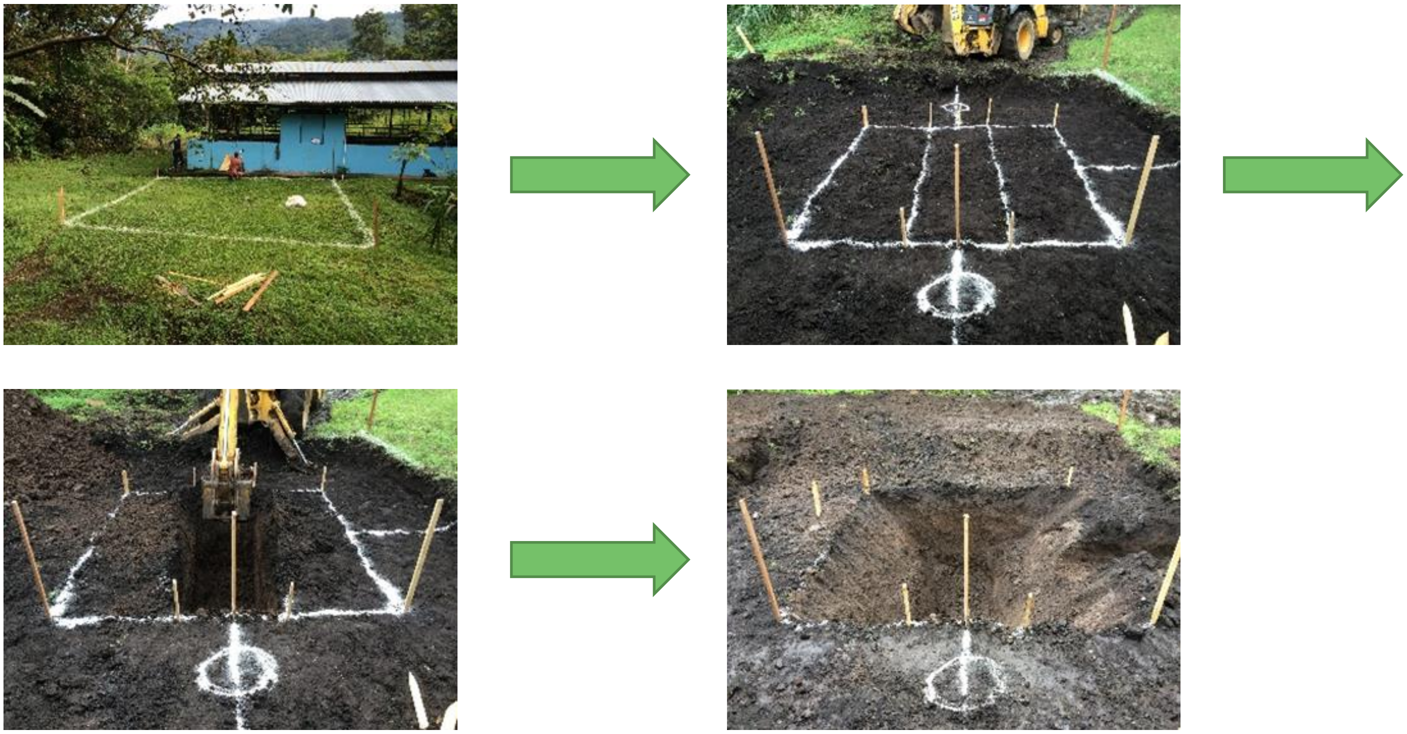


Figure 15: Steps for ditch excavation

Sometimes the water table is reached before the achieving the needed depth (p). If this happens, fill the ditch in with sand until there no longer is water and raise the retaining walls using adobes or sand bags (as if the biodigester will be installed above ground).

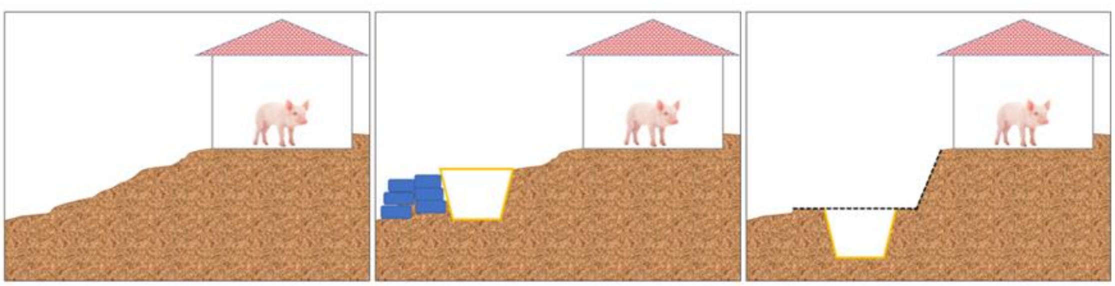


Figure 16: How to modify the ditch for different terrains

Once the ditch is excavated, make sure all the sides or smooth, holes are filled in and is root and rock free. The sides can be lined with mud, adobe, sandbags, or sheets of wood. Before the digester is installed, make sure to line the ditch with plastic or sacks to ensure it will not be punctured.

It is necessary to open two channels at each end of the ditch, where the inlet and outlet pipes will be seated. These channels are inclined (as slip or slide) at 45º and with a sufficient width for the 4” or 6” pipe to sit. These channels begin at half height of the depth of the ditch, and end at a distance equal to half the depth of the ditch (thus, 45º tilt is achieved).

If the biodigester is to be installed in an area that is known to flood, it is best to find a different install site, install it on the most elevated place of the property, or strap it down. When installing a digester in flood prone areas, strapping the digester down is necessary because as the floodwaters rise, the digester w float and potentially drift away with the current of the flood waters. To keep it from doing this, loose straps can be installed, allowing the digester to rise with the water but not float downriver.

5.4 Biodigester Construction

The construction process is more or less similar for all biodigester materials. If you have greenhouse tubular plastic it is necessary to install it as a double layer, while in the case of 500-micron polyethylene geomembrane only a single layer is needed, even though the tie of the tire tube must be tightened more.

When handling the plastic one must be careful as it is very delicate:

- Never drag the plastic roll or the cut plastic pieces.
- Be extremely careful when handling the plastic with the folds that form, rubbing with a rough surface will damage it.

First, make sure the area is free of debris and sharp objects and lay a plastic or canvas material on the ground to protect the digester during construction. Once you lay the biodigester on the protected area, make sure there is no damage. Cut the needed material length.

