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STANDARD DESIGN PROCEDURE FOR LOW-COST BIODIGESTER TECHNOLOGIES:

design, construction and monitoring of a Tubular digester in Puerto Matilde, Colombia.

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“Ci sono abbastanza risorse

per soddisfare i bisogni di ogni uomo,

ma non l’avidità di ogni uomo.”

Ringraziamenti

Desidero ringraziare per primi i miei genitori, non solo per avermi sopportato e aver pagato per la mia istruzione, ma per avermi regalato la voglia di conoscere e di esplorare.

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Sommario

Questo elaborato si inserisce all'interno del tema dei biodigestori per le applicazioni in aree rurali. L'uso di un combustibile affidabile, sostenibile, sia dal punto di vista economico che dal punto di vista ambientale, ha un ruolo centrale nel miglioramento delle condizioni di vita e sociali nei Paesi in Via di Sviluppo.

Con l'obiettivo generale di sviluppo dell'economia locale, questa tesi propone l'impianto di biodigestione per la produzione di biogas come alternativa sostenibile ai combustibili comunemente utilizzati nelle zone rurali.

All'interno dell'elaborato viene introdotta una Procedura Standard di Progettazione (SDP) in modo da poter supportare, in fase di dimensionamento, la scelta dei parametri di progetto e garantire un dimensionamento corretto delle principali componenti dell'impianto di biodigestione. L'elaborato inizia con un'analisi bibliografica dettagliata che punta a determinare le principali variabili che influenzano il processo di digestione anaerobica, vengono in seguito presentate e analizzate le tecnologie maggiormente utilizzate in ambiente rurale. Grazie alle conoscenze e alle informazioni raccolte durante l'analisi bibliografica è stato possibile formulare una procedura di dimensionamento che tenga conto delle diverse tecnologie e dei diversi contesti di applicazione.

La SDP è stata applicata al caso reale di dimensionamento, costruzione e monitoraggio di un biodigestore Tubolare nel villaggio di Puerto Matilde, Colombia. Durante la fase di monitoraggio è stato osservato l'andamento della produzione giornaliera di biogas in modo da caratterizzare il rendimento e le prestazioni del biodigestore. In conclusione, dall'analisi di impatto sociale ed economico della tecnologia è emerso un buon grado di accettazione da parte della popolazione e un tempo di ritorno dell'investimento minore della vita utile della tecnologia.

Parole chiave: digestione anaerobica, biogas, digestore Tubolare, Colombia, area rurale.

Abstract

This paper contributes to research concerning biodigester technology for rural application. The use of a sustainable and affordable cooking fuel in the rural area has a central role in improving the social and living conditions in Developing Countries.

With the general object of developing the local economy, the thesis proposes the biodigester plant for biogas production as a sustainable alternative to the common cooking fuel used in rural areas.

A *Standard Design Procedure* (SDP) is introduced in order to support the decision making process during a biodigester implementation and to guarantee a correct design of the main parameters and features of a biogas plant. The thesis starts off with a detailed literature research which aims to determine the main parameters that affect the digestion process and to give an in-depth explanation of the biodigester low-cost technology for rural applications. The purpose of the procedure introduced is to be as general as possible in order to be applied in different contexts.

The SDP was directly applied in a real case of a Tubular biodigester design, construction and monitoring in the village of Puerto Matilde, Colombia. During the monitoring phase the trend of daily biogas production was observed in order to evaluate the performance of the plant. In conclusion, the biodigester's economic and social impact is analysed – the paper concludes that the technology is widely accepted by the farmers' community and that the Pay Back Time is comparable to the technology life span.

Key words: anaerobic digestion, biogas, tubular digester, Colombia, rural area.

Introduction

In 2015, countries adopted the *2030 Agenda for Sustainable Development* and its 17 *Sustainable Development Goals*. The goals are meant to mobilize efforts on behalf of all countries to end all forms of poverty, fight inequalities and tackle climate change, while ensuring that no one is left behind.

In this new scenario, the Colombian government on 24th of November of 2016, after more than fifty years of civil war, signed the peace agreement with the Colombian guerrilla group FARC. The *Colombia's Agreement for Ending Conflict and Building a Stable and Long-Lasting Peace* is an agreement that aims to create conditions to ensure health and wellbeing of the rural population to guarantee peace and non-repetition of the conflict. The national plan pays particular attention on the eradication of extreme poverty, improving the social and living condition in the country's rural areas, and environmental protection.

For more than fifty years, the Colombian rural areas were completely abandoned by the government. The presence of civil war and the absence of infrastructures, made difficult for the rural population to find stability and consolidate its own economy.

This paper focuses particularly on the "Zona de *Reserva Campesina del Valle del Rió Cimitarra*" (ZRC-VRC), a rural area in the Colombian *Magdalena Medio Region*. The area was affected by the conflict for many years. Moreover, its economy is based on illegal mining and wood exploitation, which generates social inequalities and environmental problems. This thesis has the general objective of ensuring local economic development, helping the population to find a different and sustainable way to produce income using local resources. It was observed that one of the main critical factors which affect the population's income in rural area is the impossibility to rely on an affordable and sustainable cooking fuel. Usually methane tanks are used to cover the energy needs, having said this, they are not always reliable, so inhabitants are obliged to use firewood.

The specific objective of the thesis is to propose a biogas plant as an alternative to the common cooking fuel. Firstly, a literature analysis identifies the anaerobic digestion working principles and the parameters that could affect it. Secondly, the state of art of technologies for the rural area in Developing Countries is taken into account, in order to identify the models that could be used in the Colombian context. Thanks to the information collected during the research phase, a *Standard Design Procedure* for biodigester is chosen and design is developed. The procedure aims to be as general as possible, taking into account the difference in contexts and technologies, so that it could be used in different scenarios. Finally, the Colombian study case is presented. Thanks to the cooperation between Ingegneria Senza Frontiere Milano (ISF-MI), as technical partner, and the Asociación Campesina del Valle del Rió Cimitarra (ACVC), as local partner, it was possible to design, implement and monitor a Tubular biodigester in the village of Puerto Matilde (ZRC-VRC).

1. The anaerobic digestion process

The Anaerobic Digestion (AD) is a microbiological process where different types of bacteria decompose organic substrate, in absence of oxygen and with specific conditions of temperature and pH. The organic substrate could be composed by different substances of animal and vegetable origin. Thanks to this process the feedstock could be transformed into a rich energy gas, the biogas and into a rich nutrient fertilizer, the digestate (Vögeli et al. 2014). These two outputs are produced in a close carbon cycle (Al Seadi et al. 2008).

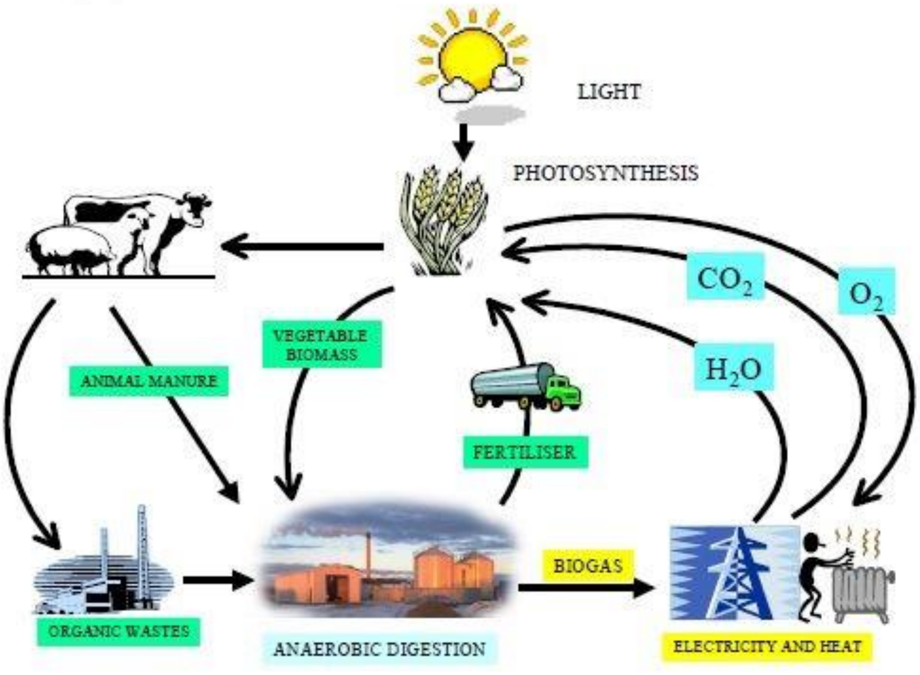


Figure 1.1 Biomass carbon cycle

In order to grow, the vegetable origin biomass (in a direct way) and the animal origin biomass (in an indirect way), take from the environment a certain quantity of energy, CO_2 and water, releasing O_2. Once the biomass life cycle ends, due to the degradation, CO_2, water and other gasses come back to the environment. With the anaerobic digestion and more in general with all the biomass base technologies, it is possible to transform the biomass in an energy vector at the end of its life cycle. Consequently, as reported in *Figure 1.1*, it is possible to exploit the intrinsic energy of biomass, maintaining the balance of CO_2. For this reason, the biomass, although releasing carbon dioxide during the combustion, is considered a renewable technology.

It is possible to identify three main sources of biomass:

Municipal	**Agricultural**	**Industry**
	• Manure;	• Slaughterhouse waste;

• Organic fraction of municipal solid waste;	• Energy crops;	• Food processing waste;
• Human excreta.	• Agro-industrial waste;	• Biochemical waste;
	• Alga biomass.	• Pulp and paper waste.

Table 1.1 Biomass divided by sector.

It is important to notice that the biomasses utilized in Developing Countries are slightly different from the ones used in Developed Countries power production plants. The most used biomass could be assembled in four categories:

- Animal manure;
- Human excreta;
- Farming residues;
- Residues from the kitchen.

The feedstocks are composed by water and dry matter however only the degradable part of this dry matter can contribute to the formation of biogas. The dry matter is identified by the Total Solid (TS) and the degradable part could be identified, with a very low error, by the Volatile Solid (VS).
The degradable part of solid matter is mainly composed by carbohydrates, protein and lipids. Thanks to the anaerobic digestion process this component will decompose in a simpler matter and transform into biogas and digestate.

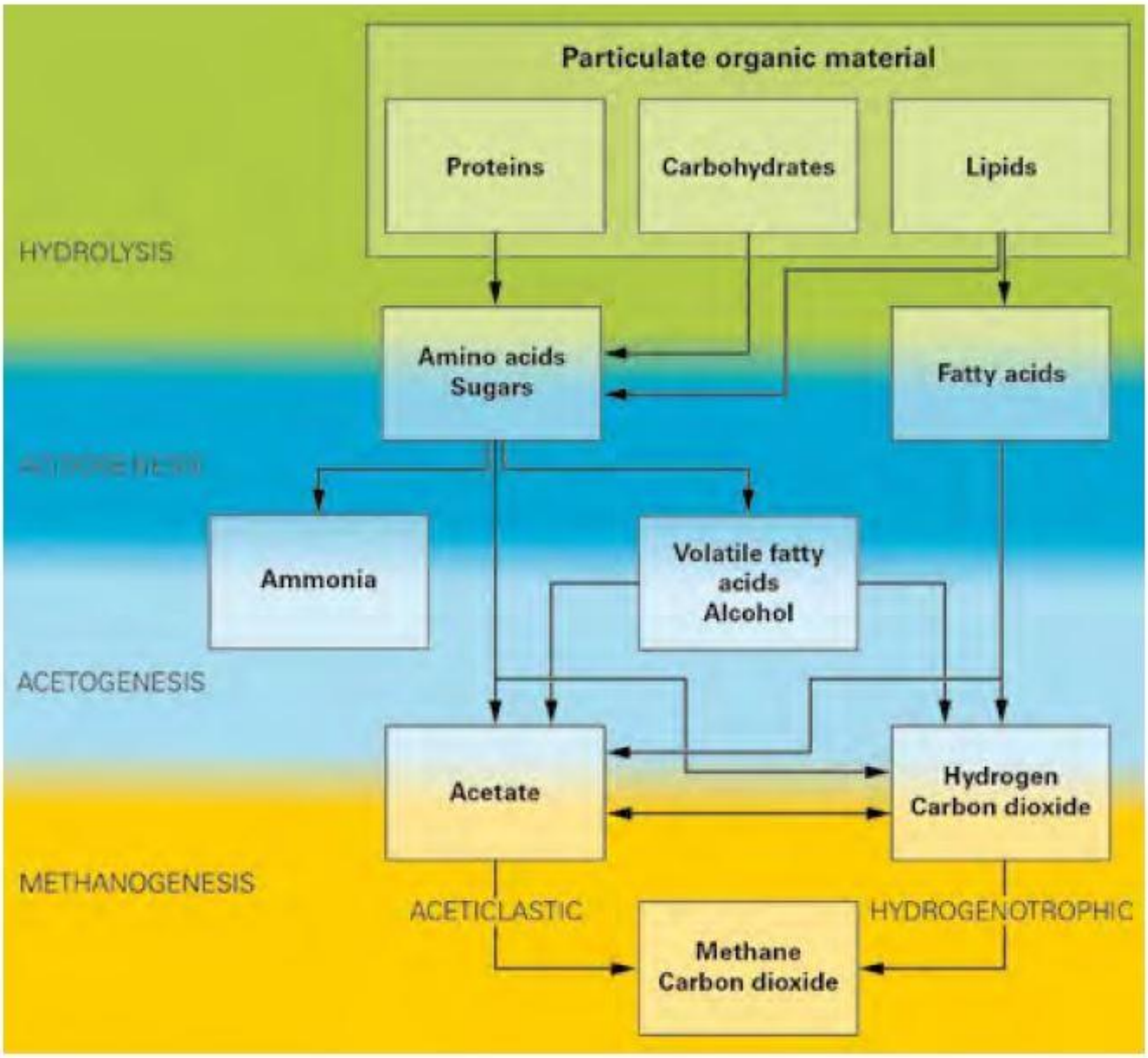
1.1 The biological process

As previously mentioned, the AD is a microbiological process of decomposition of organic matter in absence of oxygen. In general, what happens during the substrate degradation, could be explained by the following reaction:

$$C_aH_bO_cN_d \rightarrow nC_wH_xO_yN_z + mCH_4 + sCO_2 + rH_2O + (d - nx)NH_3$$

With:
s = a – nw – m
r = c – ny – 2s

The reaction shows the partial decomposition of complex organic substrate leading to the formation of methane, carbon dioxide, water and ammonia (Cecchi et al. 2005). The partial degradation does not happen in a single step, but needs different transformations. In this process four different phases are present, with different groups of bacteria acting in order to decompose the substrate's organic portion in simpler matter. These phases run parallel in time and space inside the reactor (Vögeli et al. 2014), as shown in *Graph 1.1*, where degradation steps and related products are reported.



Graph 1.1 Anaerobic digestion process.

- Hydrolysis:
  in this first step, different groups of bacteria act in order to transform complex organic material, such as proteins, carbohydrates and lipids, into liquefied monomer and polymers (e.g. amino acids, monosaccharides and fatty acids).
  The substrate degradation can be reached in two ways: a) the bacteria could directly decompose the organic material; b) they can produce extracellular enzyme dividing the organic complex molecules into oligomers and monomers, available for the next acidogenic step. The hydrolytic process could be hindered by the accumulation of amino acids and sugar because they generate interference and inhibition of hydrolytic enzyme (Cecchi et al. 2005).
- Acidogenesis:
  during this phase, the hydrolytic step products are converted by acidogenic bacteria into methanogenic substrate (Al Seadi et al. 2008). The bacteria transform the soluble organic monomers of sugars and amino acids into ethanol, long chain acids (propionic and butyric)

and short chain acids (volatile fatty acids), acetate, hydrogen and carbon dioxide (Vögeli et al. 2014). Moreover, from the degradation of amino acids ammonia is produced (Cecchi et al. 2005).

- Acetogenesis:
  all the products from acidogenesis that cannot be directly transformed into methane by the methanogenic bacteria, are converted into methanogenic substrate during the acidogenesis (Al Seadi et al. 2008). Starting from the products of hydrolysis and acidogenesis, the acetogenic bacteria produce acetic acids, formic acid, H_2 and CO_2. The mechanism of degradation strictly depends by starting product, if they are long chain fatty acids or short chain fatty acids (Cecchi et al. 2005). During this reaction, the BOD (biological oxygen demand) and the COD (chemical oxygen demand) are both reduced and the pH decreased. Hydrogen plays an important intermediary role in this process, as the reaction will only occur if the partial pressure is low enough to thermodynamically allow the conversion of all the acids (Vögeli et al. 2014).
- Methanogenesis:
  the production of methane represents the last anaerobic digestion step. The methane is the only compound that does not react in the digestion process and it represents the final product of the process. This phase is the slowest one, influencing the whole process duration (Cecchi et al. 2005).
  The methane production can take place in two ways:
  - the hydrogenotrophic bacteria produces methane oxidizing the hydrogen, using the carbon dioxide as an electrons taker, following this reaction:

    $$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$$

  - the methane production takes place from the acetic acid degradation:

    $$CH_3COOH \rightarrow CH_4 + CO_2$$

  The higher methane production is reached by the second reaction which could produce approximately the 70% of the total methane, only 30% is produced by the first reaction (Brunetti 2013).