If using greenhouse plastic, cut a second piece the same length as the first. Then, open one of the plastic sheets so it has a tubular shape and insert the second material inside of it. To do this, a person without shoes or any other sharp material must walk the material from one end to the other while other people are holding the tube open at both ends. Repeat this process with the plastic rope (the jug should be filled with water and tied in the middle of the rope). Next, the two plastic sheets need to be aligned. To do this, put one person at each end holding the outer layer. Pull the inner layer in a rhythmic and coordinated fashion to one end and then another until the two sheets (and the seam) are aligned and wrinkle free and lying on the floor.

Figure 17: Double layering the greenhouse plastic

If using geomembrane, once the needed material is cut the rope needs to be installed inside the biodigester, walking it from one end to the other (the jug should be filled with water and tied in the middle of the rope). To do this a person without shoes or any other sharp material must walk the rope from one end to the other while other people are holding the tube open at both ends.

5.5 Biogas Outlet

The biogas outlet is located along the upper part of the biodigester, where the biogas dome is formed. It is usually one or two meters from the entrance of the biodigester but as long as it is along the upper part of the biodigester, it can be modified for convenience. To install the biogas outlet:

Figure 18: Flange for the biogas outlet

- Mark the install point with a marker.
- Prepare the flange

- Cut the install point of the biodigester with scissors by folding the area and bending it (it should be shaped like a tent). Make the cut small enough for the flange male end of the flange to pass though. It is better to cut smaller and larger as needed. With the greenhouse plastic, it may be necessary to have someone enter the biodigester to make sure both layers are cut evenly.

Figure 19: Steps to install the biogas outlet

- From the inside of the sleeve, insert the male end (with its packing) and the female end (with its packing) from the outside. The order goes like this: male – hard disk – soft disk – double layer of plastic or geomembrane – soft disk – hard disk – female
- Use Teflon tape to ensure the seal and adjust the connection using a pipe wrench (do not force the thread).

5.6 Biodigester Inlet and Outlet

Next, the biodigester inlet and outlet need to be installed.

- Cut the 6" (or 4") PVC pipe into two, 1.5-meter length pieces.
- Protect the edge of each pipe that will enter the biodigester either by smoothing it out with sand paper or by wrapping it with tire tube or tape.

Figure 20: How to prepare the inlet and outlet pipe

- Place a pipe at each end of the plastic sleeve, ensuring they are centered and on the inside of the biodigester (for geomembrane there should be a layer on top of the pipe and one on the bottom, for greenhouse plastic there should be two layers of plastic on the bottom and two on the top of the pipe). The pipe needs to be placed 80 cm inside the plastic sleeve (30 cm will be inside and 50 cm will be used to tie the biodgester to the tube). Use the marker to mark the 50 cm point from the edge of the plastic.

Figure 21: How to install the PVC inlet and outlet of the biodigester. 80 cm of the 90 cm pipe should be installed inside the biodigester (left), when wrapping the biodigester with tire tube, start 30cm from the inside part and wrap the other 50 cm (right)

- Pass the rope through the pipe at each end of the biodigester
- At the entrance side of the biodigester, begin folding both outer edges of the biodigester towards the 80 cm of PVC pipe. The folds should be done accordion style, in 10 cm folds. Normally four to six folds are sufficient on each side. The folds will be long and they should be done so each fold is 1 cm (more or less, below the next one, like a ladder). These folds are then folded over the center of the pipe. Make sure the pipe is still 80cm inside of the sleeve.
- Begin tying the sleeve to the pipe, starting at the 50 cm mark previously made on the plastic. 30 cm of pipe will remain inside the biodigester without tying.
- The tie is done with the tire tube using sufficient tension and overlapping the tubing with each rotation so no plastic can be seen. Completely cover the 50 cm of plastic and 8-10 cm more of the PVC pipe. Continue a few more turns and then tie the tire tube by tucking it tightly under one of tire wraps.
- Repeat this process at the exit end of the biodigester.

In the case of having used polyethylene geomembrane, the tie of the rubber on the pipe must be very tense and strong. Since it is a more rigid material, if the folds are not tied well, water can escape from the biodigester. To avoid this, make the tie extra tight. If necessary, clamps can be included (once everything is tied) to try to completely seal the folds.

Figure 22: Steps for biodigester inlet and outlet pipe installation

5.7 Biogas Relief Valve

The biogas relief valve makes a seal so when the biodigester reaches a certain maximum pressure the biogas can escape. It is an essential component in the biodigester.

Figure 23: Tubular biodigester relief valve

To install the relief valve:

- Install a Tee in the biogas conduction line with the bottom of the Tee facing down. It is usually 2-3 meters from the biogas outlet of the biodigester.
- On the lower part of the Tee place a 30 cm PVC pipe. The outlet of the Tee will go to where the biogas is consumed.
- The 30 cm pipe sits inside the 2-liter plastic bottle that is filled with water and forms a hydraulic seal. When the water level is determined (explained in the chart below) add pin-sized holes in the bottle at the indicated water level to remove any excess water (from rain or when too much water is added when refilling the bottle) and maintain the needed pressure.
- On the out end of the Tee, place the ball valve (always placed after the biogas relief valve in the case the ball valve is accidently closed the increased pressure in the biodigester can still be released).
- Add a pole to support the biogas relief valve or attach it to a wall if possible. Make sure there are no dips in the line between the biodigester and relief valve where water could accumulate (it is better to have it drain to the biodigester or into the relief valve).

The maximum pressure of the biodigester is determined by how much water the 30 cm pipe is submerged in. Table 17 below explains how deep the pipe should be submerged based on digester material.

Table 17: Biogas relief valve pressure based on biodigester material used

Material	Amount Submerged
Greenhouse plastic	15 cm of water column (the biogas pipe is inserted 15 cm into the water
Prefabricated biodigesters (PVC geomembrane)	Depends on manufacturer, but usually 5-8 cm
Polyethylene Geomembranes	No more than 20 cm
500-micron polyethylene welded tubular	15-20 cm

5.8 Moving the Biodigester into the Ditch

Now that the ditch is excavated and the biodigester is constructed it is time to move it into the ditch. With at least two people, even better with three, move the biodigester from the build site to the installation site, avoiding sharp objects or dragging the material. There will be one person at each end, carrying the stretched biodigester and as many people as available holding the middle of the biodigester.

Figure 24: Tubular biodigester ready to be moved to the ditch

- Gently place the biodigester into the ditch, making sure it is centered and there are no wrinkles (wrinkles can be removed in the next step by using the air pressure).
- Connect the biodigester to the relief valve.

5.9 Inflate the Biodigester with Air

Once the biodigester has been moved to the ditch, it needs to be inflated to make sure it fits correctly and eliminate any creases. To do this:

- Cover one pipe end of the biodigester with a piece of plastic (about 40 x 40 cm) or a plastic bag or sleeve, securing the piece of plastic with a tire tube.
- Fill the biodigester with air
    - If you have an electric blower and access to electricity, blow air into the end of the biodigester not covered in plastic. Add air until the biodigester is filled and the relief valve begins to bubble (sign that the maximum pressure has been reached, and air escapes through the relief valve).
    - If you do not have a blower or electricity access, the biodigester can be filled manually using 3 or 4 meters of tubular plastic. Attaching one end to the open biodigester pipe, vent the plastic sleeve by quickly opening and closing it, causing air to be trapped inside. Once full, push the air into the biodigester by rolling the plastic sheet. When refilling the sleeve with air, make sure to cover the inlet pipe so the air does not escape.

Figure 25: Inflated tubular biodigester

5.10 First Fill of Water

With the biodigester sitting in the ditch and full of air, it is time to fill it with water. Either using buckets or a hose, begin filling the biodigester (make sure the outlet end is propped up so the water cannot pour out. While filling the biodigester with water, remove any other wrinkles still present because s the water accumulates inside it will be too heavy to move the plastic. Fill the biodigester with water until the internal part of the inlet and outlet pipes are covered, creating a hydraulic seal, which will keep air from entering. You will also know it is sufficiently full of water as the relief valve will begin to bubble because the maximum pressure has been reached.

5.11 Inlet and Outlet Pipe Levels

Once the water seal is achieved, the levels of the inlet and outlet pipes of the biodigester must be determined.

- The outlet pipe height needs to correlate with the relief valve. This means if the relief valve is in 15 cm of water, the bottom of the outlet pipe must be 15 cm above the ground. Once the level is determined, the pipe can be fixed in place with stones or a rope.
- The mouth of the inlet pipe must be higher than the overflow level of the outlet pipe. Simply incline the pipe to make sure the biodigester contents will not leak out. Keep in place with stones or a rope.

Figure 26: Inlet and outlet pipe placement

5.12 Inlet and Outlet Pipe Protection
Once the inlet and outlet pipe levels are determined, the tire tubing connecting the biodigester bag to the PVC pipe needs to be covered with a piece of plastic to protect it from solar radiation. The solar radiation can easily deteriorate the tire tubing in a few months

5.13 First Fill with Manure
Now that the hydraulic water seal is created, the biodigester can be filled with manure.

- If the user has accumulated manure beforehand, this can be put inside the biodigester by mixing it with enough water so it easily flows into it. An amount for the initial load is 80-100 kg (about two wheelbarrows) of manure. This initial load helps the biodigester start producing biogas beforehand.
- If manure is not accumulated the day before, the biodigester can be filled every day with the daily load for which the digester is designed. This process takes a little longer to produce biogas but also works.

Adding manure to the biodigester will begin the decomposition process of the manure but the liquid inside will not yet reach the overflow outlet. As the biodigester is loaded every day, the level will rise and eventually overflow from the outlet pipe. This may take several weeks.

5.14 Biodigester Protection
It is strongly recommended to protect the biodigester on the same day of installation to keep animals and thieves out, as within the first few weeks, most biodigesters are damaged due to these reasons. To protect it, a fence of mesh and poles can be installed or adobe walls.

It is also recommended to install a cover to protect from solar radiation, falling branches and other materials. In hot regions, where the support of the sun is not necessary to heat the biodigester, zinc roofing or opaque materials are suggested. In cooler areas, transparent materials or porous materials are better.

5.15 Biogas Conduction
Biogas conduction can be done with polyethylene tubing irrigation or in rigid PVC pipe typically used for water. Normally ½" diameter material works best for a domestic biodigester. For biodigesters larger then $10m^3$ or the biogas is traveling a long distance to the point of consumption, ¾" may be better. Install is usually done when the biodigester is already producing biogas, although it can be done earlier. The biogas conduction line runs from the relief valve to the point of biogas use.

5.16 Water Condensation Purge Valve
It is important to remember that in the pipeline the water vapor that accompanies the biogas can be condensed at any "cold" point. This is difficult to predict and is important to install the conduction line with a slope so the condensed water can drip to a low point and be purged. A point at which the water can fall is to the relief valve itself, and at the other low points it is convenient to place a tee and a stopcock. The stopcock will always remain closed and will only open from time to time to

Figure 27: Water condensation purge valve

let out the condensed water that has accumulated at that low point.

It is recommended that the biogas line be raised high enough to not obstruct the passage of personnel and animals at any time. Also, make sure to avoid the use of elbows, since the more there are, the more biogas pressure loss will occur.

5.17 Hydrogen Sulfur (H_2S) Filter

Biogas is mainly composed of methane and carbon dioxide, but also carries some H_2S. Hydrogen sulfide at high levels can be toxic and also corrodes metal elements (which is why all of the installations are plastic). When the biogas is used on the small scale, such as for cooking, it is enough to add a simple hydrogen sulfide filter. The filter is installed in the conduction line, close to the kitchen and consists of oxidized iron wool.

Since the H_2S component of the biogas is what corrodes metals, it needs to be removed. This is done with pre-oxidized iron wool. The iron wool absorbs the H_2S so it cannot pass to the kitchen.

- Find the point of installation, usually 1-2 meters from the kitchen or stove
- The filter starts with a ball valve, followed by a universal joint, a piece of pipe about 30cm, and another universal joint.
- Sometimes a pipe with a diameter larger than the conduction line is used (1" for example). This can be done using adapters between the universal joints.
- The iron wool is usually found in hardware stores and needs to be pre-oxidized. This can be done by placing it in vinegar overnight.
- The iron wool sits in the pipe between the two universal unions. It is important to not compact the iron wool into the pipe, but to keep it loose enough for the biogas to pass through it.
- The iron wool needs to be replaced when the user begins to notice an unpleasant egg-like smell in the kitchen. This smell is indicative of the presence of H_2S and that the filter needs to be changed. To change it, close the ball valve and open the two universal unions. Remove the iron wool and replace it with pre-oxidized material (this can be done beforehand and stored). The more the kitchen is used the more it will need to be changed.
- In large systems the filter can be made larger (for example, 0.5 m long and 2" in diameter pipe).

5.18 The Stove

Normal liquid propane (LPG) stoves can be adapted to biogas. LPG stoves are designed to work at pressures that are higher than those produced by biodigesters. They have an injector or diffusor, which is a very small duct just after the burner tap, which injects the LPG to the burner and mixes it with air and helps create a more suitable mixture for consumption. To adapt an LPG stove to use biogas there are two options:

- The injector is removed (it is a threaded piece) and the air mixture is reduced
- The duct of the injector is enlarged with a drill (around 3 mm in diameter) and the air mixture is adjusted to 50% or less.