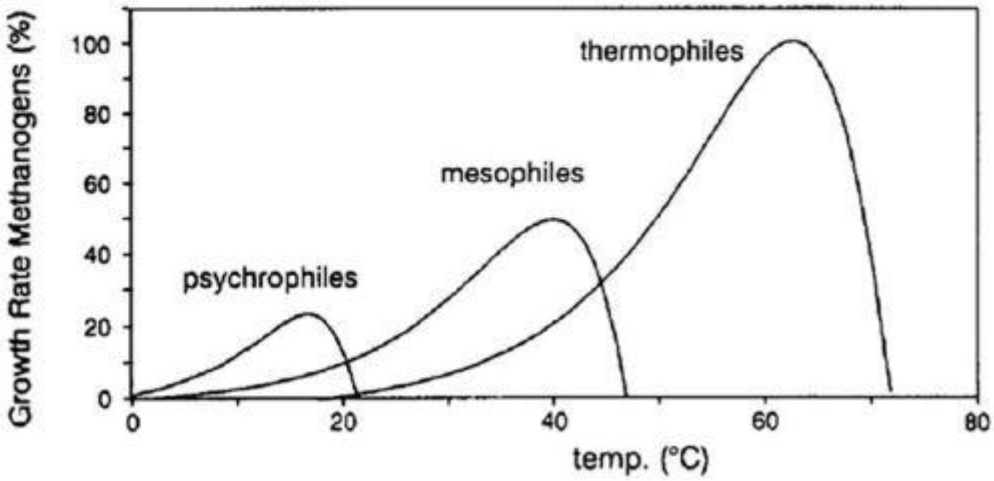
1.2 Process parameters

As previously mentioned, the anaerobic digestion needs specific operating conditions to take place. The most important parameters which must be monitored in order to guarantee the right operation are reported here:

- **pH:**
  The anaerobic digestion takes place only in a very narrow pH interval, from about 5,5 to 8,5, with an optimum in the interval 6,5-7,5. Knowing the pH value is very important because it is an index of stability and health of the process, since the methanogenic bacteria

are influenced by the ambient where they operate [1]. A low value of pH show an accumulation of volatile fatty acids, generally due to an overload of the reactor that could cause the bacteria inhibition. A high value of pH is an index of accumulation of ammonia in the reactor. This substance, if present with a concentration higher than 3000 mg/l, could inhibit the acidogenic and methanogenic bacteria (Brunetti 2013). It is possible to notice if the reactor is working in a wrong range of pH because the gas production becomes irregular, within a rising of carbon dioxide percentage. In order to adjust the pH value, in case it became more acid, one can add lime or sodium bicarbonate. On one hand, lime is cheaper but generates solid precipitation that could obstruct the piping system if used in large quantities. On the other hand, sodium bicarbonate is completely soluble and can adjust the pH value very rapidly, but presents a high cost (Vögeli et al. 2014).

- **Temperature:**
  The enzyme activity is strictly related to the reactor operating temperature. The bacterial proliferation is promoted in a temperature range that goes from 4°C to 80°C, outside this interval the anaerobic bacteria cannot survive. Inside this interval, it is possible to identify three different bacterial processes based on operating temperature:
  - *Thermophilic* (35-80°C): in order to maintain the operating temperature, heat exchangers are needed, leading to high energy consumption and economic cost. Feasible only at industrial level.
  - *Mesophilic* (10-45°C): thanks to the wide operating range it could be easily implemented in tropical and temperate region with no energy added cost.
  - *Psychrophilic* (4-20°C): appropriate for mild and cold climate region. Usually, to maintain the temperature, especially in rural areas a greenhouse is needed (Brunetti 2013).



Graph 1.2 Bacteria growth rate related to operating temperature.

In general terms an increase of temperature corresponds an increase of gas production. The nutrient, useful for the bacteria activity, are transported in and out of the cell throughout the cellular membrane. With a low temperature, the membrane becomes stiffer, decreasing the gas production (Kinyua et al. 2016).

Even if the thermophilic stage is the most productive, leading to a higher pathogen destruction, it has several problems of stability and adaptability of the bacteria at a change of temperature (-/+ 1°C/h). These problems could lead to activity inhibition, for this reason it is preferable to work within a mesophilic range. Mesophilic bacteria could resist at higher temperature fluctuation (-/+ 3°C) and does not need a strict temperature control (Al Seadi et al. 2008). Also, at a lower temperature there is less production of ammonia, which could inhibit the process.

Due to the fact that the temperature influences the production rate, it also influences the Hydraulic Retention Time (HRT) and, consequently, the reactor volume (Vögeli et al. 2014).

Bacteria	**Temperature range** *[°C]*	**HRT** *[day]*
Psychrophilic	4-20	70-80
Mesophilic	10-45	30-40
Thermophilic	35-80	15-20

Table 1.2 Relationship between operating temperature and HRT.

- **Hydraulic Retention Time (HRT):**

The HRT is the average time that the inlet flow rate needs in order to cross the digester. It is also possible to define the HRT as the time needed to reach the 80-85% of the ideal biogas production. It strictly depends by the type of bacteria and therefore by the temperature. It is possible to calculate the HRT with the following equation:

$$HTR = \frac{V_l}{\dot{V}} \qquad [day]$$

Where:

- V_l = reactor volume occupied by the liquid [m^3];
- $\dot{V}$ = volume of substrate fed by time unit [m^3/day].

According to the formula it is possible to notice that the choice of HRT influences the reactor volume and, in this way, the plant cost (Brunetti 2013).

In order to choose the right HRT value different aspects must be take into account:

- The retention time must be long enough to ensure that the quantity of exiting bacteria is greater than the amount of entering bacteria, otherwise the digestion can stop (Al Seadi et al. 2008);
- HRT must be adapted to the bacteria growth rate and, consequently, to the reactor operating temperature. The higher the temperature the lower the retention time (Kinyua et al. 2016);
- The technology and substrate used must be considered in order to design the HRT (Vögeli et al. 2014).

The choice of the HRT value is a trade-off between the cost of the plant and the gas production (Brunetti 2013).

- **Daily feeding:**

  As mentioned before, the anaerobic bacteria are very sensible to the variation of conditions, especially for what concerns the feeding substrate. For this reason, the inlet flux must be monitored and have to present determinate characteristics.

  The monitored parameters are the following:

  - *Organic Load Rate (OLR):*

    This parameter indicates the quantity of digestible substrate that enter in the digester per unit of time and volume and is defined as follow:

    $$OLR = \frac{\dot{m} \cdot VS}{V_l} \quad \left[\frac{kg_{VS}}{m^3 \cdot day}\right]$$

    Where:

    - V_l = reactor volume occupied by the liquid [m^3];
    - $\dot{m}$ = mass of substrate fed by time unit [kg^3/day];
    - VS = quantity of volatile solid per quantity of substrate [kg_{VS}/kg].

    The OLR must be chosen according to the reactor ability to decompose the substrate. If the quantity of organic matter entering in the reactor is too high, the acetogenic bacteria produces acetate faster than the methanogens bacteria can utilize, leading to a reduction in methane production. It is also possible to notice an increment of VFA. If the quantity of organic substrate is too low, the bacteria does not have enough feeding matter and this lead to a decrease of biogas production (Kinyua et al. 2016). For what concern an industrial reactor, the limit of OLR is 4-8 kg_{vs}/m^3 day. Due to the fact that the biodigesters for rural area do not present temperature control system nor mixing system, the value of OLR must be lower, because the decomposition ability of the bacteria is lower. A recommended OLR value for these technologies is 2 kg_{vs}/m^3 day.

  - *Inhibitors:*

    Even if the anaerobic bacteria, after an acclimatisation time, could operate in presence of substances that are generally toxic, the concentration of these substances in the feeding flow must be monitored. The most dangerous substances for the AD bacteria are: oxygen, hydrogen sulphide (H_2S), organic acids, free ammonia, heavy metals and other hazardous substances as disinfectants, herbicides, insecticides and antibiotics. All these substances could lead to an inhibition of the digestion (Vögeli et al. 2014).

    Even if is not a toxic substance, the quantity of lignin entering the reactor must be considered because slow down the hydrolysis phase, leading to a reduction of gas production.

  - *Ammonia:*

    It is the most common inhibitor of AD. It is common to have high ammonia concentration in the substrates with animal origin (e.g. animal slurry) due to the presence of urine. Besides, the ammonia could be produced inside the digester starting from the proteins (Al Seadi et al. 2008). The ammonia diffuses through the cellular membrane leading to an inhibition of the cell and changing its balance of potassium. The inhibition generates an accumulation of intermediate products, such as volatile fatty acids, and leads to an acidification of the reactor. Due to the fact that the inhibition mainly affects the methanogenic bacteria, the presence of ammonia generates a decreasing in methane production (Vögeli et al. 2014).

1.3 Process fluxes

Every flux that enters and exits from the biodigester presents properties that must be considered. These characteristics are useful to better design the biodigester and the system that will utilize the exiting fluxes.

1.3.1 Biomass

From the European Directive 2009/28/EC, the biomass is defined as follow:

"'Biomass' means the biodegradable fraction of products, waste and residues from biological origin from agriculture (including vegetal and animal substances), forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste".

As previously mentioned, the biomass could be divided in different groups according to its origin: municipal, agricultural or industrial.
In order to better perform the substrate digestion and avoid the bacteria inhibition, some biomass characteristics must be considered:

- **C/N ratio:**
  Represents the relationship between the quantity of carbon and the quantity of nitrogen present in the biomass, an index of degradability of the substrate.

$$\frac{C}{N} = \frac{carbon\ [\%\ dry\ substance]}{nitrogen\ [\%\ dry\ substance]}$$

  The optimum value of C/N ratio is between 20 and 25. On one hand, if the value is higher, the bacteria will rapidly consume the nitrogen, decreasing the biogas production. On the other hand, if the value is too low, the high concentration of nitrogen can lead to ammonia formation and, consequently, to the bacteria inhibition (Vögeli et al. 2014).
  The following table show the C/N ratio of different substrate:

Animal biomass			**Vegetable biomass**		
Source		*C/N value*	*Source:*		*C/N value*
Dung:			**Crops:**		
	Swine	20		*Grass*	12
	Horse	25		*Hay*	19

Cattle	25	*Straw*	48
Poultry	15	*Clover*	27
Human	6-10	*Alfalfa*	16-20
Animal waste:		**Kitchen waste:**	
Urine	0,8	*Onion*	15
Blood	3-4	*Potatoes*	25
Meat residues	5	*Lettuce*	12
Fish residues	5,1	*Tomatoes*	12
Milk whey	30-40	*Soy*	5

Table 1.3 Biomass C:N ratio.

To obtain the optimal C/N ration value, it is recommended to mix different substrate. In case of biodigester with a single biomass source, in order to reach the optimal value, it is possible to add paper or rice cell, both of which are rich of carbon (Martí-Herrero & Cipriano 2012).

- **Total Solid (TS):**
  Indicates the overall amount of solid present in the biomass and is indicated as percentage over total wet matter. This index is obtained drying the biomass in a hoven at 105°C for six hours.

$$TS = \frac{weight\ of\ dry\ matter\ [kg]}{weight\ of\ wet\ matter\ [kg]}\ [\%]$$

- **Volatile Solid (VS):**
  Indicates the overall amount of organic matter present in the biomass dry fraction. This parameter shows the maximum digestible fraction of the biomass, which is critical to calculate the OLR. This index is obtained as ratio between the different in weight between dry matter and ashes, and the weight of dry matter. The ashes are obtained burning the dry matter in a muffle at 650°C for six hours and can be considered as the not digestible part of the biomass (inorganic matter).

$$VS = \frac{weight\ of\ dry\ matter\ [kg] - weight\ of\ ashes\ [kg]}{weight\ of\ dry\ matter\ [kg]} = 1 - \frac{weight\ of\ ashes}{weight\ of\ dry\ matter}\ [\%]$$

- **Biogas Yield (BY):**
  Indicates the maximum biogas production that a substrate can produce. This index is affected by several factors, such as temperature, mixing and reactor geometry, due that it is difficult to obtain a unique value for substrate. The Biological Methane Potential (BMP) is, nowadays, the most used laboratory test that could obtain the biogas yield value. Thanks to this test it is possible to obtain the volumetric production of methane per kilograms of volatile solid present in the substrate in laboratory conditions (Vögeli et al. 2014).

1.3.2 Biogas

It is the main product of the anaerobic digestion and can be used in different applications such as heating, power production and cooking fuel.

The biogas is a mix of different gasses that comes from the anaerobic digestion of organic substrate. In *Table 1.4* is reported the common composition of biogas, that could present some variations according to the variation in temperature and substrate.

Component	Symbol	Volume concentration *[%]*
Methane	CH_4	55-70
Carbon Dioxide	CO_2	35-40
Water	H_2O	2 (20°C) – 7 (40°C)
Hydrogen Sulphide	H_2S	20-20000 ppm (2%)
Nitrogen	N_2	<2
Oxygen	O_2	<2
Hydrogen	H_2	<1
ammonia	NH_3	<0,05

Table 1.4 Biogas components.

The concentration of water changes according to the temperature. Greater the temperature grater is the quantity of water that evaporates.

Before using the biogas for whatever application, various cleaning treatments are needed in order to avoid corrosion and ambient pollution. The most used are desulphurization, elimination of water and, only for high pressure storage applications, carbon capture. These treatments will be analysed in-depth in the following chapter.

To better understand how biogas can substitute traditional fuel, in the table are reported the calorific value of different fuels and their corresponding quantity to obtain 1m^3 of biogas.

Fuel	Calorific value	Equivalent to 1m^3 of biogas
Biogas	6-6,5 *[kWh/m^3]*	
Diesel – Kerosene	12 *[kWh/kg]*	0,50 [kg]
Wood	4,5 *[kWh/kg]*	1,30 [kg]
Hard coal	8,5 *[kWh/kg]*	0,70 [kg]
Propane	25 *[kWh/m^3]*	0,24 [m^3]
Natural gas	10,6 *[kWh/m^3]*	0,60 [m^3]
Liquefied petroleum gas	26,1 *[kWh/m^3]*	0,20 [m^3]

Table 1.5 Fuel equivalent to 1m^3 of biogas.

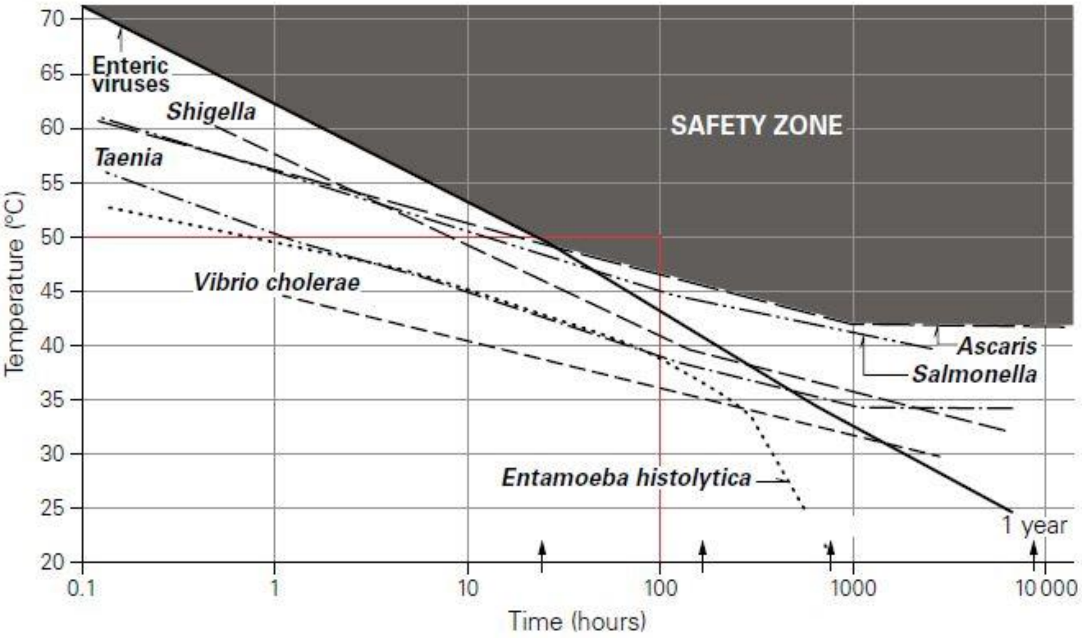
1.3.3 Digestate

Initially considered as a by-product, the digestate, also known as Biol, started to gain importance due to its use as natural fertilizer. It is widely used in substitution of chemical fertilizer and the commonly used dung and compost (Martí-Herrero et al. 2008). More liquid compared with entering flux and almost odourless, it contributes to the air cleaning. During the anaerobic digestion, almost the 25-30% of the dry matter is transformed into biogas and the C/N ratio decrease till 15:1 (Vögeli et al. 2014). Before digestion all the nutrients present in the biomass are present in the form of molecules, thanks to the digestion these molecules are transformed into smaller inorganic water soluble compounds that can be easily assimilated by the plant (Sasse et al. 1991). Substituting the raw dung with digestate for fertilizing the yield, it is possible to notice an increase of yield production. This is directly related to the hydrolytic process that the nutrients undergo during the anaerobic digestion (Garfí et al. 2011). The utilization of digestate as fertilizer, due to its ability to increase production, promotes the reduction of deforestation (Martí-Herrero et al. 2008).

Thanks to anaerobic digestion, the COD and the BOD decrease, reducing the water organic pollution. Even if the problem of organic pollution is reduced, it is not fully eliminated, so it is recommended to not throw too much digestate into the river because, in great quantity, this could cause water pollution (Vögeli et al. 2014).

For what concern the pathogen reduction, in general terms, the low-cost biodigester does not reach a complete elimination of pathogens, but only a reduction (Rowse 2011).

The level of hygenisation depends mainly on two parameters: temperature and HRT. The higher the biodigester operating temperature, the better the inactivation of bacteria - this means that it is preferable to work in the thermophilic temperature range. If the temperature is not high enough, a greater retention time is needed. In the low-cost digesters, a complete hygenisation cannot be reached because they generally work in mesophilic range, with a too low temperature and a high HRT is not feasible because of the incrementation of the costs. A post treatment is needed (Vögeli et al. 2014).



Graph 1.3 Time-temperature relation for digestate sanitation

In the study “Agricultural reuse of the digestate from low-cost tubular digester in rural Andean communities” (Garfì M. & Co; 2011) one can find important results that underline how the use of Biol, mixing with the compost or directly used, can increase the yield productivity compared with pre-compost manure. In particular, it is reported that:

- The production of potatoes field is increased by 27,5% using digestate as fertilizer;

- The production of forage field is increased by 1,4%, using 50% dose of digestate, and by 8,8%, using 100% dose of digestate.

Using of digestate as fertilizer, rather than pre-compost manure or chemical fertilizer, the following benefits were observed:

- **Production**: improve the crop yield production and, if used as fertilizer for forage or alfa-alfa production, it can increase field production and the milk production of the animals that are fed with it;
- **Environmental**: due to the fact that the digestate was previously decomposed by the bacteria in the biodigester, the production of greenhouse gasses, such as methane, during the decomposition in field, is decreased, leading to a lower environmental impact. Also, increasing the field productivity, less land for cultivation is needed, leading to a reduction of deforestation (Garfí et al. 2011);
- **Economical**: due to the use of digestate rather than the chemical fertilizer, there is a reduction of the expenses for farmers. Increasing the field productivity, additional income is generated, as more production is sold at the market (Martí-Herrero et al. 2008).