Figure 28: Stove burner installation

These are general ideas that work in adapting LPG stoves to biogas, but the opening for mixing with air really depends on the pressure of the biogas that is being used and the height above sea level.

There are also traditional burners on the market that can be purchased at hardware stores and can be connected directly to the biogas line but are less efficient than adapted LPG stoves.

6. Daily Operation

The operation of the biodigester is simple:
Each day the biodigester must be charged with the daily load defined in the design. When loading the digester, make sure no leaves, straw, branches, or sand enter the interior the biodigester. To help prevent this, a concrete box is installed to mix the water and manure before being fed via gravity into the biodigester. A concrete box can also be installed at the exit of the biodigester to hold the biol.

In the exit pipe, on days when mixture is not loaded, the biodigester contents can form a crust or hard cover, making it difficult to unload the biol. This hard layer can be broken using a stick or pipe (be careful to not rip the biodigester when doing this).

If a biodigester is loaded with more than it was designed, it is said to have "diarrhea", and the biol that comes out will be fresh and smelly and less biogas will be produced. Moreover, it may be the case that "indigestion" occurs and the biodigester is acidified. If this occurs, it is recommended to stop loading the biodigester for a week, and start loading it the following week with half the load established in the design, and see how it reacts.

If a biodigester is loaded with less than the established design amount, it is said to be on a "diet" and will produce less biogas (less raw material enters to produce biogas). On the other hand, it will produce good quality biol, but less quantity. A biodigester can be maintained on a diet throughout its useful life, but it cannot be expected to produce the estimated biogas and biol quantities from the original design.

7. The First Biogas Production

Normally in hot climates biogas will be produced in two or three weeks, while in cold climates this can be delayed up to three months. But how does one know if biogas is being produced?

If the biodigester is left full of air, it is normal that in the following days the biodigester will appear somewhat deflated, and a few days later it will inflate again. The relief valve will then start to bubble, especially on warm days, indicating biogas is being produced. If the dome only lowers, there is probably a leak somewhere and the digester needs to be reviewed for leaks, starting with the biogas outlet and going to the relief valve.

When the dome is inflated (ONLY if the dome is well inflated) a combustion test can be conducted using the ball valve located after the relief valve. It is very important to ensure that the dome is inflated, and that the biogas will come out. Open the valve a little, making sure no one is in directly in front of it and using a lighter see if the biogas will light (be careful because there can be a lot of pressure and a powerful flame can rise up to one meter).

- If the biogas ignites and the flame is maintained, it means that everything goes well and can be used in the kitchen or at the point of consumption.
- If the biogas is ignited but not maintained, it is necessary to try to regulate the flow a little with the ball valve. If this continues, it means that the biogas is not ready to use and the test should be redone next week.
- If the biogas does not ignite, it means that we are producing CO_2, not methane. You have to be patient and always give at least one month in warm weather from the first load, and up to three months in cold climates.

If after a thoughtful start time the biogas does not ignite, it is advisable to stop feeding the biodigester for a week. After a week, begin loading it with half the daily load, and see how it reacts. If the biodigester is not producing and pig manure is the source, try mixing in cow manure as well as it is more stable and the bacterial consortium is more robust.

8. <u>The First Biol Production</u>

If the biodigester was only filled as described above (with water until the hydraulic seal of the inlet and outlet pipes and 80-100 kg of manure), it would have been full to one third of its liquid capacity. Therefore, with the successive daily loads the biodigester will accumulate material (manure plus water) but will not over flow. It will take several weeks to get it to overflow (around two thirds of the design retention time of the biodigester).

When the first overflow occurs, it will be biol. The quality of this initial biol is not assured, because the biodigester and the bacterial consortium that inhabits it will not yet be stabilized. As a general rule, it is said that when biogas is being produced, there will be good biol. The quality biol is characterized by not having an odor reminiscent of fresh manure and it does not attract insects, mainly flies.

From here you can start using the biol. If the user decides to store the biol in a concrete pool, make sure it is properly covered or it will not be as effective (the nitrogen will dissipate).

9. <u>Maintenance</u>

In addition to daily, regular feeding of the digester, there are three central actions in the maintenance of the biodigester:

- Make sure the relief valve has enough water to keep the pipe properly submerged in the water as many centimeters as desired. If water has evaporated, add more.
- Purge the condensed water in the conduction line. If the user hears noise in the pipe when cooking or if the flame goes back and forth from small to large, it is an indicator water is in the line. Another indicator is when the biodigester is inflated and the valves that allow the biogas to reach the kitchen can be opened but no biogas comes out, there is likely a water obstruction. Purge the water from the condensation purge valve.
- Change the hydrogen sulfide trap. When the user notices a rotten egg smell or their mouth has a metallic (indicators of hydrogen sulfide), this means the iron wool needs to be changed. Close the valve before the filter, remove the universal unions, remove the iron wool and replace it with pre-oxidized (rusted) wool. Remember, always have pre-oxidized iron wool on hand, and it can easily be oxidized by placing it in vinegar overnight.

10. Extra Details

10.1 Recirculating the Biol

The biodigester is usually loaded on a daily basis, but there are cases where it is not, which is not a problem. For a biodigester to function correctly, frequent loads are required but they can be daily, every two days or weekly. As long as the total volume being added to the digester on a weekly basis is known, the daily load can be averaged to correctly size the digester. For example, a biodigester is loaded three times a week with 100 kg of manure and 300 liters of water (400 liters total). This makes a total of 12000 liters a week and a daily average of 1200/7=171.4 liters. The biodigester will be designed using the average daily load of 171.4 liters.

10.2 Time without Loading the Biodigester

Once a biodigester is in operation it is difficult to "kill" it. If it is no longer being fed, it will stop producing biogas for a few days until there is no longer raw material for the bacteria to break down. When there is no longer any raw material, the bacterial consortium enters "hospitalization" and the biodigester can be maintained like this for a few months. When a manure load is made again (even if it is six months later) the biodigester will react in a few days returning to produce biogas. Therefore, if a biodigester has not been loaded for a while, it is not necessary to empty it to restart the process.

10.3 Biol Use Recommendations

The biol can be applied as a fertilizer to all types of crops, grasses, fruit trees, flowers, gardens, etc.

It is most easily used in irrigation, especially when the biol can flow via gravity to the crops, following a pipe, channel or canal. It can also be used in drip irrigation (must be filtered beforehand), or in sprinkler, pump or tractor irrigation.