2. State of art technologies in developing countries

In Developing Countries many people rely on traditional biomass for cooking, this behaviour generates several problems, such as social exclusion, deforestation and internal pollution. In others cases, it is possible that a family is obliged to spend a great part of its income to cover the energy bill (gas and electricity). The problem could be identified in the absence of clean and affordable cooking fuel. In this context, the biodigester technologies, are considered appropriate technologies to tackle with the problem of the cooking fuel supply. As already mentioned, when we talk about technologies for Developing Countries we referred to a class of low-cost technologies without strictly control systems. In a biodigester reactor this means that there are no temperature control system or mixing system, in this way the technology result cheaper and less complex. These characteristics made the biodigester a technology easy to manage and built, with low cost of implementation and maintenance (Martí-Herrero et al. 2014).

Generally, in all biogas systems, it is possible to identify three macro components:

- *The reactor (or digester):* is the central part of the plant and the most difficult to design properly. Exist different types of digester, made with different materials and with different geometries in order to be adaptable to the different environmental conditions;
- *The digestate post treatment system:* is a piping and tank system that guarantees to treat and use the digestate in a proper way;
- *The distribution system:* is composed by the piping system for gas distribution, filter system, valves and storage tanks.

2.1 Digester technologies

In this paragraph, the most used technologies will be analysed and compared.

Fixed Dome digester

This type of digester was one of the first applied in rural areas. It was developed in India in 1978 and later modified and applied as well in China and other countries (Rajendran et al. 2012).

There are different models, they mainly differ in geometry while the working principle remains the same:

- Chinese model: it was the first model of biodigester, was designed in China and implemented mainly in its rural area. The digestion chamber is composed by a cylinder with hemispherical extremities.

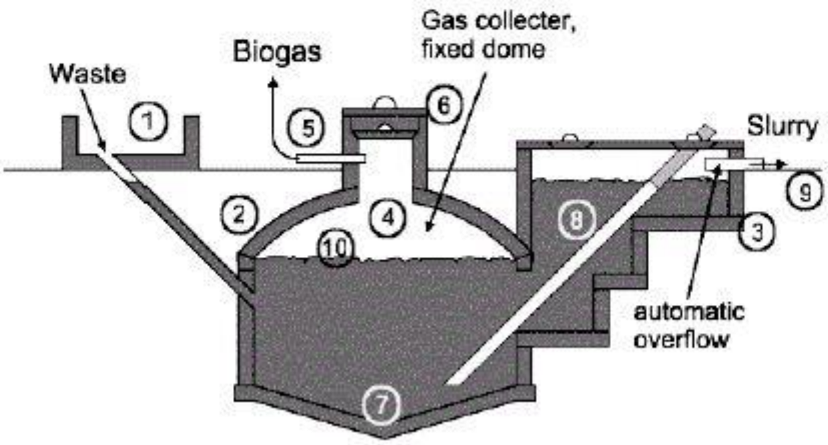


Figure 2.1 Fixed dome digester: Chinese Model

- Janata model: it is also called Indian Model because it was mainly installed in India. It is characterized by a flat floor and a partition in the middle for help the substrate recirculation. It was abandoned due to structural problem.

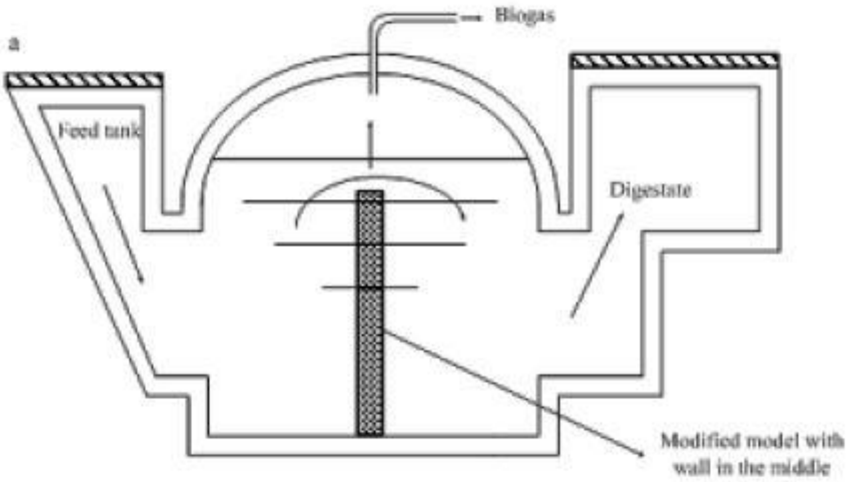


Figure 2.2 Fixed dome digester: Janata Model

- Deenbandhu model: it replaced the Janata model, its new shape guarantee an optimal structural resistance.

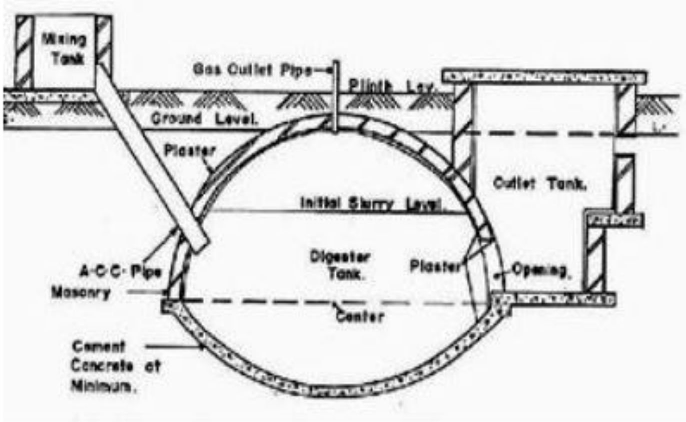


Figure 2.3 Fixed dome digester: Deenbandhu Model

This digester is mainly composed by three parts:

- *Inlet pipe*: the pipeline is used to fill the biodigester with the biomass. It is sometimes coupled with a small tank on the top, which acts as a funnel, in order to simplify the filling. The inlet pipe is characterized by a small diameter (usually 4”) compared with the outlet pipe. The pipe could be built both in PVC or concrete. The tank is usually built with bricks.
- *Digester chamber*: is composed by two parts, the gas holder and liquid volume tank. The liquid volume tank is the part where the anaerobic digestion happens. The gas holder is used to store the biogas produced and to increase its pressure. The different models of Fixed Dome digesters differ in the shape of floor and dome. The whole structure is made by concrete and bricks and must be waterproof in order to avoid losses.
- *Compensation pit*: is a concrete tank used for collect the digestate. The digestate level in the tank also gives information about the biogas quantity inside the gasholder. When the digestate reaches the maximum level of the tank it starts to flow out (Rajendran et al. 2012). All the models are built underground in order to weaken the temperature fluctuation between day and night (Brunetti 2013). Due to the fact that this technology present only fixed part is not possible to open the gasholder and remove the unavoidable sediment of inert material. Overtime the reactor volume decreases leading to a reduction of the production (K C et al. 2013).

Advantages:

- Relative low construction cost;
- Long life span;
- Not damageable due to underground construction;
- Job creation and local employment;

Disadvantages:

- Specific technical skills are needed;
- Difficult to repair once constructed;
- Specific sealant is required for the inside plastering.

A good example of Fixed Dome digester implementation is given by the project made in 2008 by “Biogas Sector Partnership Nepal” (BSP-N) in cooperation with the “International Committee of the Red Cross” (ICRC) in the Kaski, Chitwan and Kanchanpur District Jail. After the end of an internal war in Nepal in 2006, the living and sanitation conditions inside the prisons were very low due to

the old infrastructures and the overcrowding. To improve the living condition and decrease the environmental impact of the prisons, was decided to implement five Chinese model biodigester in order to treat the sewage and the kitchen waste of the prison. The gas produced by the biodigester is directly used in the kitchen to reduce the cost of cooking fuel.
The project present the following characteristics:

	Digester				
Parameters	*#1*	*#2*	*#3*	*#4*	*#5*
Total volume [m^3]	10	20	10	35	10
Substrate volume [m^3]	7,5	15,3	7,5	24,9	7,5
Inlet flow [l/day]	324,5	751,5	563,5	765,5	519
HRT [day]	23	20,5	13,5	32,5	14,5
Average operating temperature [°C]	26,4	25,6	29,8	28,8	30
Biogas production [m^3/day]	2,82	12,4	4,41	6,02	4,59
Average CH_4 content [%]	67	57	76	78	72

Table 2.1 Project parameters (Lohri et al. 2010).

Even if the Fixed Dome digester is a model that is widely used and accepted in Nepal, the use of human faeces as feedstock initially produced scepticism among the users, that disappeared after it was proved that this doesn't affect the food taste. It was reported an improvement of living conditions thanks to a smoke reduction in the kitchens and the improvement of the hygienic conditions.
It is also interesting to notice, the digesters economic performances:

	Digesters		
Parameters	*#1+2*	*#3+4*	*#5*
Saving of cooking fuel [US$/year]	412	1176	575
Saving of septic tank emptying [US$/year]	644	308	31
Cost of biogas system [US$]	7154	8078	2240
PBT [year]	1,5	5,4	3,7

Table 2.2 Economic analysis (Lohri et al. 2010).

From the chart, could be notice that the PBT is very small compared with the average life span of a Fixed Dome digester (usually in between 20 and 25 years) and an average specific cost of 205,55 US$/$m^3$ (Lohri et al. 2010).

Another interesting study was done by *A.K. Kalia* and *S.P. Singh* where a Deenbandhu model was compared with a new Fixed Dome digester model, the Himshakti. Two biodigesters per type of 1 m^3 and 2 m^3 were built and monitored for two years under the same operating conditions (average operating temperature of 18,26°C and HRT= 55 days) and with the same substrate feeding (25kg of cattle dung per day mixed in equal part with water). The study aims to demonstrate that the new design and construction technique of the Himshakti model could led to higher biogas production and a reduction of the construction cost. The new model, compared with the Deenbandhu model, present a higher wall thickness and a flat floor. The greater dimension of the perimeter walls led to

a higher structural resistance and the different design leads to a higher biogas production. From an economic point of view, the new model, due to the bigger walls, could better use stone in front of bricks, generating a saving of the 9% of the total construction cost. This benefit increase with the increasing of the dimensions (Kalia & Singh 2004).
The data from the study are reported in the following table:

	Digester			
Parameters	*Deenbandhu $1m^3$*	*Himshakti $1m^3$*	*Deenbandhu $2m^3$*	*Himshakti $2m^3$*
Total cost [US$]	135,2	138,1	215,8	212,4
Specific production [l_{bio}/kg_{dung}]	28,78	32,76	30,01	33.68
Total production [m^3]	633	720	1215	1482

Table 2.3 Deenbandhu-Himshakti: parameters comparison (Kalia & Singh 2004).

Floating Drum digester

The Floating Drum digester, also known as KVIC, was developed in India in 1962. Even if its design is pretty old, it is already widespread used (Rajendran et al. 2012).

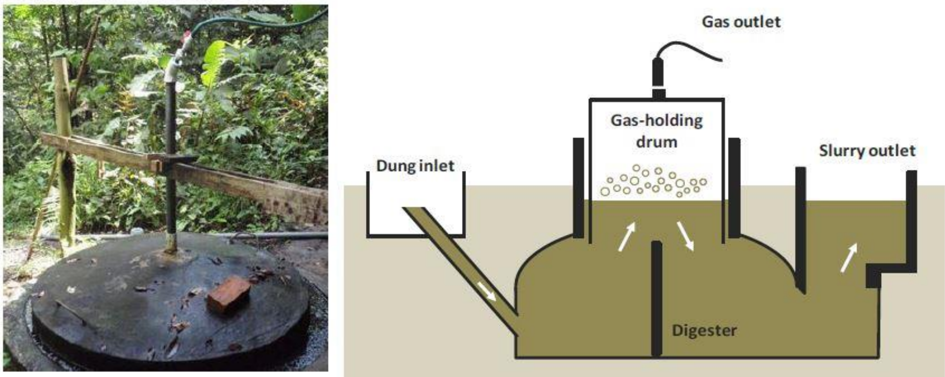


Figure 2.4 Floating Drum digester

As it is possible to see from the *Figure 2.4*, the inlet pipe and the compensation pit design are the same of Fixed Dome digester. The main difference is the movable and floating gasholder. This part is made of metal and painted with oil paint in order to protect it against corrosion. The drum can move up and down according to the quantity of gas produced and used. Thanks to this it is possible to have a visual indicator of the quantity of gas available. It is also possible put some weights on the drum in order to increase the gas pressure, in this way it is possible to cover bigger distance between the digester and the house. The gas is released at constant pressure. To avoid gas leakages, the drum is surrounded by a water jacket, however it needs a lock in order to block it when the it rises too much to prevent that the biodigester get open. The structure also needs a guiding frame to avoid tilting of the drum (Vögeli et al. 2014).
There are several models of Floating Drum digester and, like the different models of Fixed Dome digester, they differ for the digester chamber shape. It is possible to identify three main models:

- <u>Pragati model</u>: with hemispheric digestion chamber;

- KVIK model: with cylindrical digestion chamber and internal septum for help the recirculation of the digestate;
- Ganesc model: with conic base digestion chamber.

The most used is the Pragati model, with the hemispherical shape, because it has a better surface to volume ratio and improves the digestate recirculation (Brunetti 2013).
Thanks to the floating drum it is also possible to open the digester and clean it when the solid parts deposit at the bottom of the digester (Rakotojaona 2013).

Advantages:

- Simple and easy operation;
- Visual indicator;
- Constant gas pressure;
- Relative long life span of the plant;
- Construction errors do not lead to major problems in operation and gas yield.

Disadvantages:

- High material cost for the steel drum;
- Regular maintaining cost for the drum painting;
- Corrosion problem for the drum leads to an increase of cost;
- Specific technical skills are needed.

The Indian NGO Biotech, in association with Swiss Federal Institute of Aquatic Science and Technology (EAWAG), implemented in 2010 a series of domestic biogas plant in order to face with the problem of the river water pollution due to the toilet that direct discharge in the river. The system, called Toilet Linked Biogas Plant, consist in a prefabricated Floating Drum digester that is directly linked with the toilet and, if possible, with another inlet pipe for feed the digester also with kitchen waste.

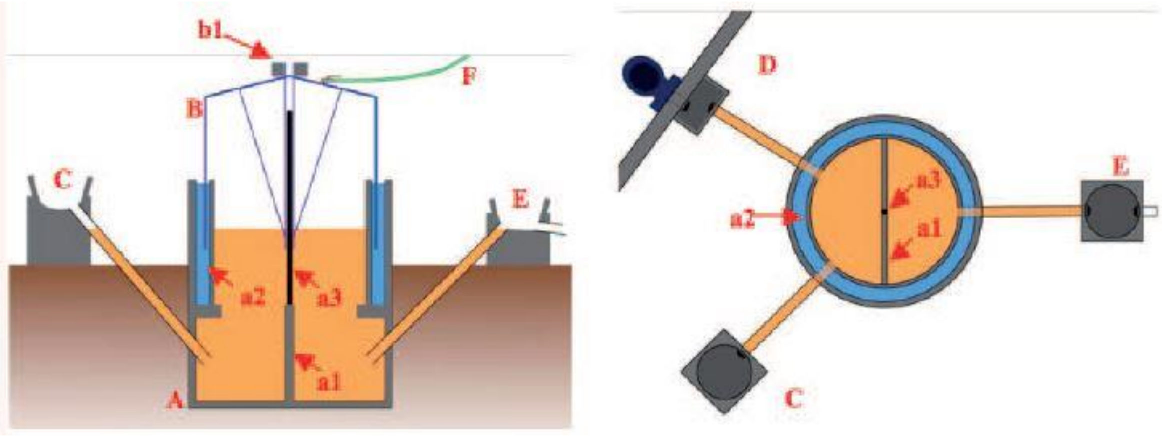


Figure 2.5 Toilet Linked Biogas Plant: cross section and upper view (Mulleger et al. 2011).

The plant was implemented and study in the city of Kochi in the department of Kerala, south India. It was recorded a good performance under a technical point of view: the reactor of 2,4m^3, working with an average temperature of 29°C and an HRT of 30 days, produces an average of 690 litres of biogas per day with an inlet flow of 80 litres of substrate (a mix of human faeces and kitchen waste). Also for what concern the environmental impact, was demonstrated that the use of this kind of digester for the waste water treatment, generates a sensible reduction of the COD and BOD, in this way it is possible to discharge the waste water directly in the river. On the other hand, from an economic point of view, the project present several problems: due to the interruption of national subsidies for biogas plant, the cost for the plant was unsustainable for the families:

	Total investment cost [US$]	**PBT** [year]
With national subsidies	120	3
Without national subsidies	600	15

Table 2.4 Economic analysis (Mulleger et al. 2011).

As mentioned before, this is one of the main problem related to this technology, the high cost of investment that is difficult to be faced by a single family. The Floating Drum digester still remain a good technology when applied at multi-family or community level, because the high investment cost could be divided (Mulleger et al. 2011).

Another project implemented by Biotech is the Floating Drum power plant for the fish market waste treatment in Thiruvananthapuram in the Indian state of Kerala. This plant aims to produce electric energy, thanks to a 5 Kw generator, in order to light the market and the surrounding streets.
The plant structure is showed in the *Figure 2.6*:

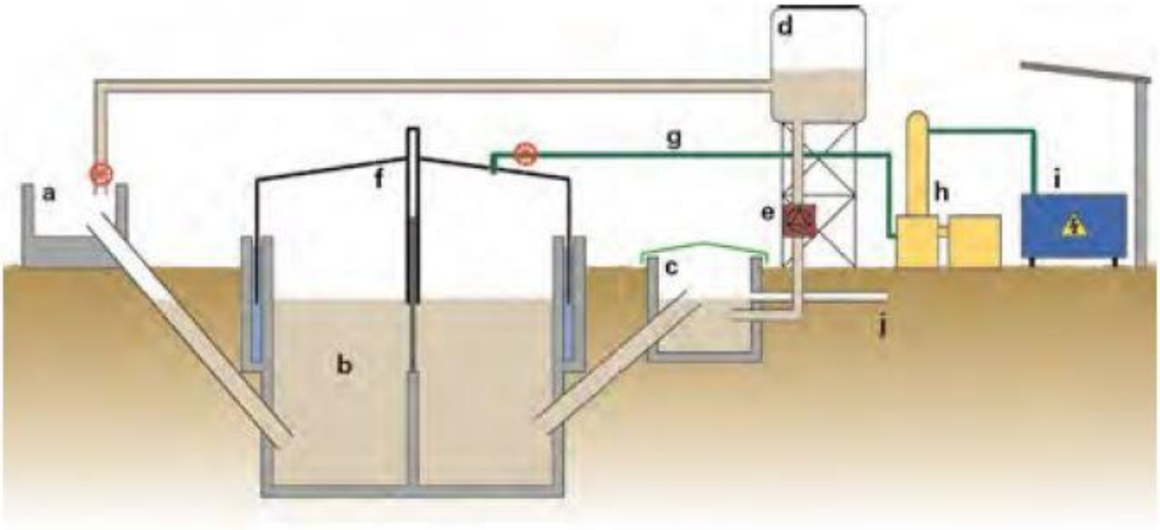


Figure 2.6 Thiruvananthapuram plant scheme (Heeb 2009).

There are some interesting features in this plant:

- The plant was designed with a feeding capacity of 250 kg per day of substrate, but nowadays is working with a daily feeding of 85,5 kg, this means a very high HRT that lead to a complete digestion of the substrate, producing a very liquid digestate (TS=0,97%);
- Due to the very liquid digestate was decided to implement a loop feeding system, in this way no dilute water is needed;

- It is present a scrubbing system in order to remove the CO2 from the biogas and use them in an internal combustion engine. Even if this system increase the biogas qualities, it presents a very high initial investment cost.

In the following table are reported the constructive and performance parameters of the plant:

Parameters	*Value*
Total volume [m^3]	25
Substrate volume [m^3]	21,3
Inlet flow [l/day]	85,5
HRT [day]	249
Average operating temperature [°C]	29,3
Biogas production [m^3/day]	4,97
Average CH_4 content [%]	66,8

Table 2.5 Project parameters (Heeb 2009).

The total cost of the project is reported in the following table:

Investment costs:		
	Material	13980 US$
	Labour	20970 US$
	Total investment costs	34950 US$
Operational and Maintenance cost:		
	Annual operation expenses	2621 US$
	Annual maintenance contract	1748-2650 US$

Table 2.6 Economic analysis (Heeb 2009).

As mentioned for the previous example, the main problem of this technology remains the high investment cost and, especially in this case, the Operational and Maintenance cost. Even if it is a very versatile technology, with a wide range of applications, it doesn't present economical attractiveness (Heeb 2009).

Tubular digester

The first plastic tubular digester was installed in Colombia and in Ethiopia in the 80s and then modified and improved in 1992 in Vietnam, substituting the plastic tube with a polyethylene tube lowering the cost (Kinyua et al. 2016).

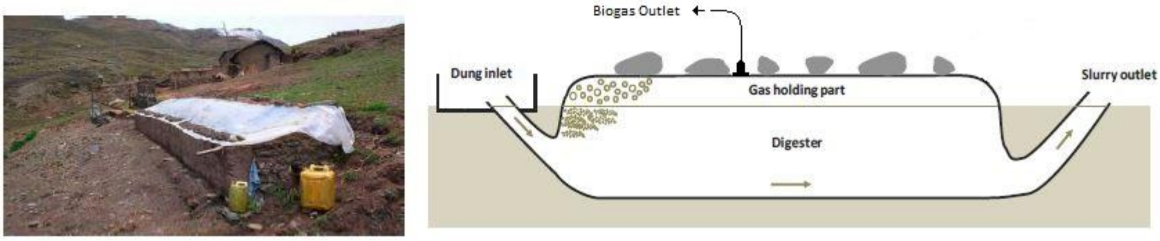


Figure 2.7 Tubular digester

This technology is the simplest and cheapest one due to the absence of expensive materials and specialized manpower. The digester is composed by an inlet and outlet pipe, that don't need concrete tanks as the other technologies, and a digestion chamber made with a prefabricated tubular plastic bag (Garfí et al. 2016). The high-quality balloon digesters are usually pre-fabricated and already equipped with a valve for the biogas exit. This part represents the highest cost of the plant, but is also possible to build it locally sealing PVC sheet.

The digester is buried in a trench with a special shape and an inclination from the enter to the exit. The inclination is needed in order to separate the different digestion phases and for helping the substrate to flow from the enter to the exit (Rajendran et al. 2012). As already mentioned this technology doesn't have a mixing and heating system, thus the inclination is mandatory also to help the mixing of the substrate. The produced biogas is partially cumulated in the upper part of digester and, to increase its pressure, some weights are placed on the balloon, taking care to not damage it (Vögeli et al. 2014).

This technology is very adaptable to different climate regions, it is both used in hot climate region (e.g. tropical region of south east Asia and South America) and in cold climate region (e.g. Andean plateau). In order to obtain a good performance even in cold climate it is mandatory to add a greenhouse covering the digester and an isolation layer in the trench. The greenhouse is added for two reasons: to increase the digester working temperature, increasing the biogas production, and to lowering the temperature fluctuations between day and night (Martí-Herrero et al. 2014). The isolation layer is needed for two reasons: avoid the damaging of the balloon and isolate it from the cold ground. It is proved that the digester without isolation, at the equilibrium, reaches the same temperature of the ground (Nzila et al. 2012).

Another strength point of this technology is the easy transportation of the balloon digester. The high quality pre-fabricated PVC bag are not always locally available, however could be easily transported (Garfí et al. 2016).

Thanks to its simple design, ease of installation and the absence of specialized manpower, this technology is widespread used for household applications in developing countries such as Colombia, Ethiopia, Tanzania, Vietnam, Cambodia, Costa Rica, Peru, Bolivia, Ecuador, Argentina, Chile and Mexico, where the installation of Fixed Dome and Floating Drum digester have been reported too expensive (Surendra et al. 2014).

Even if it is a very adaptable technology, some problems of short lifespan are observed:

- easy deterioration of PVC under extreme environmental conditions, such as rain, strong sun and cold,
- occlusion of the digester, due to the accumulation of solids in the bottom of the digester.

<u>Advantages:</u>

- Low cost;
- Ease of transportation;
- Easy to construct;
- High digester temperature in warm climate;
- Adaptability to different climate regions;

<u>Disadvantages:</u>

- Relative short lifespan;
- Susceptibility to mechanical demand;
- Material not usually available locally;
- Low gas pressure requires extra weights;
- Scum cannot be removed from the digester.

- High skilled manpower not required.

The wide field of applications of the Tubular digester is demonstrated by the high number of digesters used at high altitude, especially in Andean area.
An example of a high-altitude application is the project done in 2007 by the Peruvian NGO Practical Action for Peru in cooperation with Engineers Without Borders Spain and Green Empowerment (USA) in the Department of Cajamarca in norther region of Peruvian Andes. The project aims to improve the living condition reducing the amount of traditional biomass used for cooking with biogas produced using cow manure. The project involved 12 households in the rural area of the region, that is located at 3300 m a.s.l., and aims to build a Tubular digester for every family.
The technical characteristics of the biodigester are reported in the table:

Parameters	*Value*
Total volume [m^3]	7,5 – 10
Substrate feeding [kg/day]	20 – 27
Average operating temperature [°C]	<25
HRT [day]	90
Biogas production [m^3/day]	0,53 ± 0,01
Average CH_4 content [%]	60

Table 2.7 Project parameters (Garfí et al. 2010).

From the table is possible to see that the total biodigester volume is very big compared to the quantity of biogas produced, this is caused by the low operating temperature that lead to a great HRT and so to a big volume. The biogas produced cover the 63% of the total family needs. This is the main problem related with the high-altitude applications, in order to achieve good production big volume are needed.
From an economical point of view, the project present the following result:

Total investment cost:		400 US$
Total income save:		
	Fertilizer saving	46 US$/year
	Increase field production	75 US$/year

Table 2.8 Economic analysis (Garfí et al. 2010).

The project was totally subsidized by the NGOs, so for the families there were only economic benefit. The total saving is quite low because the cooking fuel substituted was firewood available for free, so it doesn't produce economic benefits. The project has a good impact under a social and environmental point of view, in fact was reduced the total amount of firewood used for cooking (-1,88 t/year per family) and was reduced the total time spent by women and children for the wood collection (-2,5 h/week). In addition, the living conditions were improved reducing the internal pollution and smoke due to the use of firewood (Garfí et al. 2010).

A summary of many differences among presented models is reported in *Table 2.9*.

	Fixed Dome	**Floating Drum**	**Tubular**
Lifespan [years]	15 - 20	10 - 15	3 – 7
Skills level required	High	High	Low
Total volume $[m^3]$	5 - 50	5 - 50	2 – 15
Total cost	1000-1800 $	1600-1900 $	500-600 $
Main cost voice	Manpower	Steel drum and manpower	PVC digester bag
Material	Bricks and concrete	Steel drum, bricks and concrete	Pre-fabricate PVC bag
Waste to water ratio [kg/l]	1:1	1:1	1:3
V_{gas}/V_{tot} $[m^3_{gas}/m^3_{tot}]$	1/4	Variable	1/5
Specific production $[m^3_{gas}/m^3_{dig}\ d]$	0.35 - 0.7	0.35 - 0.7	0.09 - 0.47

Table 2.9 Comparison between different technologies (Brunetti 2013).

The data about the total cost are referred to a Peruvian study case reported in literature. It was decided to use this study case as example because the context characteristics are more similar to the Colombian one.

As it possible to see, Fixed Dome and Floating Drum digester have quite similar characteristics, this is because both have similar geometry and material. The main difference between them is the steel drum that increases the cost and the skills required for the construction of the Floating Drum digester. The difference in the *Lifespan* is due to the corrosion problem related to the steel drum.

The Tubular digester presents completely different characteristics, it is very cheap, compared to the other technologies, but it also has a very short lifespan compared to the others. It is possible to notice that the only relevant cost of this technology is the PVC bag, this because the easy construction technique allows to self-build it avoiding the cost of manpower. This is not possible for other technologies.

Also, the *Total volume* is quite different among the technologies, this is related to different factors:

- For Fixed Dome digester is difficult to reach big volume due to the problem related to the construction of a very big and resistant hemispherical ceiling.
- The Floating Drum digester could reach very big volume but, due to the fact that is a low-cost technology with no mixing system, is not possible to overcome a certain limit, otherwise digestion problem and scum formation could happen.
- For Tubular digester is not possible to work with big volume because this would mean big length that could generates problems in phase separation inside the digester and substrate flowing. If big volume is needed it is better build different small digesters rather than one big digester.

The *Waste to water ratio* represents the quantity of water that must be added in order to dilute the entering substrate. In order to help the flowing of the substrate inside the digester, the Tubular digester presents a high *Waste to water ratio*, otherwise obstruction could happen. The *Specific production* is the quantity, in cubic meters, of biogas produced per volume of digester per day. This characteristic is directly related to the *Waste to water ratio* and vary with substrate and temperature. It is possible to see that a Tubular digester presents a lower *Specific production* due to the fact that the substrate is very diluted so the concentration of volatile solid in the digestion chamber is very low leading to a low *Specific production*.

An interesting comparison study between Fixed Dome digester and Tubular digester, with the same biogas production, is reported in "*Plan del programa nacional de biodigestores de Bolivia*" (Martí-Herrero et al. 2013). The study reports that a Fixed Dome digester of 6 m^3 total volume costs 1004 US$ and an equivalent Tubular digester of 11,3 m^3 costs 503 US$. In the cost are included the labour, for both, and the greenhouse for the Tubular one. The Fixed Dome digester presents a lifespan of 20 years, and the Tubular model only 5. Making an economic comparison over a 20 years' lifecycle, the total cost of the Tubular model become 1088 US$, considering that the greenhouse and the tubular plastic are replaced three times after installation along 20 years. Even if the total cost of the Tubular digester is higher, the lower initial investment cost can cover an economic-social gap that other models do not (Martí-Herrero et al. 2014).

2.2 Digestate post treatment and use

In order to use the digestate, due to the presence of pathogen, a post treatment is needed, especially if is sprayed as fertilizer on the crops. The digestate, when flow out from the biodigester, is composed by a solid part and a liquid part with variating percentage according to the digested substrate. The treatments are different for the solid part and for the liquid part, so a separation is needed. It is possible to divide the two phases for precipitation using a specific pre-fabricated tank. In this way, it is possible to treat separately the two phases.

For the solid part is useful to use a composting as a post-treatment in order to eliminate the pathogen. Thanks to the composting the temperature of the digestate increase reaching the 50°C, in this way few days are enough in order to eliminate all the pathogens.

For the liquid part a Treatment Wetland is suggested to decrease the quantity of bacteria with a system with no energy consumption. This kind of filter could be self-build with very low cost and easily integrated with the plant.

Unfortunately, experiences from developing countries show that a post-treatment step is seldom implemented (Vögeli et al. 2014).

A good example of post-treatment system is the one constructed by the Non-Governmental Organization Technologies for Economic Development (TED) in Meseru (Lesotho). In order to improve the food security of the village, acting on the reuse of the digestate for field irrigation, in cooperation with the German NGO Bremen Overseas Research and Development Association (BORDA), a Planted Gravel Filter (PGF) was constructed in order to perform a post-treatment of the digestate. The PGF is filled with gravel or pumice stones and planted with aquatic plants. The plant roots promote a biochemical absorption of the pathogen and the pumice stone provide a physical filtration of the flux. This filter permit the direct reuse of the digestate with a very low operating and maintaining cost compared with a conventional septic tank. In addition, the filter is completely underground and only the plant are visible and provide a nice visible to the whole system (Mulleger et al. 2011).

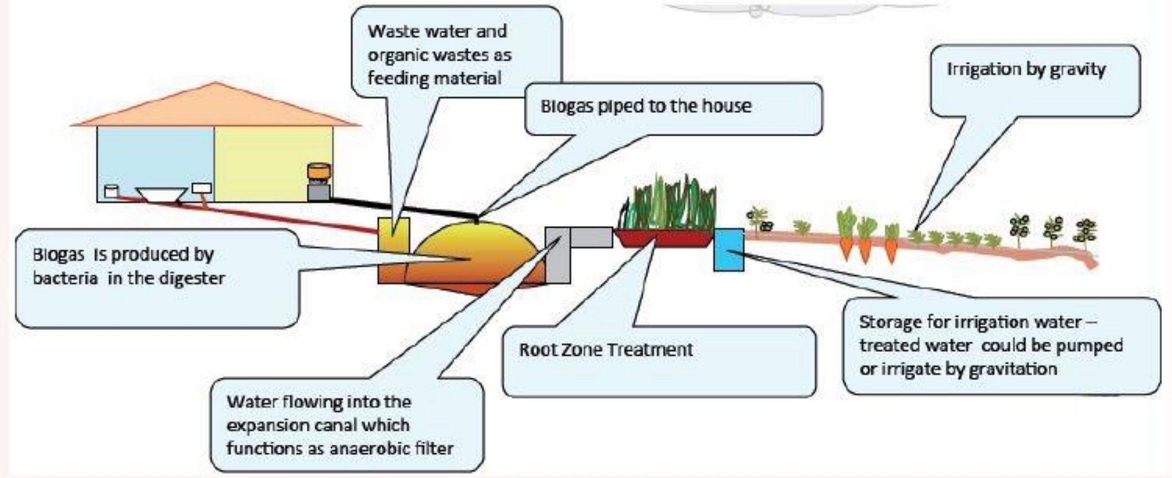


Figure 2.8 Plant scheme of Planted Gravel Filter (PGF) (Mulleger et al. 2011).

2.3 Distribution system

The distribution system is the same for every digester. The components on the pipeline are always the same, what change is the length of the pipeline, according with the site topography. Every equipment present on the pipeline could be self-built, this also help to reduce the total cost of the plant.
In the following image is reported the scheme of a standard distribution system:

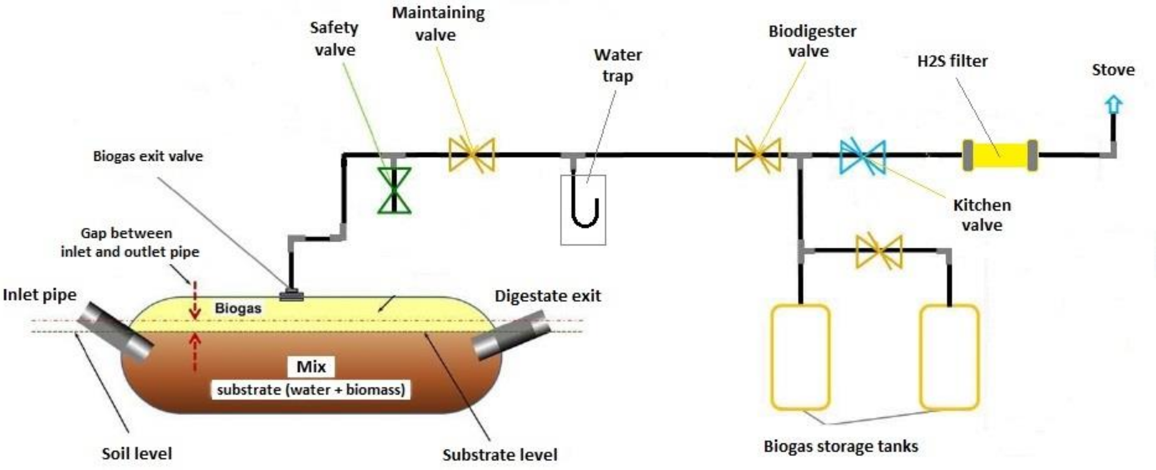


Figure 2.9 Distribution systeme scheme

The pipeline is composed by the following equipment:

- **Safety valve:** this appliance is positioned between the biodigester and the maintaining valve and is mandatory in order to discharge the overpressure of the biodigester. The hydraulic head must be properly designed in order to avoid gas leakages.
- **Water trap:** especially in the Tubular model, the quantity of water inside the digester is very high, and a part of it, due to the high temperature, evaporates flowing in the pipeline.

Condensing in the pipes the water can locks it and generates problem of overpressure, so must be eliminated.

To eliminate the water from the pipeline there are mainly two plant solutions:

  - Put an opening valve in the lower point of the plant. In this way, all the water that condense in the pipe flow down cumulating in the nearby of the valve. Open it is possible to discharge all the water in a specific bucket.
  - If the site permit it, build the biodigester at a lower level than the users. In this way, thanks to the natural inclination of the pipeline, the water that condense in the pipe come back to the biodigester without locking the distribution system.

- **Biogas Storage Reservoir:** the biogas reservoirs are used for two reasons: are buffer reservoirs that can guarantee the quantity of biogas necessary for the user and, decoupling the production and the user, it is possible to obtain a constant pressure higher than the one achieved with only the biodigester. The Floating Drum digester doesn't need this device because already have its storage volume that could be pressurized.