The biol can be applied to the leaves of the plant (foliar applications) using a backpack. Do make sure to filter the biol through fabric or netting before filling up the backpack as large particles can block the spray nozzle. For foliar application it is recommended:

- Do not dilute the biol in the backpack, as it is already diluted.
- Apply the biol when there is minimum sun (early morning or late afternoon)
- Do not apply the biol when the crops are flowering because the biol has a certain repellent effect that would scare off the pollinating insects. Only apply the biol during the growth of the plant, stop while it is flowering, and then continue again when the fruit starts forming.
- Do not apply biol 15 days before harvesting the crops or introducing animals to pasture. If biol is applied, make sure to sanitize the fruits (the sun and weather can also help kill possible pathogens). If animals are set to pasture and biol has recently been applied, this can be problematic because cows do not like the smell and one must wait until it washes away for the cows to pasture.
- It has been seen that the higher the frequency of application, the better results (in field trials up to weekly applications). It is recommended to apply the biol at least twice: once before flowering and once after the fruit is forming.
- If frost is expected, foliar application of the biol can help protect the plant from frost damage as it helps the plant recover. Also, apply the biol immediately after the frost.

11. Examples

Example 1

A family lives in the Bolivian highlands and has 10 milking cows that they milk every day. The ambient temperature is cold, with nights in winter when it freezes, and average temperatures around 10ºC. The cows weigh around 450 kg each and spend 2 hours every day in the milking parlor. What biodigester size would be best and how much biogas and biol will it produce?

The first thing is to determine the volume of the biodigester, the daily load and the retention time.

To estimate the daily load of the biodigester, the daily manure is first calculated. For this, it is considered that each cow, for every 100 kg of live weight, will produce 8 kg of manure per day (see Table 2). Therefore, each cow of 450 kg of weight will produce 8 x (450/100) = 36 kg/d of fresh manure. For a family that has 10 cows, they will produce 36x10 = 360 kg/d of manure. We are told that the cows spend 2 hours a day in stables, so to calculate the manure available, and making use of Table 4:

$$Manure\ available = \left(\frac{nº\ hours\ stabled}{24\ hours}\right) \times daily\ manure$$

There are (2/24) x 360 kg = 30 kg of manure available per day.

Because it is cow manure, according to Table 4, it is necessary to mix manure: water 1: 3, that is, it will be necessary to add 30x3 = 90 liters of water to the 30 kg of manure, making a daily load of 120 liters per day. In this way, it will also produce 120 liters of biol per day.

Being in such a cold climate it is convenient to implement solar passive heating design: using dark colors, isolating the ditch and putting the biodigester in a compact greenhouse. By doing this, according to Table 6 the biodigester can achieve working temperatures of 13 to 17ºC.

Referring to Table 7 for cow manure, 90 days of retention time is recommended with a potential to produce 31 liters of biogas per kg of fresh cow manure.

To calculate the amount of biogas that is expected to be produced, the value of 31 liters of biogas per kg of fresh cow manure is used. Therefore, if 30 kg of cow manure enter each day, it is expected to produce 30x31 = 930 liters of biogas per day.

With 120 liters of daily load and 90 days of retention time, making use of Equation 1, we have 120x90 = 10800 liters of liquid volume of biodigester or 10.8 m^3 of liquid volume.

The liquid volume can be used to calculate the dimensions of the biodigester using the materials available. Using Table 15:

C (m)	r (m)	a (m)	b (m)	p (m)	A_{ditch} (m^2)	L (m)	D (m)	L/D
2	0.32	0.40	0.50	0.50	0.225	48.0	0.64	75.4
3	0.48	0.60	0.80	0.75	0.525	20.6	0.95	21.5
4	0.64	0.80	1.05	1.00	0.925	11.7	1.27	9.2
5	0.80	1.00	1.30	1.25	1.438	7.5	1.59	4.7

6	0.95	1.15	1.60	1.45	1.994	5.4	1.91	2.8
7	1.11	1.35	1.80	1.70	2.678	4.0	2.23	1.8
8	1.27	1.55	2.10	1.95	3.559	3.0	2.55	1.2
9	1.43	1.75	2.35	2.20	4.510	2.4	2.86	0.8
10	1.59	1.95	2.60	2.45	5.574	1.9	3.18	0.6
14	2.23	2.75	3.65	3.45	11.040	1.0	4.46	0.2

Looking at the L / D ratio, the biodigester with a circumference of 4 (length 11.7) gives a L / D ratio between 5 and 10, making it the most suitable biodigester. The ditch dimensions are: lower width (a) of 0.8, upper width (b) of 1.05 and depth (p) of 1 m.

Example 2
A producer has a pig farm in a warm region, with average temperatures of 25ºC. It has 5 mother sows of 100kg each, 30 young pigs of 30kg each, 30 piglets of 2 kg each, and 20 pigs ready for sale with 50 kg of weight each. What biodigester size should be proposed and how much biogas and biol will it produce?

In the case of farms where there are animals of different weights, it is best to make a table (as done for the example in section 1.3) to determine the daily manure.

Pigs	# of animals	Average weight (kg)	Kg of manure produced per daily per 100 kg of live weight (kg)	Live weight (kg)	Daily manure produced (kg)*
Mother	5	100	4	500	20
Young	30	2	4	60	2.4
Piglet	30	30	4	900	36
For sale	20	50	4	1000	40
			TOTAL (kg)	2460	98.4

Based on this information, there is 98.4 kg of manure per day, and because the pigs are always stabled, it corresponds to the available manure.

Because it is pig manure, according to Table 4, a mixture of manure: water of 1: 4 is necessary. Therefore 98.4x4 = 393.6 liters of water will be necessary, which form a daily load of 98.4 + 393.6 = 492 liters per day.

Being in a warm region (average temperature of 25ºC), and according to Table 7, no solar design is required and the biodigester works at that same temperature. According to Table 8, for pigs living at 25°C, 35 days of retention time is needed, with a potential to produce 61 liters of biogas per kg of pig manure introduced to the biodigester. With the average daily manure produced is 98.4 kg, a total of 6,000 liters of biogas will be produced per day.

Therefore, having a daily load of 492 liters and a retention time of 35 days, the liquid volume of the biodigester will be 492x35 = 17220 liters or 17.22 m^3.