  Different storage systems could be used, according to the biogas final utilization:
  - *Low-pressure system:* consist basically in transparent plastic bag, UV resistant, available pre-fabricated in different size or can easily self-built on site. This is the simplest and cheapest solution but it's also the most fragile because is very susceptible to damage by weather and vandalism. It is used for simple house systems (e.g. cooking devices, lamps and heating systems).
  - *Medium-pressure system:* a gas storage tank is used to store the biogas at 5-20 bar. The compression in this pressure range could be achieved with a single stage compressor. It is seldom used for multi house applications.
  - *High-pressure system:* a special gas bottles are used to store the biogas at 200 bar. Hydrogen and H_2S must be removed before the compression to avoid corrosion. It is used for engine applications. It is feasible only for large plant application due to the high costs and due to the fact that all the CO_2 compressed and stored is a cost without benefits (Vögeli et al. 2014).

- **H_2S filter:** the hydrogen sulphide is a colourless gas with a characteristic smell of rotten egg. It is toxic with a concentration above 15 parts per million (ppm), but it can be smelled at only 0,1 ppm. A good air dilution could avoid the toxicity problem related to hydrogen sulphide. This gas is present in very low percentage in the biogas and could easily eliminated with a filter. This filter could be bought pre-fabricated or could be self-built.

  The self-built filter consists in a tube with an iron sponge previously oxidized inside. The hydrogen sulphide reacts with the iron oxide producing iron sulphide (1). To regenerate the filter is sufficient to put it under the sun radiation generating iron oxide and sulphur (2):

$$(1)\quad FeO + H_2S \rightarrow FeS + H_2O$$

$$(2)\quad 2\,FeS + O_2 \rightarrow 2\,FeO + 2\,S$$

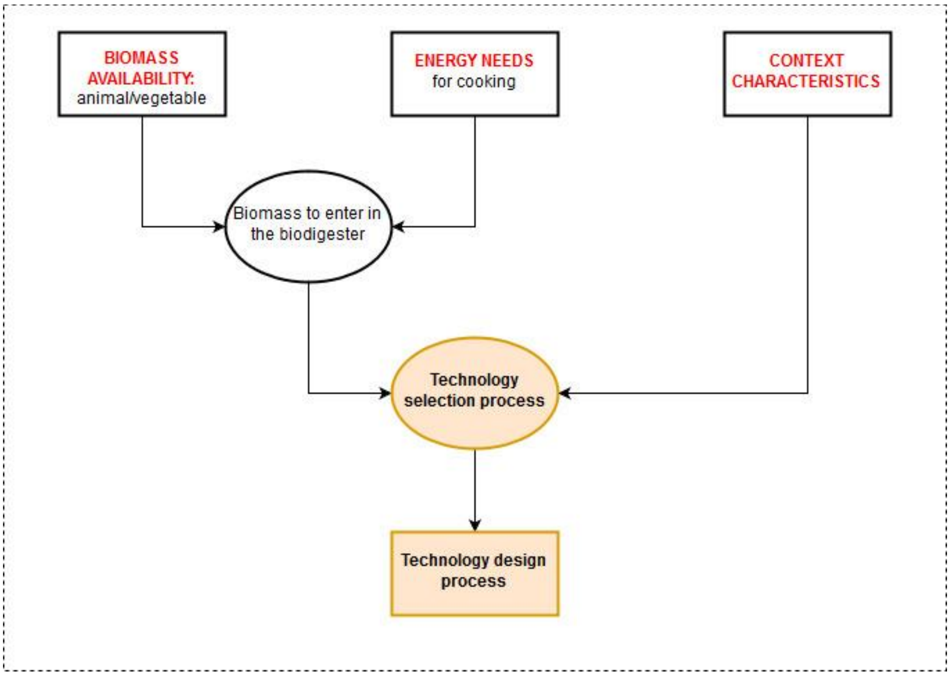
3. Design and monitoring procedure

The design of a biodigester depends on different aspects and parameters and is influenced especially by the context characteristics.
This chapter is divided in two part:

- The presentation of a "*Standard Design and Monitoring Procedure*" for the choice and sizing of low cost biodigester for rural applications. The procedure is based on bibliography's data and will be then corrected and used for the biodigester design in the particular case of Colombian Study Case;
- The presentation of the data of biomass properties analysed in laboratory and their comparison with the bibliography data in order to understand if possible to directly use the "*Standard Design Procedure*" or corrections are needed.

3.1 Standard Design Procedure

The procedure that will be presented in this paragraph aims to be as general as possible in order to be used in every context and in both with a demand driver or resource driver case. In order to simplify the model and to adapt it to the study case, the "Standard Design Procedure" is designed for cooking energy demand.
The general process structure is reported in the following diagram:



Graph 3.1 Standard Design Procedure

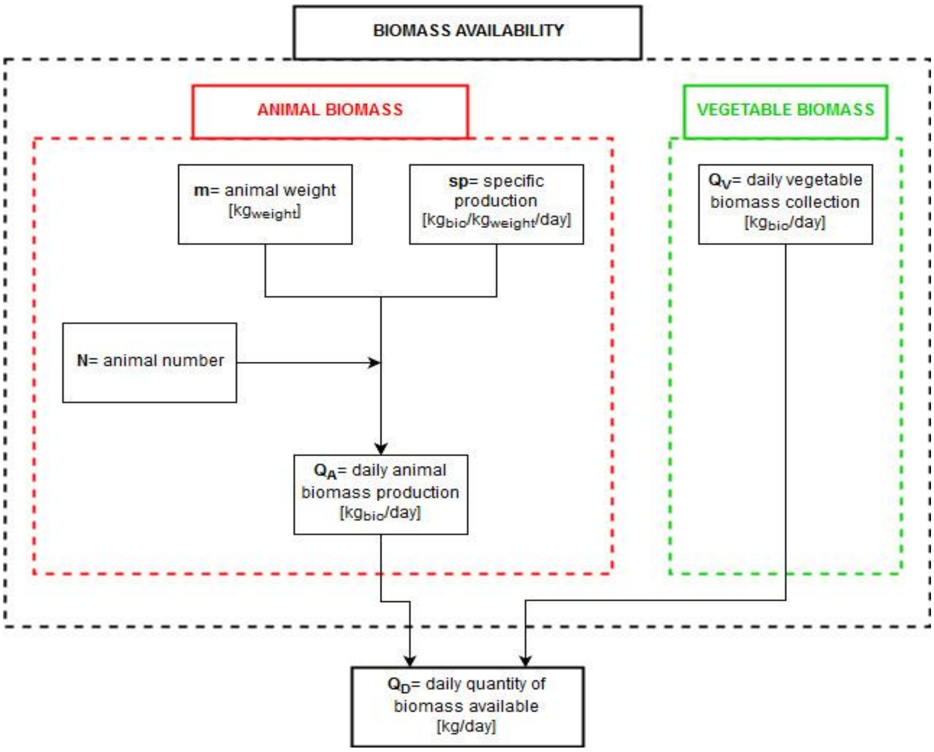
Three inputs are present in the process: the biomass availability, the energy needs and the context characteristics. The first two blocks tell us if the process is demand driving or resource driving, by the matching of these two blocks it is possible to calculate the quantity of biomass that must be inserted in the biodigester in order to satisfy the energy needs. The third block is mandatory in order to properly choose the technology because different characteristics lead to different type of digester. As output is present the "Technology Design Process" for the different technologies according to the context characteristics and the quantity of biomass needed.

3.1.1 Biomass availability

This section is composed by two parts: the animal biomass daily production and the vegetable biomass daily production. These two parts are divided because their daily production is calculated in different way and because the biogas production of them is calculated in different way.

For what concern the vegetable biomass daily production, it depends only by the quantity of biomass that is collected every day, so a monitoring of biomass collection is necessary.

For what concern the animal biomass daily production it is possible to make a calculation of the biomass production based on the types of animal, their weight and their number. Obviously, the production can change with the season, the nutrition and the type of breeding. In the following chart the logical scheme of the block is reported:



Graph 3.2 Biomass availability: calculation procedure.

Let's now analyse the different blocks that compose the Biomass Availability block.

Animal Biomass

The quantity of manure produced by an animal strictly depends on its age and weight. Every animal has its specific production so, if in the farm are present different animals, this difference must be taken into account. Especially for the swine, whose specific production changes a lot with the age, and so, with the weight.

The calculation of the total daily biomass production is obtained as follows:

$$Q_A = \sum_i N_i \cdot m_i \cdot sp_i$$

Where:
Q_A= daily animal biomass production [kg/day];
N= number of animal [-];
m= animal weight [kg_{weight}];
sp= specific production of manure [kg_{bio}/kg_{weight}/day];
i= animal type.

In the following chart are reported different values of specific production of manure according to the animal type and to its growth stage.

Animal Type		Specific Production [kg_{bio}/kg_{weight}/day]
Beef:		
	Dairy cow	0.08
	Not lactating cow	0.045
	Calf	0.008
Swine:		
	1-10 kg	0.01
	10-25 kg	0.08
	25-100 kg	0.065
	100-180 kg	0.06
	180-200 kg	0.088
Poultry:		0.02

Table 3.1 Specific Production of dung per farming animals.

Vegetable Biomass

In the vegetable biomass, it is possible to insert all the energy crops and all the vegetable waste coming from the kitchen and from the food industry. All the food waste that come from the animal industry are excluded from this group, because they have different characteristics that cannot be associated with vegetable biomass.

As mentioned before, it is not possible to perform a quantity calculation as done for the animal biomass production. A study of the waste production and energy crops cultivation must be done on site in order to obtain the daily vegetable biomass collection (Q_V).

Biomass Availability

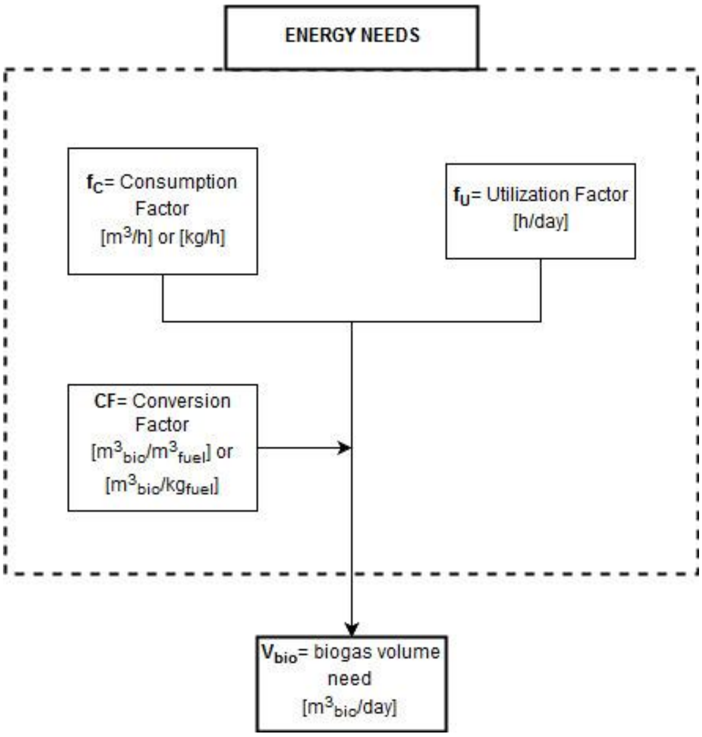
The daily quantity of available biomass is obtained by the summation of the daily vegetable biomass and the daily animal biomass:

$$Q_D = Q_A + Q_V$$

Where:
Q_D= daily quantity of available biomass [kg/day];
Q_A= daily quantity animal biomass production [kg/day];
Q_V= daily quantity vegetable biomass collection [kg/day].

3.1.2 Energy needs

This block aims to calculate the quantity of biogas need to supply to the house's energy needs for cooking. The Energy needs are related to the family cooking habit and, of course, to the number of people. The quantity of biogas need depends by the type of fuel used and, of course, by the quantity. The output of this block is expressed as quantity of biogas needed by the kitchen per day and so is also useful for design the biogas tanks dimension.
The block is organized as follow:



Graph 3.3 Energy Needs: calculation procedure.

To calculate the cubic meter of biogas needed to satisfy the energy demand, the following formula is used:

$$V_{bio} = \sum_i f_{C_i} \cdot f_U \cdot CF_i$$

Where:
V_{bio}= daily volume of biogas needed [m^3_{bio}/day];
f_C= consumption factor [m^3/h or kg/h], express the quantity of fuel used for cooking per unit of time. In a farm, it is possible that are used different fuel, for example when the gas tank it's over it is possible that the family is forced to use other fuel like wood or charcoal, so it must be taken into account;
f_U= utilization factor [h/day], express the quantity of time that the cook stoves are used in a day;
CF= conversion factor [m^3_{bio}/m^3_{fuel} or m^3_{bio}/kg_{fuel}], according to the type of fuel used in the cook stoves, this factor convert the quantity of that fuel in biogas cubic meters;
i= type of fuel.

In the following chart are reported the Conversion Factor of the most used cooking fuel in Developing Countries (Vögeli et al. 2014):

Type of fuel	CF	
Diesel, Kerosene	2.000	[m^3_{bio}/kg_{fuel}]
Wood	0.769	[m^3_{bio}/kg_{fuel}]
Cow dung	0.833	[m^3_{bio}/kg_{fuel}]
Plant residues	0.769	[m^3_{bio}/kg_{fuel}]
Hard coal	1.429	[m^3_{bio}/kg_{fuel}]
Propane	4.167	[m^3_{bio}/m^3_{fuel}]
Natural gas	1.667	[m^3_{bio}/m^3_{fuel}]
Liquefied Petroleum Gas	5.000	[m^3_{bio}/m^3_{fuel}]

Table 3.2 Conversion Factor from fuel to biogas cubic meters.

It is important to notice that these values of CF are calculated under the hypothesis of methane percentage in biogas equal to 60%. This percentage is widely accepted and used in bibliography.

3.1.3 Context characteristics

The characteristics of the location where the biodigester will built influence a lot the choice of the technology and some parameters. In this paragraph, some features that must be considered during the biodigester design process will be listed, not only for what concern the parameters, dimensions and types of biodigester, but also for the logistic during the construction, operation and maintenance.

- **Altitude:** it is the most important parameter because, especially in the tropical region, the temperature doesn't change with the season but with the altitude and so it is possible to identify similar mean temperature for every range of altitude. It is possible to identify three main regions:

Region	Altitude range	Mean temperature
Tropical/Rain forest	0-2000 m	T > 20°C
Valley	2000-3000 m	15°C < T < 20°C
Altiplano	3000-4500 m	0°C < T < 15°C

Table 3.3 Relationship between climate regions and average ambient temperature (Lüer 2010).

This characteristic mainly influence:

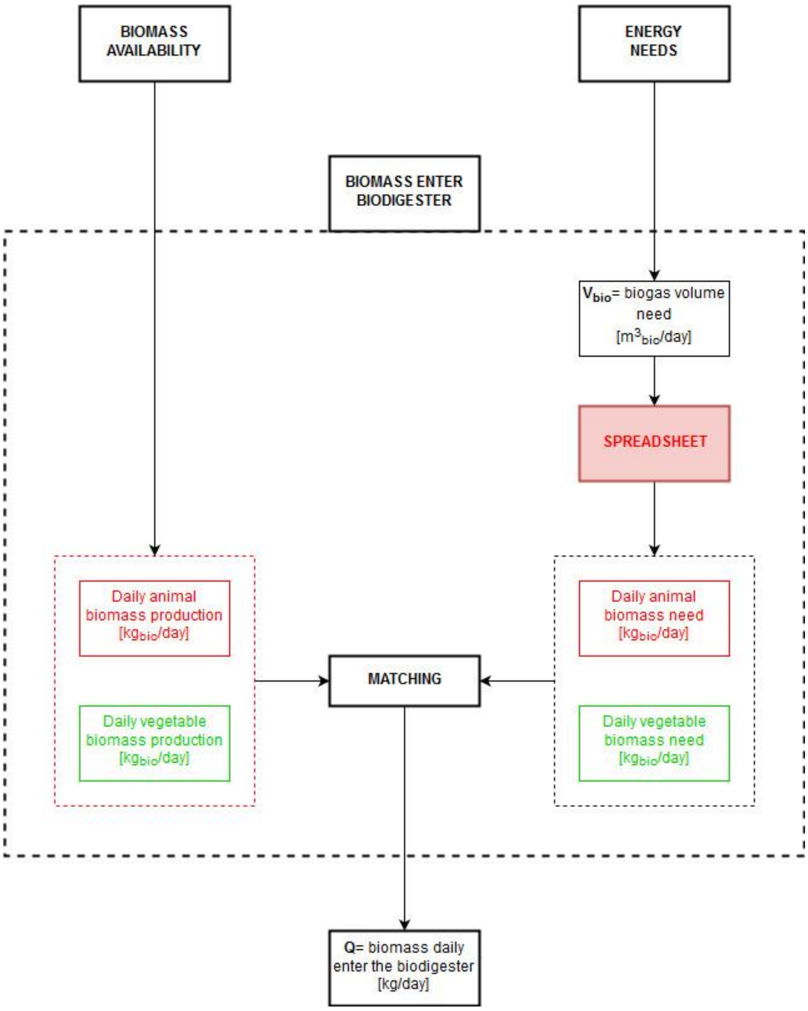
- The choice of the HRT due to the fact that this parameter is related to the temperature of the process, and so, to the mean temperature of the ambient;
- The choice of the biodigester type, because not all the biodigester can be applied in every climate region due to the characteristic of isolation of the technology;
- The infrastructures that must be built within the biodigester, for example the greenhouse in case of biodigester in Altiplano region or other cold regions.

- **Season and climate:** the season, and its characteristic, must be considered especially during the construction phase because they influence the soil condition. The rain season could be problematic because, due to the strong precipitations, the roads could be closed or difficult to run leading to problems of material transportation during the realization phase. On the other hand, during the dry season, especially in sandstone and clay area, the absence of water make the soil hard to be dug.
- **Transportation service and connections**: if the project location is far away from the main centre, the transportation services of the region and the connection road, or river, and their condition must be considered. First of all, for the transportation of the material during the construction phase, but also in case of substitution of features during the operating and maintenance period. As seen before, this part is also related to the season.
- **Biodigester location:** the biodigester couldn’t be positioned farther than 30 meters from the tanks due to the low pressure of the biogas that make difficult to reach the tanks. For the farmer comfort, it is also useful put the biodigester near to the place where the biomass is collected. If the two place are far away from each other is better to place the biodigester near to the tanks because, otherwise, a compressor must be insert to win pressure drop between the biodigester and the tanks increasing, in this way, the complexity and the cost of the plant.
- **Water:** the presence of water is fundamental for the biodigester application. The quantity of water needed is proportional to the biodigester dimension and to the energy demand of the kitchen. The presence of water must be ensured for the whole operating period and also the quality must be considered in order to avoid problem to the bacteria inside the biodigester.
- **Technical skills:** the technical and professional skills of the workers in the location must be considered both during the construction and the operation phase. Especially for the maintaining phase capacity building must be performed.

The characteristics already listed are the most important and must be always considered in every project implementation. Of course, every project present peculiar problematic that must be evaluated during the design phase.

3.1.4 Matching biomass and energy needs

This block aims to calculate the exact quantity and type of biomass for supply to the energy needs. The daily biomass enters the biodigester is calculated matching the biomass, animal and vegetable, available and the biomass need in order to produce the daily biogas volume need.
The process is represented in the following diagram:



Graph 3.4 Biomass enters biodigester: calculation process.

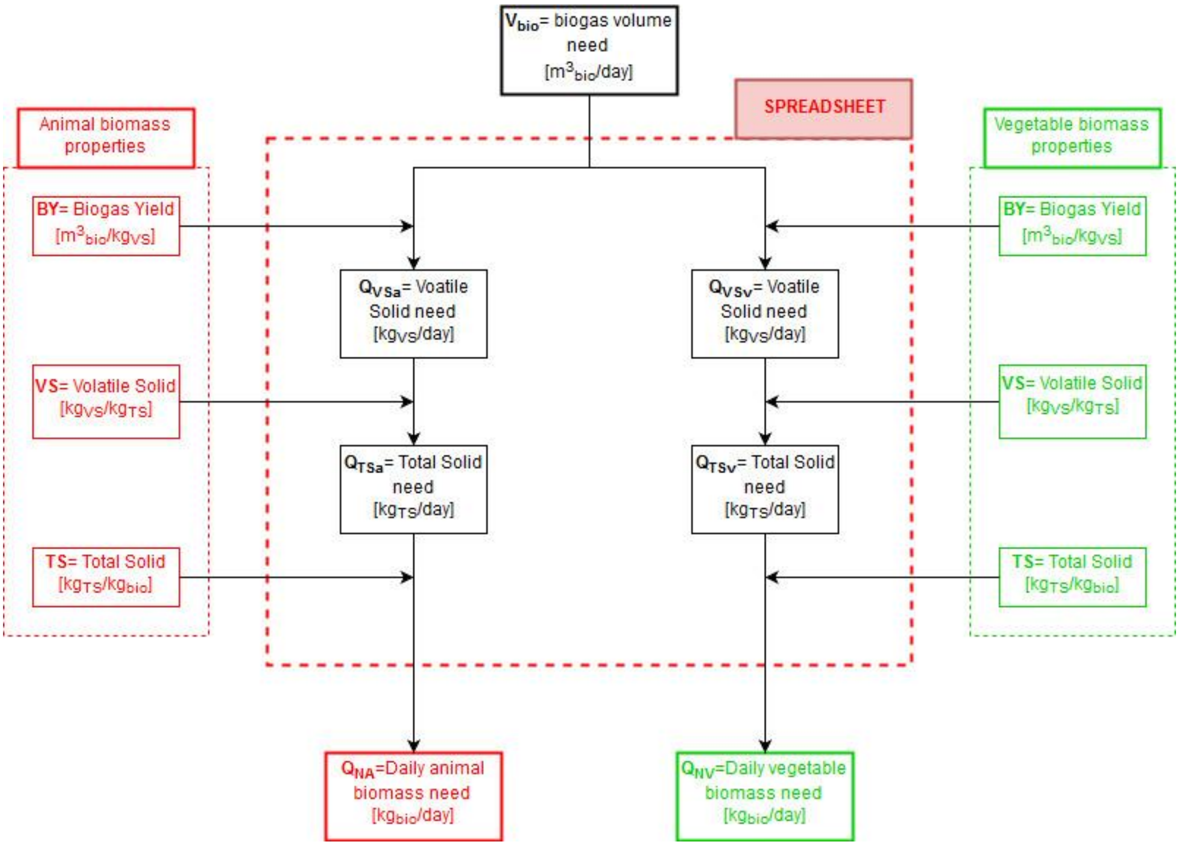
Inside the main block there are two calculation cells:

- Spreadsheet: this block aims to transform, thanks to the characteristic of the available biomass, the biogas volume need into biomass need;
- Matching: it is a logical process that gives back the total quantity of biomass daily enter the biodigester and its composition (e.g. quantity of vegetable biomass and animal biomass).

Spreadsheet

The block calculates the quantity of animal and vegetable biomass that is necessary to enter in the biodigester in order to supply to the whole energy demand.

Knowing the biomass properties, it is possible to calculate the quantity of biomass as follow:



Graph 3.5 Spreadsheet structure.

The block, inside, is divided in two columns, the left one for the animal biomass and the right one for the vegetable biomass.

For what concern the daily animal biomass need, the calculation is performed as follow:

1. Calculation of the Volatile Solid need:

$$Q_{VSa} = \frac{V_{bio}}{BY}$$

Where:

Q_{VSa}= daily Volatile Solid demand from animal biomass [kg_{VS}/day];

V_{bio}= daily biogas volume demand [m^3/day];

BY= Biogas Yield [m^3_{bio}/kg_{VS}].

2. Calculation of the Total Solid need:

$$Q_{TSa} = \frac{Q_{VSa}}{VS}$$

Where:
Q_{TSa}= daily Total Solid demand from animal biomass [kg_{TS}/day];
Q_{VSa}= daily Volatile Solid demand from animal biomass [kg_{VS}/day];
VS= Volatile Solid concentration for animal biomass [kg_{VS}/kg_{TS}].

3. Calculation of the daily animal biomass need:

$$Q_{NA} = \frac{Q_{TSa}}{TS}$$

Where:
Q_{NA}= daily animal biomass need [kg_{bio}/day];
Q_{TSa}= daily Total Solid demand from animal biomass [kg_{TS}/day];
TS= Tolatile Solid concentration for animal biomass [kg_{TS}/kg_{bio}].

In this way, it is possible to obtain the overall quantity of animal biomass in order to guarantee the production of the whole quantity of biogas necessary to satisfy the kitchen's energy needs. This calculation could be performed for every animal present in the farm just changing the biomass properties.

For what concern the daily vegetable biomass need, the calculation is performed as follow:

1. Calculation of the Volatile Solid need:

$$Q_{VSv} = \frac{V_{bio}}{BY}$$

Where:
Q_{VSv}= daily Volatile Solid demand from vegetable biomass [kg_{VS}/day];
V_{bio}= daily biogas volume demand [m^3/day];
BY= Biogas Yield [m^3_{bio}/kg_{VS}].

2. Calculation of the Total Solid need:

$$Q_{TSv} = \frac{Q_{VSv}}{VS}$$

Where:
Q_{TSv}= daily Total Solid demand from vegetable biomass [kg_{TS}/day];

Q_{VSv}= daily Volatile Solid demand from vegetable biomass [kg_{VS}/day];
VS= Volatile Solid concentration for vegetable biomass [kg_{VS}/kg_{TS}].

3. Calculation of the daily vegetable biomass need:

$$Q_{NV} = \frac{Q_{TSv}}{TS}$$

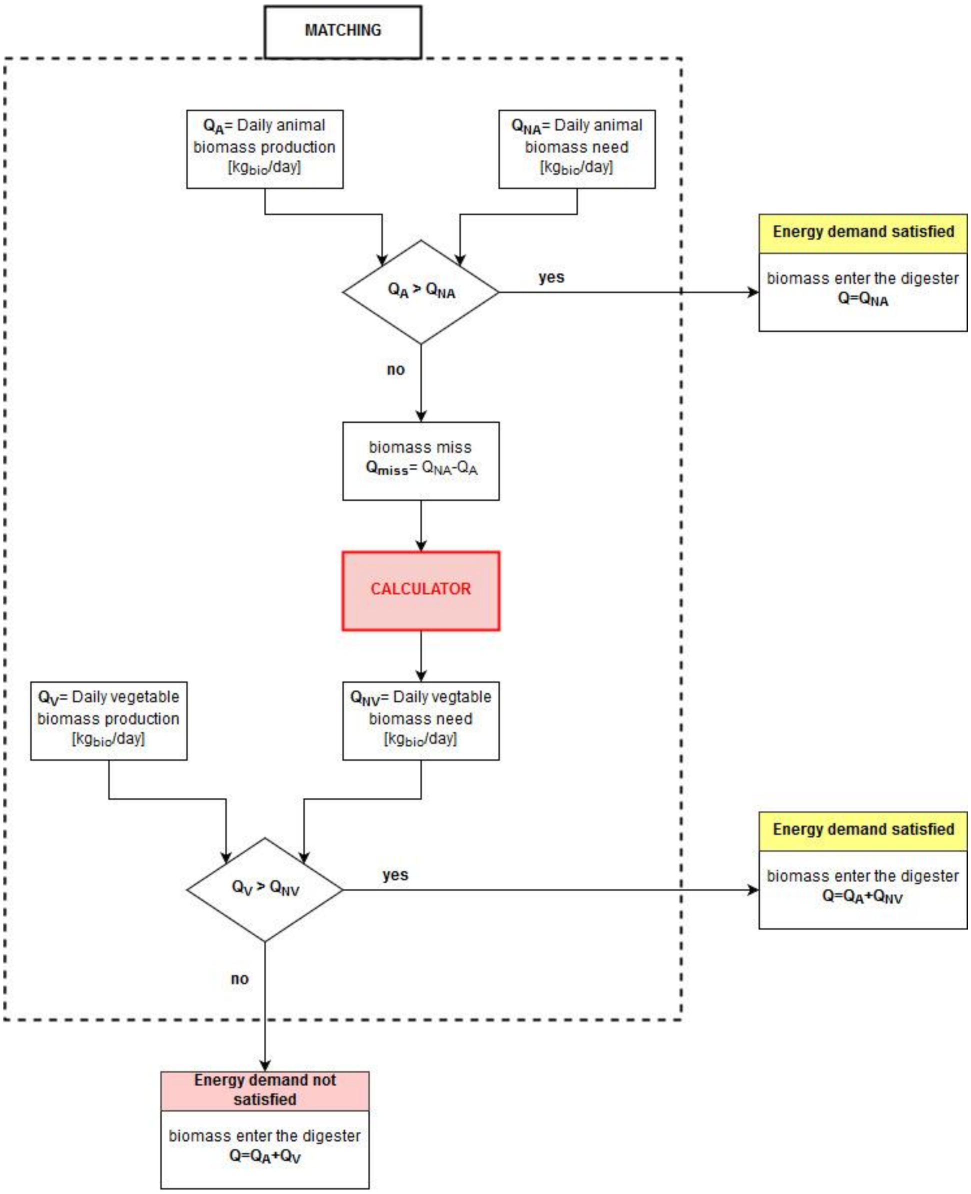
Where:
Q_{NV}= daily vegetable biomass need [kg_{bio}/day];
Q_{TSv}= daily Total Solid demand from vegetable biomass [kg_{TS}/day];
TS= Tolatile Solid concentration for vegetable biomass [kg_{TS}/kg_{bio}].

In this way, it is possible to obtain the overall quantity of vegetable biomass in order to guarantee the production of the whole quantity of biogas necessary to satisfy the kitchen's energy needs. This calculation could be performed for every kind of crop cultivation and vegetable biomass present in the farm just changing the biomass properties.

Matching

The decision process of the quantity of biomass that enter the biodigester is influenced by the context. If not specified it is better to consume as first all the animal biomass and then, if the animal biomass is not sufficient, use in addition the vegetable biomass. This choice is made according to the fact that the animal biomass, if not properly treated, is very polluting due to its degradation process. The vegetable biomass could be used as feed for the animal, in this way the degradation, and its environmental problems, are voided.

The logical process of the Matching is reported in the following diagram:



Graph 3.6 Matching: logic process.

1. The animal biomass available and the animal biomass need must be compared to understand if the vegetable biomass is necessary.
   The comparison can produce two results:
   - The biomass need is lower that the biomass available. In this way, it is possible to cover all the demand with only the animal biomass. In this case the biomass that enter the biodigester is equal to:

     $$Q = Q_{NA}$$

     Where:
     Q= daily total biomass needs [kg_{bio}/day];
     Q_{NA}= daily animal biomass need [kg_{bio}/day].

- The biomass need is higher than the biomass available. In this way is not possible to cover all the demand just with the animal biomass, but a mix of biomasses is needed.

2. Calculation of the quantity of biomass that miss in order to satisfy the energy demand:

$$Q_{miss} = Q_{NA} - Q_A$$

Where:
Q_{miss}=quantity of biomass missing [kg_{bio}/day];
Q_{NA}= daily animal biomass need [kg_{bio}/day];
Q_A= daily animal biomass available [kg_{bio}/day].

3. The "*Calculator*" block works as follow: the quantity of missing biomass must be transformed in biogas demand, in this way is obtained the quantity of missing biogas that must be produced by the vegetable biomass:

$$V_{bio}^{miss} = Q_{miss} \cdot TS \cdot VS \cdot BY$$

Where:
V_{bio}^{miss}=quantity of missing biogas [m^3_{bio}/day];
Q_{miss} =quantity of biomass missing [kg_{bio}/day];
TS= Tolatile Solid concentration for biomass [kg_{TS}/kg_{bio}];
VS= Volatile Solid concentration for biomass [kg_{VS}/kg_{TS}];
BY= Biogas Yield [m^3_{bio}/kg_{VS}].

Now, using the tool "*Spreadsheet*", it is possible to calculate the quantity of biomass necessary to supply to the whole biogas need.

4. Once the quantity of biomass need is obtained, must be compared with the biomass available to verify if it is possible to cover all the biogas demand. As mentioned before, two result can be obtained:
   - The biomass demand is lower than the biomass available. In this way, it is possible to cover all the demand with a mix of animal biomass and vegetable biomass. In this case the biomass that enter the biodigester is equal to:

$$Q = Q_A + Q_{NV}$$

Where:
Q= daily total biomass needs [kg_{bio}/day];
Q_A= daily animal biomass available [kg_{bio}/day];
Q_{NV}= daily vegetable biomass need [kg_{bio}/day].

- The biomass demand is higher than the biomass available. In this way, it is not possible to cover all the demand with a mix of animal biomass and vegetable biomass. In this case the biomass that enter the biodigester is equal to:

$$Q = Q_A + Q_V$$

Where:
Q= daily total biomass needs [kg_{bio}/day];
Q_A= daily animal biomass available [kg_{bio}/day];
Q_V= daily vegetable biomass available [kg_{bio}/day].

3.1.5 Technology selection process

In order to select the appropriate technology, it is useful to compare the different available technologies of low cost biodigester for rural application looking at different technical characteristics.
The most important parameters selected for the comparison are:

- Digestion useful volume;
- Life span;
- Initial investment cost;
- Construction time;
- Maintenance;
- Climate conditions.

During the selection is important to taking into account the "*Context Characteristics*" already mentioned in the previous paragraph, especially for what concern the "Climate conditions" and "*Skills, labour and material*" that are strictly related to the location.
In this paragraph, will be compared the three technologies mainly used in Developing Countries and already described in the previous chapter:

- Tubular Digester;
- Fixed Dome Digester;
- Floating Drum Digester.

Digestion Useful Volume
In the following chart are reported the dimension of the digestion chamber that the different technologies can have:

Graph 3.7 Volume range for digester technologies.

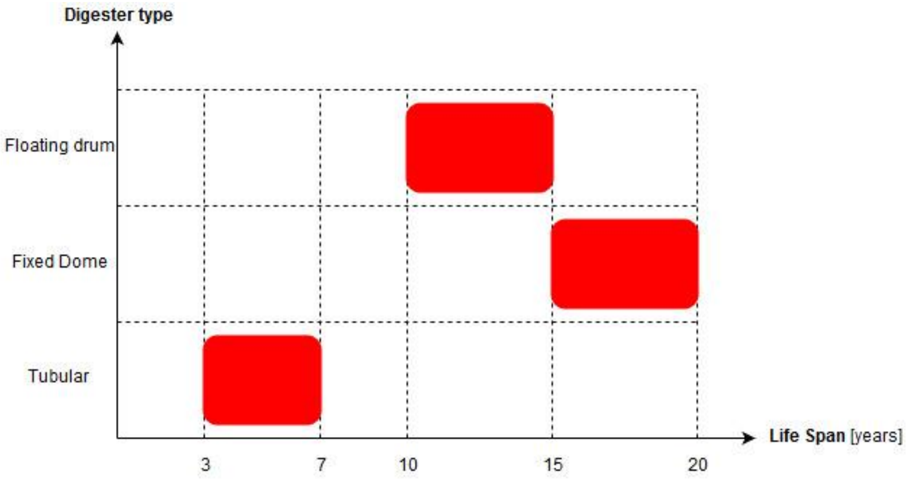
It is easy to see that the Tubular Digester is preferable for the small application, instead of the other two that present very high volume. In case it is mandatory to use a Tubular Digester (e.g. high altitude application) it is better to divide the overall digester volume in different small tubular digester rather than built a huge one. In a Tubular Digester, the volume is proportional to the length, so big volume means that the digester is very long, this could generate problem in the biomass flowing and mixing inside the digester, diminishing the digestion efficiency.

The volume depends by three parameters:

- The daily quantity of biomass enters the biodigester, and so by the energy demand;
- The Waste to Water ratio, a parameter that is characteristic of every technology and identify the quantity of water used to dilute the biomass enters the biodigester;
- The HRT.

In the next paragraph, will be deeply explained the relationship between these parameters and the volume.

Life Span



Graph 3.8 Life span for digester technologies.

As it is possible to see from the chart, there is a huge difference among the Tubular Digester and the other technologies. This is due to the fragility of the plastic bag that, due to the effect of the sun, tends to deteriorate very fast when is not properly covered.

For what concern the Floating Drum, it is useful to remark that, even if present a quite long life span, the steel drum must be substitute every 3 or 5 years due to the problem of corrosion and this can increase the total cost of investment.

The Fixed Dome model is the most resistant but cannot be repaired in case of problem at the digestion chamber (e.g. leaks, clogging, foam formation…) on the contrary the other two model could be repaired, easily substituted or opened.

In conclusion, it is possible to say that the Life Span strictly depends by how aggressive is the environment where the biodigester is (e.g. effect of the sun, rain, humidity…) and by the level of maintenance.