Once the required liquid volume is known, it is time to shape it. If the standardized plastic and ditch dimensions of Table 11 are taken, the table below is constructed:

C (m)	r (m)	a (m)	b (m)	p (m)	A_{ditch} (m^2)	L (m)	D (m)	L/D
2	0.32	0.40	0.50	0.50	0.225	76.5	0.64	120.2
3	0.48	0.60	0.80	0.75	0.525	32.8	0.95	34.3
4	0.64	0.80	1.05	1.00	0.925	18.6	1.27	14.6
5	0.80	1.00	1.30	1.25	1.438	12.0	1.59	7.5
6	0.95	1.15	1.60	1.45	1.994	8.6	1.91	4.5
7	1.11	1.35	1.80	1.70	2.678	6.4	2.23	2.9
8	1.27	1.55	2.10	1.95	3.559	4.8	2.55	1.9

9	1.43	1.75	2.35	2.20	4.510	3.8	2.86	1.3
10	1.59	1.95	2.60	2.45	5.574	3.1	3.18	1.0
14	2.23	2.75	3.65	3.45	11.040	1.6	4.46	0.4

In this case there is a single biodigester that gives an L / D ratio that is between 5 and 10. This corresponds to using a plastic of circumference 5, ditch of length 12 m, and dimensions of a = 1m, b = 1.3 and p = 1.25, to achieve 17.22 m3 of liquid volume.

But what happens if you do not have plastic of that circumference? It could happen that there is no plastic of 5 m in circumference and there is no option to manufacture them in PVC or polyethylene geomembrane. In this case, for example, you can consider using the plastic of 4 m in circumference, which is usually the most available in the markets. According to the table above if this plastic is used, a biodigester of 18.6 m in length is required, giving an L / D = 14.6, which is much higher than the acceptable range for tubular biodigesters.

One option is to divide the system into two biodigesters (or three, or as needed) and connect them in series, one after another. The biodigesters connected in series work as a single biodigester, since only the first biodigester is loaded, and the overflow of biol from the first biodigester will feed the second and so on. The complete system will maintain the total retention time, but each biodigester will complete only half of the process.

Following the example, if the required liquid volume of 17.22 m^3 is divided between two biodigesters (which will be placed in series), it implies that each biodigester will have 8.61 m^3. If the table above is redone, using this volume and the plastic of circumference 4m, it gives:

C (m)	r (m)	a (m)	b (m)	p (m)	A_{dicth} (m^2)	L (m)	D (m)	L/D
4	0.64	0.80	1.05	1.00	0.925	9.3	1.27	7.3

With two biodigesters 9.3 m long each, manufactured with a plastic of circumference 4 m, each one has to achieve an L/D of 7.3, almost at the optimum value of 7.5.

Example 3
An elderly couple has two oxen (1000kg each) that live in the warm valleys where the average temperature is 20ºC. The couple wants a biodigester to cook about two and a half hours a day. What biodigester dimensions do you propose and how much biogas and biol will it produce?

In this case, we start with a biogas requirement, and we will have to see if the manure produced by their oxen is sufficient.

The family requires 2.5 hours of biogas for cooking, but to be conservative the calculations are made for 3 hours of cooking. According to Table 9, a domestic kitchen consumes 300 liters of biogas per hour, so this couple requires 300x3 = 900 liters of biogas per day.

They have oxen, which for the case is similar to cows. They live in the warm valley at an average environmental temperature of 20ºC which, according to Table 6 is a valley. Using Table 7, the retention time is determined to be 65 days with 33 liters of biogas produced per day per kg of manure.

If the family needs 900 liters of biogas per day, it means that 900/33 = 27.3 kg of fresh manure per day will be needed. To make sure the oxen produce enough manure, calculate the amount of manure available per day. The weight of the oxen are 1000kg, producing a total of 160kg of manure per day. If the animals sleep near the house, only 25% of this manure can be collected, which means 40 kg/d of available manure per day, more than enough for the family's requirements (40kg produced per day > 27.3kg per day required).

From here the digester can be sized based on the required manure needed per day (27.3 kg) or the manure available per day (40 kg). This can be based on the interest in treating all the collected manure, the budget and the digester install space available.

In this example, the family wants to treat all the manure they collect, which will also increase the biogas they have available to cook with.

With the manure: water ratio 1: 3, it means a daily load of (40 + (40 x 3))= 160 l/d. Considering a retention time of 65, the required liquid volume is (65 x 160)= 10400 liters, that is, 10.4 m^3.

Using the required liquid volume, it is time to shape the digester. If the standardized plastic and ditch dimensions of Table 11 are taken, the table below is constructed:

C (m)	r (m)	a (m)	b (m)	p (m)	A_{ditch} (m^2)	L (m)	D (m)	L/D
3	0.48	0.60	0.80	0.75	0.525	19.80	0.96	20.63
4	0.64	0.80	1.05	1.00	0.925	11.24	1.28	8.78
5	0.80	1.00	1.30	1.25	1.438	7.23	1.6	4.52

Looking at the L / D ratio, the biodigester with a circumference of 4 (length 11.24) gives a L / D ratio between 5 and 10, making it the most suitable biodigester. The ditch dimensions are: lower width (a) of 0.8, upper width (b) of 1.05 and depth (p) of 1 m.

Example 4
An NGO receives a tubular biodigester 7 meters in circumference and 12 meters long and wants to know where it should be installed. With what amount of manure and water do you need to load the biodigester and how much biogas will it produce?

The answer to the question will depend on two things, the working temperature of the biodigester (and therefore the climate and if it has a passive solar design) and the type of manure with which it is loaded.

The first thing is to calculate the liquid volume of a biodigester that is 12 m long and 7 m in circumference. Taking the value of the vertical area of the ditch recommended for a circumference of 7 m from Table 11, we have that A_{ditch} = 2.678 m^2, and using Equation 10 that says $V_L = A_{ditch} \times L$, the liquid volume of this biodigester can be calculated which will be 2.678x12 = 32 m^3.

To see if the biodigester meets the tubular biodigester criteria, calculate the L/D ratio. The diameter of a circumference of 7 m will be twice its radius (Equation 8), and its radius according to Table 11 is 1.11 m. Therefore, the diameter will be 1.11x2 = 2.22 m and the L/D ratio will be 12/2.22 = 5.4 which is in the range of 5 to 10 for tubular biodigesters.

Suppose we want to see how a biodigester with 32m^3 of liquid volume would work in valleys where dairy is made. The valleys have an average environmental temperature of 14 to 18ºC, and according to Table 6 it is important to consider solar design and the biodigester will have a working temperature around 18-22ºC more or less. In the case of cow manure, at that working temperature, according to Table 7, 65 days of retention time is recommended, with a potential of 33 liters of biogas per kg of cow manure entering the biodigester.

Then, if you have a tubular biodigester with 32 m^3 of liquid volume (that is, 32000 liters), and works at a temperature that requires 65 days of retention time, going back to Equation 1 the daily load is:

$$DL = \frac{V_L}{RT} = \frac{32000}{65} = 492.3\ liters\ per\ day$$

Being cow dung, and according to Table 3, the mixture ratio is 1: 3. Therefore, if the daily load is divided into four parts, one part will be manure and three will be water. Therefore, if the daily load is divided by 4, the amount of manure in it will be obtained, which in this case is 492.3 / 4 = 123.1 kg/d of fresh cow dung. If this value is multiplied by 3 you have the amount of water, which will be 123.1x3 = 369.2 liters. Thus, the 123.1 kg of manure plus the 369.2 liters of water gives a daily load of 123.1 + 369.2 = 492.3 liters.

Those 123.1 kg/d of cow manure, which have a potential to produce 33 liters of biogas each, imply that the biodigester will produce 123.1x33 = 4061.5 liters of biogas per day.

How many cows will be needed to feed the biodigester? 123.1 kg of available manure per day are required. Let us suppose that in these valleys the cows spend 2 to 3 hours a day for milking. In this case, let us consider 3 hours of stabling. From Table 3 we can draw the following equation:

$$Manure\ available = \left(\frac{nº\ house\ stabled}{24\ hours}\right) \times daily\ manure$$

In this case, we know the manure available and the hours stabled, and what we need to know is the daily manure:

$$Daily\ manure = \left(\frac{24\ hours}{nº\ hours\ stabled}\right) \times manure\ available$$

Thus, the daily manure produced in 24 hours so that in 3 hours 123.1 kg will be produced, will be (24/3) x123.1 = 984.8 kg. To know how many cows are needed to produce that daily amount of manure in one day, we use the value in Table 2 of 8 kg of manure per 100 kg of live animal weight. In this case, to produce 984.8 kg of manure, (984.8 / 8) x100 = 12310 kg of live weight is needed. If we assume dairy cows of 450 kg, those 12310 kg of live weight will equal 12310/450 = 27.4 cows.

Then, the biodigester, 12 meters long and 7 meters in circumference, can be installed with solar design on a farm in the valley region where about 27 cows are milked a day and are housed for 3 hours a day. Under these conditions, the biodigester will produce about 4m^3 of biogas per day.

What can be done with that amount of biogas? These 4000 liters of biogas produced daily, is energetically equivalent to 3 liters of gasoline per day or 6.4 kg of firewood per day, according to Table 8. The farm could use it in multiple ways, using the consumptions per hour of reference of different devices shown in Table 9.

For example: using 1200 liters to cook 4 hours a day (300 liters per hour), have a gas refrigerator on 24 hours with an average consumption of about 1200 liters per day (50 liters per hour), turn on a small pump (1 hp of water three hours a day for 1200 liters more, 400 liters per hour), or turn on a biogas lamp for 3 hours using 360 liters of biogas (120 liters per hour).You could also use it to power a 15 hp mechanical milking machine for an hour and a half for 3250 liters (2500 liters an hour), leaving a surplus of 750 liters, which if you use a rice cooker (140 liters of biogas per hour) to cook will be good for you. It could also generate electricity with a 1.2 kW generator for 5 hours, using 3000 liters of biogas per day (600 liters per hour), and leave the remaining 1000 liters to cook each day.

12. Table Guide

Table 2: kg of manure produced daily based on animal type

Animal	kg of manure produced per day per 100kg of live weight $(\mathbf{kg/d})$
Cow	8
Pig	4
Goat/sheep	4
Rabbit	3
Horse	7
Adult	0.4 kg per adult
Child	0.2 kg per child

Table 3: Calculation of manure available

Case	Manure Available
Stabled 24 hours	$= daily\ manure$
Stabled only at night	$= 0.25 \times daily\ manure$
Stabled only a # of hours	$= \left(\frac{\#\ hours\ stabled}{24\ hours}\right) \times daily\ manure$

Table 4: Mix of water for daily load to biodigester

Manure	Ratio manure: water
Cow	1:3
Pig	1:4
Llama/sheep/guinea pig	1:8-9

Table 5: Relationship between ambient temperature and retention time recommended to achieve acceptable biogas production

Temperature		Retention Time (RT)
ºC	ºF	
35	95	25-30 days
30	86	30-40 days
25	77	35-50 days
20	68	50-65 days
15	59	65-90 days
10	50	90-125 days

Table 6: Biodigester working temperature

Eco region (altitude, meters above sea level)	Ambient Temperature		Working Temperature of Biodigester (ºC)				
	ºC	ºF	Biodigester without Passive Solar Design		Biodigester with Passive Solar Design		Criteria
			ºC	ºF	ºC	ºF	
Warm Tropical (<300)	28-32	82-90	28-32	82-90	Solar design not needed		----
Tropical (300-1,000)	23-27	73-81	23-27	73-81	Solar design not needed		----
Valley (1,000-2,000)	18-22	64-72	18-22	64-72	23-27	73-81	Dark color + ditch insulation
High Valley (2,000-3,000)	13-17	55-63	13-17	55-63	18-22	64-72	Dark color + ditch insulation + greenhouse
Highlands (3,000 – 4,500)	8-12	46-54	8-12	46-54	13-17	55-63	Dark color + ditch insulation + greenhouse

Table 7: Retention time and Biogas Production based on Working Temperature of Biodigester

Working Temperature of Biodigester		Fresh Cow Manure		Fresh Pig Manure	
ºC	ºF	Retention Time (days)	Biogas* (l/kg)	Retention Time (days)	Biogas* (l/kg)
33-37	91-99	30	39	25	71
28-32	82-90	40	38	30	67
23-27	73-81	50	35	35	61
18-22	64-72	65	33	50	59
13-17	55-63	90	31	65	54
8-12	46-54	125	29	90	50

*The biogas is expressed for 25ºC and 1 atmosphere of pressure, assuming 65% methane content (CH_4). The biogas produced per kilogram of fresh manure is referential, and really should apply a range of +/- 10%, to be able to consider the different factors that can affect it (moisture of manure and animal diet).

Table 8: Energy equivalents to biogas	
1000 liters ($1m^3$) of biogas is equivalent to:	
5,647 kcal	Energy (65% CH_4)
6,056 kWh	Energy (65% CH_4)
1.6 kg	Wood
1.2 kg	Dry Manure
1.1 liters	Alcohol
0.75 liters	Gasoline
0.65 liters	Gas-oil
0.76 m3	Natural Oil
0.7 kg	Carbon
3.3 kWh_t	Heat (65% CH_4; 50% performance)
2 kWh_e	Electrical (65% CH_4; 30% performance)

Table 9: Biogas consumption per hour based on use

Biogas Use	Consumption of Biogas (l/h)
Domestic stove	300
Industrial stove	450
Pig heater	300
Lamp (equivalent to 60W)	120
Rice cooker (2L)	140
Water boiler (14 kW)	2,500
Water boiler (26 kW)	5,000
Refrigerator (100L)	30 (in a cold zone)
	75 (in a hot zone)
Motor < 5hp (per 1hp)	400
Motor > 5hp (per 1hp)	250
Milking machine (15hp)	2,500
Generator (1.2 kW)	600
Generator (3 kW)	2,100
1kWh electricity (5 - 20 kW)	1,600