Initial Investment Cost

The Initial Investment Cost is mainly related to two voices: the material and the labour. In the following table are reported the main cost voices for the different technologies and how the influence the cost of investment.

Technology	**Cost voice**		**Initial Investment Cost**
	Labour	*Material*	
Tubular Digester	Not relevant, could be self-built.	PVC digester bag.	Low
Fixed Dome Digester	Very relevant, specialized worker are needed.	Bricks and concrete.	Quite High
Floating Drum Digester	Very relevant, specialized worker are needed.	Steel drum, bricks and concrete.	High

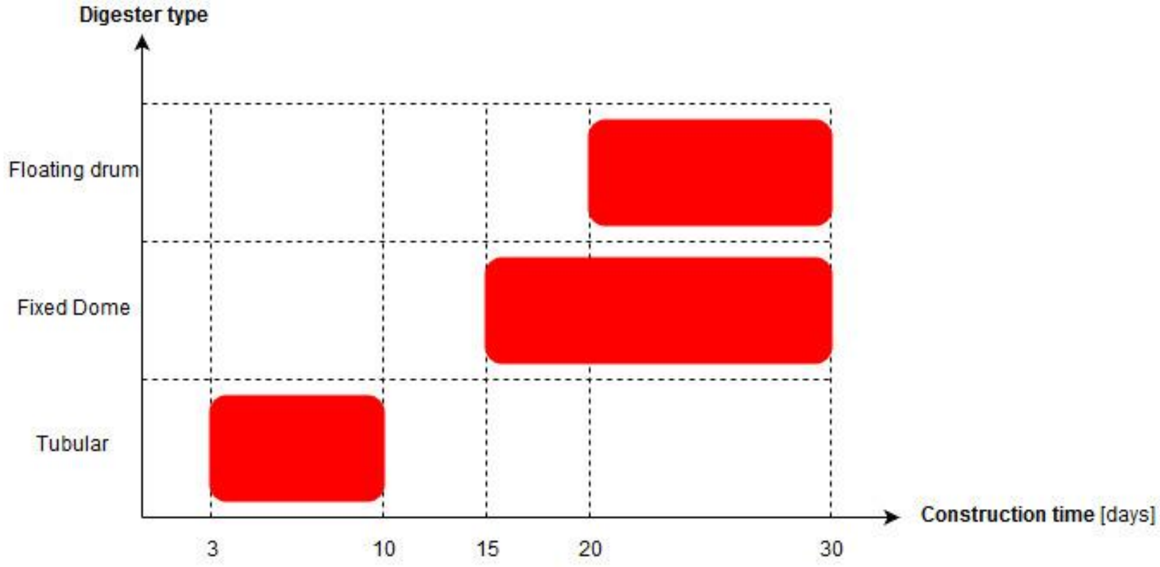
Table 3.4 Investment voice cost for digester technologies (Lüer 2010).

From the table is evident that the Floating Drum model is the most expensive. The high cost is caused by the combination of the great amount of specialized labour needed and the cost of the steel drum, that is the most expensive part of the apparatus.

The Fixed Dome Digester present a cost that is lower rather than the Floating Drum technology but remain still high because specialized workers are required. Combining the labour with the long time that the construction phase needs, result a cost that is quite high. On the other hand, the materials are quite cheap and easy to find.

Due to the fact that could be self-built and doesn’t need specialized workers, the Tubular model is the cheapest one. The main cost voice is the PVC digester bag. This features could be bought already equipped with the exit valve or built starting from a PVC sheet. The self-built solution is cheaper but, in the end, present a lower quality rather than an industrial one. The absence of heavy material and the versatility of the PVC digester bag make the material transportation very easy.

Construction time



Graph 3.9 Construction time for digester technologies.

To build a low cost biodigester for rural application, the construction phases that must be done are the following:

- Digging the hole for the digestion chamber;
- Build the digestion chamber;
- Built the distribution system.

Excluding the third point, that takes the same time for every technology, the main difference, about construction time, between the Tubular Digester and the other technologies is the time needed for built the digestion chamber. The time needed for dig the soil is, more or less, the same for the three technologies, a bit more for the Fixed Drum model because all the chamber is underground, while, in the other two model, only the liquid volume part of the chamber is underground. In the Tubular Digester, the digestion chamber is made by the PVC bag, so it is already built, while, in the other two model, must be built with bricks and concrete with a particular shape that could takes lot of time.

Maintenance

A good operating and maintenance could improve the digester life span, especially for the Tubular model that is so fragile.

In the following table are reported the peculiar maintenance operation that must be done for the different technologies:

Technology	Maintenance operation	Frequency	Cost
Tubular Digester	Check the PVC bag condition	Every week	Quite low

	Substitute PVC bag	Every 3-7 years	Quite high compared to initial investment
Fixed Dome Digester	Nothing in particular	-	-
Floating Drum Digester	Drum painting	Every 1-2 years	Quite high
	Substitute the steel drum	Every 5 years	Quite high

Table 3.5 Maintenance operations and cost for digester technologies (Lüer 2010).

It could be notice from the chart that the Fixed Dome digester doesn’t present any extra maintenance costs or operation beyond the ordinaries. This is because it doesn’t present any part subjected to deteriorating process. Even if this is a positive stuff, in case of leak or damage, the Fixed Dome model cannot be repaired because is completely closed.

The Floating Drum digester presents a very high maintenance cost due to the corrosion that affect the steel drum forcing to painting it every 1 or 2 years and to substitute it every 5 years with a very high cost.

Compared to the other technologies, the Tubular model present a very simple maintenance operation that consist to repair the leaks, if occur, welding the PVC and substitute the bag at the end of life. The bag substitution presents a very high cost if compared with the total investment, but a very low cost if compared to the other technologies.

Climate condition

As explained in the “Context Characteristics”, every climate region present peculiar characteristics that influence the choice of the digester.

For the warm and temperate regions, every technology could be used because the temperature is quite high and it is possible to remain in the mesophilic range. In the cold region, such as Altiplano, it is better to choose a Tubular digester coupled with a greenhouse. This because the soil, at the equilibrium, reach the same temperature of the air and so all the technologies that are built underground work within a temperature that is too low. On the contrary, the Tubular model is not totally underground and if properly isolated and covered with a greenhouse, could maintain an acceptable temperature.

3.1.6 Technology design process

The design of a biodigester consists in the dimensioning of the liquid volume and gas volume that together represent the overall digester volume.

The digester volume is influenced by three parameters that mainly depend by the technology and the mean operating temperature, and so by the context:

- Hydraulic Retention Time (HRT): as explained before, the HRT is the average time that the inlet flow rate needs in order to cross the digester and reach the 80-85% of the maximum ideal biogas production. Depends by the temperature, lower the temperature, higher the HRT because the bacterial activity is reduced due to the low temperature and so they need more time in order to digest the substrate. The HRT value is arbitrary chose according to the average temperature:

Climate region	Average temperature	HRT
Tropical/Rain forest	T > 20°C	25-30 days
Valley	15°C < T < 20°C	30-45 days
Altiplano	0°C < T < 15°C	60-90 days

Table 3.6 Relationship between climate regions and HRT (Lüer 2010).

These are only suggested values, it is always possible to increase the HRT in order to reach a higher production, or decrease its value in order to reduce the cost (Vögeli et al. 2014).

- Gas Volume Ratio (x): this value is characteristic for every technology, express the ratio of the total digester volume that is occupied by the gas. This value is 0 for the Floating Drum digester because the gas is cumulated in the steel drum and not in the digester volume, so all the digester volume is occupied by the liquid (Martí-Herrero et al. 2014).
- Waste to Water ratio (WtW): indicates the quantity of water necessary in order to dilute the biomass. Depends by the technology and it is higher for the Tubular digester because it needs to work with a very liquid substrate in order to avoid problems of clogging (Rakotojaona 2013).

In the following table are resumed the characteristics of the different technologies:

Technology	**x** $[m^3_{gas}/m^3]$	**WtW** $[kg_{bio}/kg_w]$
Fixed Dome	1/4	1:1
Floating Drum	0	1:1
Tubular	1/5	1:3

Table 3.7 Waste to Water ratio and Gas Volume ratio for digester technologies (Rajendran et al. 2012).

Once given the technologies characteristics and the daily quantity of biomass enter the digester it is possible to proceed with the total volume calculation.
The digestion of a substrate is a biological process that depends by the bacteria activity that could be influenced, in a positive or negative way, bay every, even small, change of the operating environment. This could lead to a lower gas production, in this way the energy demand could not be satisfied. It would be appropriate to apply a *safety factor* in order to guarantee the right biogas production even in case of problem, such as lower bacterial activity due to the temperature or substrate characteristic changes. The daily biomass quantity calculation is a linear process, so the safety factor could be applied to the biogas demand or to biomass demand.

The design process is performed as follow:

1. Design a proper Safety Factor in order to overestimate the gas production:

$$Q_{bio} = SF \cdot Q_D$$

Where:

Q_{bio}= real biomass quantity that daily enters the digester [kg_{bio}/day];
Q_D= designed biomass quantity that daily enters the digester [kg_{bio}/day];
SF= safety factor [-].

2. Calculate the total mass flow rate that daily enter the biodigester. This flow rate is composed by the substrate and the water used to dilute them:

$$\dot{Q}_{day}^{tot} = Q_{bio} \cdot \left(1 + \frac{1}{WtW}\right)$$

Where:
$\dot{Q}_{day}^{tot}$= daily quantity of mix enters the digester [kg/day];
Q_{bio}= biomass quantity that daily enters the digester [kg_{bio}/day];
WtW= waste to water ratio [kg_{bio}/kg_w].

Due to the fact that the biomass used is very humid, so it has a high content of water, and due to the high water quantity, that is added in order to dilute the biomass, it is possible to consider the mix density equal to the water density and, in this way, pass from a mass flow rate to a volume flow rate:

$$\dot{V}_{day}^{tot} = \frac{\dot{Q}_{day}^{tot}}{\rho_{water}}$$

Where:
$\dot{V}_{day}^{tot}$= volume flow rate of mix that daily enter the digester [m^3/day];
$\dot{Q}_{day}^{tot}$= daily quantity of mix enters the digester [kg/day];
ρ_{water}= water density [kg/m^3].

3. Calculation of the total digester volume:

$$V_{tot} = \frac{HRT \cdot V_{day}^{tot}}{1 - x}$$

Where:
V_{tot}= total digester volume [m^3];
$\dot{V}_{day}^{tot}$= volume flow rate of mix that daily enter the digester [m^3/day];
HRT= hydraulic retention time [day];
x= gas volume ratio [m^3_{gas}/m^3].

Once calculated this value the general design process is over. The dimensions of the digestion chamber (such as depth, diameter, length…) must be designed according to the digester model because for every type of technology are present different models that have different chamber shape and so must be properly designed. This document doesn't tackle with this design problem. In the next chapter, will be deeply analysed the design process for a Tubular digester.

3.2 Biomass characteristics: comparison between bibliography and laboratory data

This paragraph aims to present the laboratory procedure and the data obtained during the laboratory experience at *Universidad del Paz* of Barrancabermeja and compare this data with the bibliography. Also, the biodigester monitoring procedure used to obtain the efficiency of digestion of the Tubular digester and applied to the farm "*Finca Comunitaria de RecrÍa de Bufalo*" in the ZCR of Cimitarra river valley will be explained.

Two biomass parameters were analysed in laboratory:
- Total Solid content of animal biomass of swine;
- Volatile Solid content in dried animal biomass of swine.

The data obtained where then compared with data collected from bibliography in order to adjust the biodigester design model. The biomass samples were analysed in the Chemistry Laboratory of the Universidad de la Paz of Barrancabermeja.

To design the biodigester data from bibliography regarding the biogas yield of swine biomass were also collected.

The samples for the tests were collected directly in field for five consecutive days every two weeks for three times in order to follow the animal growth.

In the pigsty were initially present twelve pigs divided into five liveries, in order to collect a homogeneous sample, the dung was collected from every livery every 24 hours and mixed together. In this way, the sample could better represent the average characteristics of the whole pigsty.

For the weight measurement, the following balance was used:

Producer: *Ohaus Explorer*
Model: *EX225M/AD*
Maximum weight: *220 g*
Accuracy: *0,1 mg*

Figure 3.1 Balance Ohaus Explorer, EX225M/AD.

3.2.1 Total solid

This parameter represents the overall amount of solid present in the biomass and is indicated as percentage over total wet matter. It is important to know its value due to the fluctuation that affect it in relation with the diet followed by the animal and the type of breeding. Also, the definition of the solid matter is the starting point to define the Volatile Solid.
It is important to verify that the value of solid content is not too high or too far from the bibliography value, otherwise a correction of the design model is needed especially for what concern the water flow rate for the biomass dilution.
For the biomass drying process, the following hoven was used:

Producer: *Memmet*
Model: *Horno universal UNplus*
Maximum temperature: *+330 °C*
Accuracy: *0,5 °C*
Convection: *forced*
Electric connection: *220V; 50/60 Hz*
Power: *2000 W*

Figure 3.2 Hoven Memmet, UNplus.

Experimental procedure:

1. Divide the sample biomass in the pot. Put a quantity of biomass in between of 15g and 30g in order to facilitate the drying process.
2. Measure the weight of wet biomass.
3. Put the biomass in a ventilated hoven previously set at 105°C.
4. After 6 hours remove the biomass from the hoven.
5. Measure the weight of dried biomass.

Figure 3.3 Biomass before drying treatment.

Figure 3.4 Biomass after drying treatment.

The value of Total Solid is calculated as follow:

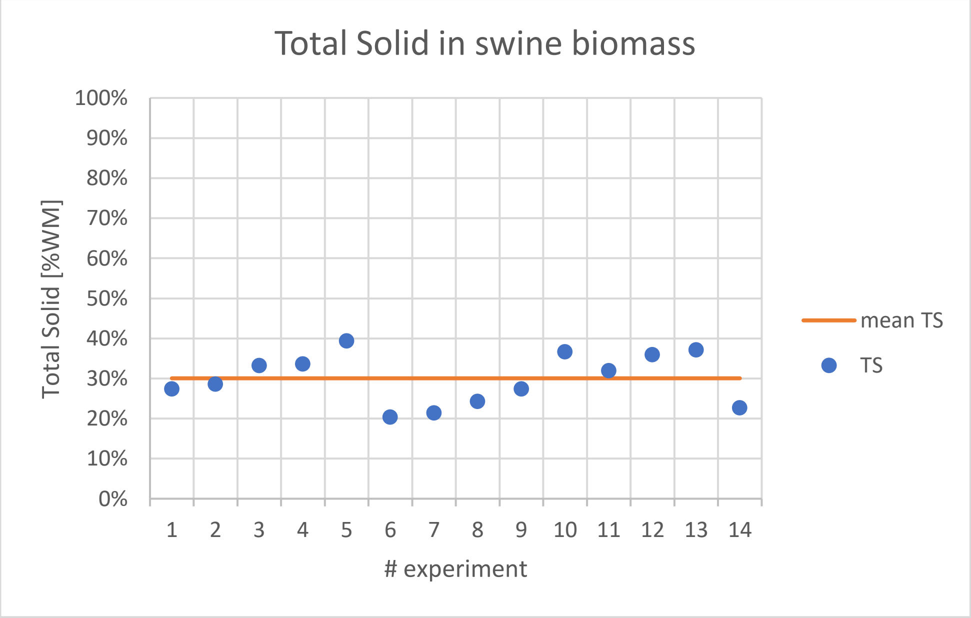
$$TS = \frac{weight\ of\ dry\ matter}{weight\ of\ wet\ matter}\ [\%WM]$$

The results obtained during the laboratory test are reported in the following table.

Week	**# experiment**	**Wet matter** *[g]*	**Dry matter** *[g]*	**TS** *[%WM]*
1	1	17.2382	4.7341	**27.46%**
	2	20.0823	5.7561	**28.66%**
	3	21.8961	7.2846	**33.27%**
	4	18.4970	6.2204	**33.63%**
	5	16.5361	6.5226	**39.44%**
2	6	17.2270	3.5120	**20.39%**
	7	17.3740	3.7310	**21.47%**
	8	16.2010	3.9440	**24.34%**
	9	20.8350	5.7140	**27.43%**
	10	22.9106	8.4123	**36.72%**
3	11	26.9010	8.6011	**31.97%**
	12	17.1811	6.1777	**35.96%**
	13	18.6586	6.9385	**37.19%**
	14	22.5121	5.1124	**22.71%**

Table 3.8 Experimental results Total Solid.

In the following graph the trend of the data confronted with the mean value is reported:



Graph 3.10 Total Solide in swine biomass trend.

The measured value of Total Solid for the swine biomass result: **30,05 ± 6,29** %.

In the following table the data regarding the Total Solid in swine biomass present in bibliography are reported:

Reference	**TS** *[%WM]*
(Mayerle & Neiva de Figueiredo 2016)	5.50 %
(Ferrer et al. 2009)	6.40 %
(Ferrer et al. 2009)	8.20 %
(Ferrer et al. 2009)	7.30 %
(Ferrer et al. 2009)	8.90 %
(Brunetti 2013)	5.35 %
(Qiao et al. 2011)	28.14 %
(Alvarez & Lidén 2008)	30.80 %
(Esposito et al. 2012)	10.15 %
(Bordoni et al. 2015)	24.00 %
(Sasse 1988)	17.00 %

Table 3.9 Total Solid literature values.

From the data collected from the bibliography result a value of Total Solid in swine biomass equal to: **13,79 ± 9,57 %**.

	Literature value	*Present value*
Total Solid	13,79 ± 9,57 %	30,05 ± 6,29 %

Table 3.10 TS: comparison between literature value and present value.

The difference between the bibliography data and the data collected in the farm, even if is not negligible, could be caused by the age of the swine and by their diet. If the swine are fed with dry food, the concentration of Total Solid in the faeces could double compared to value that usually have (Bordoni et al. 2015).

It is necessary to wait that the animals reach the adult age in order to have the most significant data, nowadays is only possible to monitor the variation in the Total Solid concentration and adapt, time by time, the dilution water in order to obtain the desired concentration of solid entering the digester to avoid clogging.

3.2.2 Volatile solid

This parameter represents the overall amount of organic matter present in the biomass and is expressed as percentage of dry matter. The volatile solids are that part of the biomass that is transformed in gas during the combustion process and is considered equal to the organic content. The biomass organic part is the biomass fraction that is digested by the bacteria and transformed into biogas, so, higher is the value greater is the production. As mentioned before the Volatile Solid are used for calculate the Organic Load Rate (OLR) that must be lower than 2 kg_{VS}/m^3 per day in order to avoid inhibition of the bacteria.