BIOGAS DIGESTER DESIGN – USEFUL TABLES

Table 10: Biodigester lengths based on circumference						
Circumference (m)	**Roll Width (m)**	**Radius (m)**	**Diameter (m)**	**Longitude of Tubular Biodigester**		
				Minimum (m)	**Maximum (m)**	**Optimum (m)**
2	1	0.32	0.64	3.2	6.4	4.8
3	1.5	0.48	0.95	4.8	9.5	7.2
4	2	0.64	1.27	6.4	12.7	9.5
5	2.5	0.80	1.59	8.0	15.9	11.9
6	3	0.95	1.91	9.5	19.1	14.3
7	3.5	1.11	2.23	11.1	22.3	16.7
8	4	1.27	2.55	12.7	25.5	19.1
9	4.5	1.43	2.86	14.3	28.6	21.5
10	5	1.59	3.18	15.9	31.8	23.9
14	7	2.23	4.46	22.3	44.6	33.4

Table 11: Trapezoidal ditch dimensions based on biodigester circumference							
Biodigester Tube		**Trapezoidal Ditch**			**A_{ditch} (m^2)**	**A_{biogas} (m^2)**	**A_{total} (m^2)**
C (m)	**r (m)**	**a (m)**	**b (m)**	**p (m)**			
2	0.32	0.40	0.50	0.50	0.225	0.056	0.28
3	0.48	0.60	0.80	0.75	0.525	0.131	0.66
4	0.64	0.80	1.05	1.00	0.925	0.231	1.16
5	0.80	1.00	1.30	1.25	1.436	0.359	1.79
6	0.95	1.15	1.60	1.45	1.994	0.498	2.49
7	1.11	1.35	1.80	1.70	2.678	0.669	3.35
8	1.27	1.55	2.10	1.95	3.559	0.890	4.45
9	1.43	1.75	2.35	2.20	4.510	1.128	5.64
10	1.59	1.95	2.60	2.45	5.576	1.394	6.97
14	2.23	2.75	3.65	3.45	11.040	2.760	13.80

Table 15: Comparison of optimum digester measurements based on circumference								
C (m)	**r (m)**	**a (m)**	**b (m)**	**p (m)**	**A_{dich} (m^2)**	**L (m)**	**D (m)**	**L/D**
...	**...**	**...**	**...**	**...**	**...**	**V_L/ A_{ditch}**	**2 x r**	**L/D**
...	**...**	**...**	**...**	**...**	**...**	**V_L/ A_{ditch}**	**2 x r**	**L/D**
Yellow: standard values								
Grey: to be calculated								

13. Operation and Maintenance Manual

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TUBULAR BIOGAS DIGESTER OPERATION AND MAINTENANCE MANUAL

Daily Biodigester Load:

Manure:	
Water:	

Daily Operation:

- Load the digester with the daily mix, making sure there no leaves, straw, branches or sand entering the biodigester.
- Remove the same amount of biol as the daily mix being added, putting it on plants as a fertilizer.
- If no daily load is being added, mix the biodigester using the rope to make sure a hard crust does not form on the outlet pipe.
- Check the biogas relief valve, making sure the correct water level is maintained and the pipe is properly submerged.

Weekly Monitoring:

- Walk around the biodigester, making sure there are no objects that can possibly puncture the digester
- Check the condensation relief valve for built up condensation by removing the stopper and removing water as needed.

Troubleshooting:

-The biol smells like manure: this occurs when the biodigester is being loaded with more manure and water mixture then what it was designed for. If this happens, stop loading the digester for a week and start loading it the following week with half the load established in the design, see how it reacts. Overloading the digester also causes less biol to be produced

-The manure to water design load is not being reached: if the amount of manure and water mix is less than what the digester was designed for, less biogas will be produced (biol will be better quality but les quantity). A biodigester can be maintained like this throughout its life but expect less biogas and biol production.

-The biogas smells like rotten eggs or the person who is cooking has a metallic taste in their mouth: it is likely the iron wool in the hydrogen sulfide trap needs to be replaced. Close the ball valve located before the hydrogen sulfide trap, open the two universal unions and remove the iron wool. Replace the iron wool with pre-oxidized iron wool (iron wool placed in vinegar overnight). Reinstall the hydrogen sulfide trap and open the ball valve.

-The pipe is making a noise or the burner flame size is inconsistent (back and forth from large to small): this is an indicator that water is in the line. Remove the water from the biogas line by removing the plug from the condensation purge valve.

-The biodigester is inflated but biogas is not coming out of the stove: this is another indicator of water being in the biogas line. Remove the water from the biogas line by removing the plug from the condensation purge valve.

-All the animals were sold: once a biodigester is in operation it is difficult to kill it. If the biodigester is no longer being loaded with manure and water mixture, biogas will no longer be produced. The digester can remain in a resting state for a few months. When the manure and water mixture is available again, it will take a few days for the digester to begin producing biogas. If the biodigester has not been loaded for more than a few months, it is necessary to empty it and restart the process again.

Biol Use Recommendations

The biol can be applied as a fertilizer to all types of crops, grasses, fruit trees, flowers, gardens, etc.

It is most easily used in irrigation, especially when the biol can flow via gravity to the crops, following a pipe, channel or canal. It can also be used in drip irrigation (must be filtered beforehand), or in sprinkler, pump or tractor irrigation.

The biol can be applied to the leaves of the plant using a backpack. Do make sure to filter the biol through fabric or netting before filling up the backpack as large particles can block the spray nozzle. For leaf application it is recommended:

- Do not dilute the biol in the backpack, as it is already diluted.
- Apply the biol when there is minimum sun (early morning or late afternoon)
- Do not apply the biol when the crops are flowering because the biol has a certain repellent effect that would scare off the pollinating insects. Only apply the biol during the growth of the plant, stop while it is flowering, and then continue again when the fruit starts forming.
- Do not apply biol 15 days before harvesting the crops or introducing animals to pasture. If biol is applied, make sure to sanitize the fruits (the sun and weather can also help kill possible pathogens). If animals are set to pasture and biol has recently been applied, this can be problematic because cows do not like the smell and one must wait until it washes away for the cows to pasture.
- It has been seen that the higher the frequency of application, the better results (in field trials up to weekly applications). It is recommended to apply the biol at least twice: once before flowering and once after the fruit is forming.
- If frost is expected, foliar application of the biol can help protect the plant from frost damage as it helps the plant recover. Also, apply the biol immediately after the frost.

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14. Calculation Sheets