The same samples used for the Total Solid test were also used for the Volatile Solid test.

For the biomass burning process, the following muffle was used:

Producer: *Terrigeno*
Model: *D8*
Maximum temperature: *+1200 °C*
Accuracy: *1 °C*
Electric connection: *220V; 60 Hz*

Figure 3.5 Muffle Terrigeno, D8.

Experimental procedure:

1. Set the muffle at 650°C and wait that reach the equilibrium point;
2. Measure the weight of the dry biomass;
3. Put the sample in muffle for 6 hours;
4. Measure the weight of the ashes remained after the process.

Figure 3.6 Biomass after burning process.

The value of Volatile Solid is calculated as follow:

$$VS = \frac{weight\ of\ dry\ matter - weight\ of\ ashes}{weight\ of\ dry\ matter} = 1 - \frac{weight\ of\ dry\ ashes}{weight\ of\ dry\ matter}\ [\%DM]$$

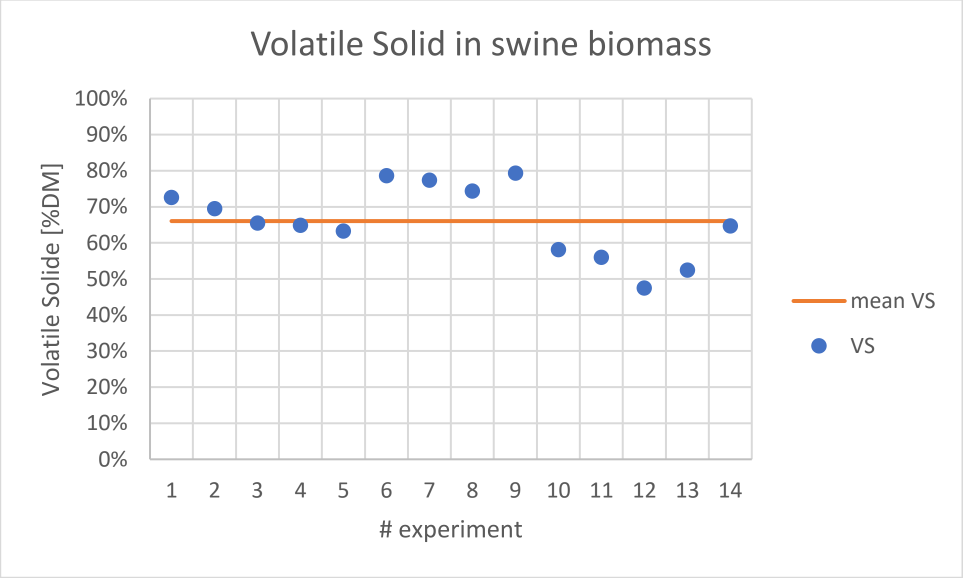
The results obtained during the laboratory test are reported in the following table.

Week	# experiment	Dry matter *[g]*	Ashes *[g]*	VS *[%DM]*
1	1	4.7341	1.2979	**72.58%**
	2	5.7561	1.7551	**69.51%**

	3	7.2846	2.5096	**65.55%**
	4	6.2204	2.1818	**64.93%**
	5	6.5226	2.3931	**63.31%**
2	6	3.5120	0.7510	**78.62%**
	7	3.7310	0.8430	**77.41%**
	8	3.9440	1.0080	**74.44%**
	9	5.7140	1.1800	**79.35%**
	10	8.4123	3.5188	**58.17%**
3	11	8.6011	3.7845	**56.00%**
	12	6.1777	3.2417	**47.53%**
	13	6.9385	3.2980	**52.47%**
	14	5.1124	1.8035	**64.72%**

Table 3.11 Experimental results Volatile Solid.

In the following graph is reported the trend of the data confronted with the mean value:



Graph 3.11 Volatile Solide in swine biomass trend.

The measured value of Volatile Solid for the swine biomass result: **66,04 ± 9,96** %.

In the following table are reported the data regarding the Total Solid in swine biomass present in bibliography:

Reference	**VS** *[%DM]*
(Mayerle & Neiva de Figueiredo 2016)	75.00 %
(Ferrer et al. 2009)	68.60 %
(Ferrer et al. 2009)	75.70 %

(Ferrer et al. 2009)	53.60 %
(Ferrer et al. 2009)	67.10 %
(Brunetti 2013)	76.92 %
(Qiao et al. 2011)	79.16 %
(Alvarez & Lidén 2008)	57.70 %
(Esposito et al. 2012)	81.83 %
(Bordoni et al. 2015)	82.50 %
(Sasse 1988)	82.35 %

Table 3.12 Volatile Solid literature values.

From the data collected from the bibliography result a value of Volatile Solid in swine biomass equal to: **72,77 ± 9,46 %**.

	Literature value	*Present value*
Volatile Solid	72,77 ± 9,46 %	66,04 ± 9,96 %

Table 3.13 VS: comparison between literature value and present value.

The value calculated in laboratory and the value that emerges from the bibliography study, are quite close and similar.

3.2.3 Biogas yield

This parameter indicates the maximum biogas production that a substrate can reach. It is an important parameter for a biogas plant but is difficult to calculate it. The only tool that is nowadays available for calculate a theoretical value of the biogas yield is the Biological Methane Potential test (BMP test). This test consists in reproduce, in laboratory scale, a controlled digestion process and measuring, day by day, the substrate biogas production. The substrate is diluted with water and mixed with a starter, in order to accelerate the starting process, and is put in a close reactor at constant temperature condition. With this test is possible to analyse different biomass, different mix of biomass, the variation of digestion time related to a variation of operating temperature and, of course, the maximum biogas production of a substrate.

This test wasn't realized for two reason:

- The laboratory of the university was not prepared for realize the BMP test;
- The low cost biodigester for rural application does not present heating and mixing system so the variables that can influence the biogas production are too many and the theoretical value is difficult to be reached.

For these reasons was preferred to evaluate the biogas yield with a bibliography study, in order to obtain a starting value for design the biodigester, and then monitor the biodigester in order to understand biogas yield of the biomass in operating conditions.

The monitoring phase will be take 90 days starting from the first day after the initial biodigester filling. The data of gas production will be taken thanks to a gas flow meter put on the gas pipeline that exit from the biodigester. The data will be noted every day at the same hour in order to have the data regarding 24h of digester working.

For the volumetric biogas production, the following gas flow meter was used:

Producer: *Wuhan Acme Agro-Tech*
Model: *Biogas flow meter, JBD2.5-SA*
Maximum flow rate: *4 m^3/h*
Minimum flow rate: *0,04 m^3/h*
Pressure losses: *< 200 Pa*

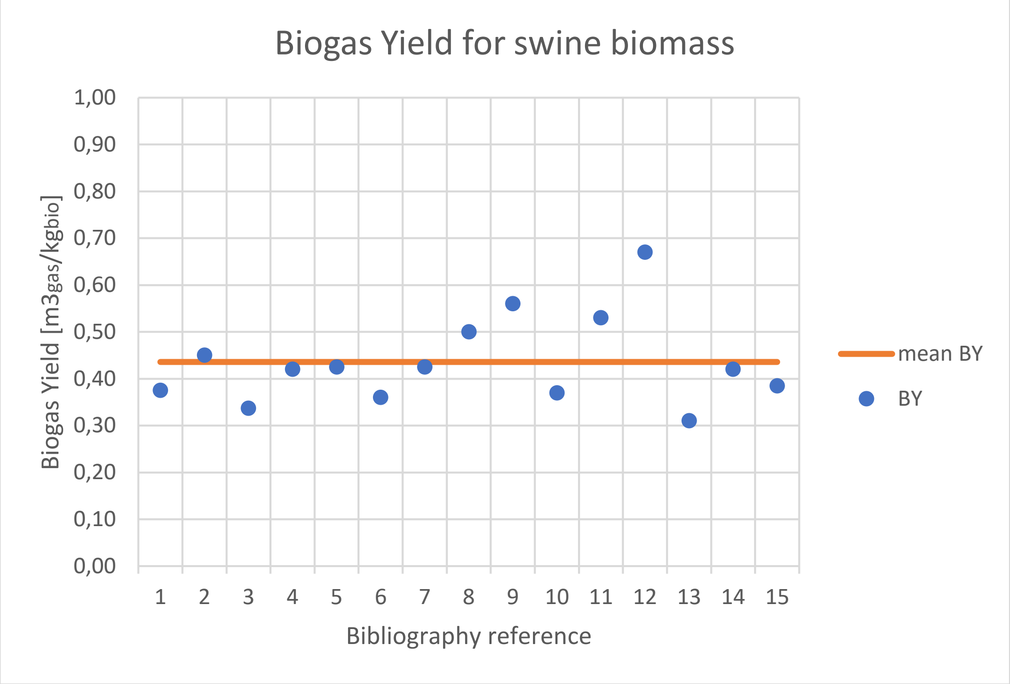
Figure 3.7 Gas flow-meter Wuhan Acme Agro-Tech, JBD2.5-SA.

The results of the bibliography study are summed up in the following table:

Reference		BY
		[m^3_{gas}/kg_{bio}]
[1]	(Al Seadi et al. 2008)	0.38
[2]	(Molina & Rostoni 2012)	0.45
[3]	(Vögeli et al. 2014)	0.34
[4]	(Garfí et al. 2016)	0.42
[5]	(Kinyua et al. 2016)	0.43
[6]	(Rajendran et al. 2012)	0.36
[7]	(Brunetti 2013)	0.43
[8]	(C.R.P.A. 2008)	0.50
[9]	(Danieli et al. 2011)	0.56
[10]	(Grignani et al. 2011)	0.37
[11]	(Del Risco et al. 2011)	0.53
[12]	(Chae et al. 2007)	0.67
[13]	(Alstals et al. 2011)	0.31
[14]	(C.E.P.I.S. 2013)	0.42
[15]	(Qiao et al. 2011)	0.39

Table 3.14 Biogas Yield literature values.

In the following graph is reported the trend of the data confronted with the mean value:



Graph 3.12 Biogas Yiel for swine biomass trend.

From the data collected from the bibliography result a value of the Biogas Yield for swine biomass equal to: **0,4358 ± 0,1261** m^3_{gas}/kg_{bio}.

4. Context analysis

The design and construction of biodigester is part of a wider project implemented in the "*Zona de Reserva Campesina del Valle del Rio Cimitarra*" (ZRC-VRC) by the association "*Associacion Campesina Valle del Rio Cimitarra*" (ACVC) to improve the housing and living condition of the farmer in the rural area.

In this chapter, will be introduced the historical, geographical and social context, in order to better understand the reasons that lead to the choice of a biodigester as appropriate technology for the rural area.

4.1 The Colombian and Magdalena Medio context

The Magdalena Medio region correspond to the geographical area located in the central part of the Magdalena river valley. It is considered a strategic area. Its importance is due to the presence of mining raw material (e.g gold, carbon and emerald), oil industry, farming and agricultural enterprises, but also for its location, in fact it has a central role for the transportation routes that connect Bogotá with the Atlantic coast, and so with the export with Central and North America. For this last reason, the region is also important for the illicit market and narcotic traffic.

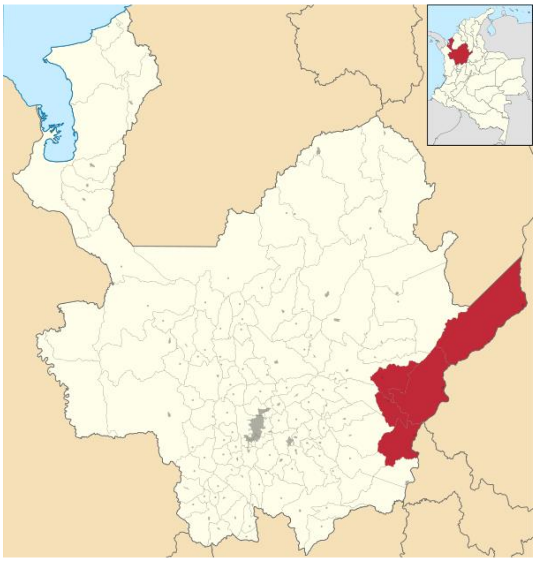


Figure 4.1 Magdalena Medio location (ACVC 2012).

Due to its strategic importance, this area, during the 1980's and 1990's, was interested by the widespread violence generated by the Colombian civil war, in particular was under the influence of guerrilla organizations, such as FARC and ELN, and paramilitary groups, generating an internal farmer displacement (Centro de Memoria Historica 2014).

4.1.1 Zona de Reserva Campesina del Valle del Rio Cimitarra

The Peasant Farmer Reserve of Cimitarra river valley (ZRC-VRC from its Spanish acronym), is an area located among the Antioquia and Bolivar department, on the opposite side of Magdalena river compared to the city of Barrancabermeja, from which is 40 km far away. The ZRC-VRC has an extension of about 1.840 km^2, that include the municipalities of Yondò, Cantagallo, Remedios and San Pablo, the population is estimated to be around 10.000 inhabitants. Every community is composed approximately by 200 inhabitants, organized in juridical-administrative figure organized in Community Action Boards(ACVC 2012).

The territory is mainly covered by rain forest and its weather is characterized by the presence of two seasons: the rainy season and the dry season, that interchanges twice a year. The mean temperatures are within 29,2°C, during March, and 27,9°C, during October; the precipitation reach the maximum value of 436 mm during the rainy season in October and the minimum value of 64 mm during the dry season in January (Climate-data.org 2016).

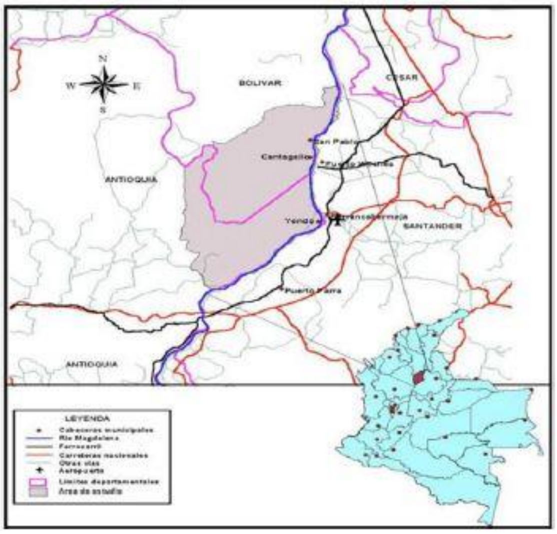


Figure 4.2 ZRC-VRC geographic location (ACVC 2012).

The Peasant Farmer Reserve Zones (ZRC from its Spanish acronym) were introduced by the Law 160 of 1994 as an answer to the farmers' protest march done in the same year (Molina Portuguez 2011). The ZRC's primary objects are:

- Contain the expansion of the agricultural border, in order to maintain the natural state of the reserve and to avoid the use of its land for agriculture;
- Correct the inequitable concentration of land ownership;
- Create conditions of strengthening and sustainably developing the peasant farmer economy;
- Regulate land use and tenancy, granting preferential distribution to peasant farmers with scarce resources;
- Establish a comprehensive model for sustainable development;
- Protect the peasant farmer economy and food sovereignty.

With this objects, in between 1997 and 2002, six ZRCs were established by the Government and, in December 2002, was initiated the ZRC of the Cimitarra River Valley (PBI 2015).

However, the 10th of April of 2003, the Government of Alvaro Uribe decided to suspend the legal recognition of the ZRC of the Cimitarra River Valley arguing that it generated social conflict in the region. The recognition of the area as a ZRC was an obstacle for the big project that the Government was trying to finalise, like, for example, the mining concession (e.g. gold and oil) for international corporation and the concession for the cultivation of palm oil (Molina Portuguez 2011).

After years of conflict and protest, in February 2011, thanks to the Government of Juan Manuel Santos, the area was recognized again as ZRC (PBI 2015). Even today, even with the recognition of reserve zone, there are a lot of problems in recognition of the land for the farmers, generating uncertainty and supporting the generation of new conflicts.

4.1.2 Associacion Campesina del Valle del rio Cimitarra

The Small-scale Farmer Association of the Cimitarra River Valley (ACVC from its Spanish acronym) is a Non Governmental Organization made up of 120 Community Action Boards (JACs from their Spanish acronym), cooperatives, fisherman committees and other groups of rural workers that operate inside the ZRC-VRC. it works mainly in the municipalities of Yondò, Cantagallo, San Pablo and Remedios (Molina Portuguez 2011).

During the 90s several peasant farmer movement emerged asking for more rights on their land and for more protection against the paramilitary and guerrilla groups that were strongly present in the region. All this movements were not so organized and were unable to bring about the social change they desired. In 1996, the ACVC was founded by peasant farmers of the Magdalena Medio region and, as a first result, achieved the recognition of the Cimitarra River Valley as a Peasant Farmer Reserve (PBI 2015).

The main aim of the association is to solve the social unbalance in the region, this is seen as a fundamental aspect in order to reach the peace in the region.

The ACVC's primary objects are:

- The diffusion and implementation of the Land Reform, in order to solve the problems of land needs, credits and technical assistance, to guarantee social benefits for all, social security, a developing plan for rural economy and a community participation to the land use and management;
- The defence of human right;
- The conservation and defence of the natural resources and wilderness of the area, generating a collective consciousness about the ration use and exploitation of natural resources;
- The strengthening of the different peasant farmer associations, promoting solidarity and cooperation among them;
- The promotion of the rural agro-economy, the defence of farmer rights according to the Law 160 of 1994;

- The improvement of the life condition for the farmers, promoting and developing basic services such as electric energy, aqueduct system, sanitary installation and gas system (ACVC 2012).

Even after 20 years of presence and working of the association on the territory, the conditions of the rural population are still very low. The life conditions are generally insecure, people live in house made with wood, sheet metal roof and topsoil ground, the basic service are, more or less, absent. There is also a huge problem of food security: low level of local production and the low variety lead to a poor nutrition (Vaccarone 2016).

4.1.3 The Colombian peace-making process

After almost 52 years of civil war, the 24th of November of 2016 the Colombian Government, under the leadership of the President Juan Manuel Santos, and the main Colombian guerrilla group FARC-EP (*Fuerzas Armadas Revolucionarias de Colombia-Ejèrcito del Pueblo*), signed in La Habana, under the supervision of the Government of Cuba, Norway, Venezuela and Chile, the "*Colombia's agreement to End Conflict and Built Peace*". This agreement was reached after several difficulties and years of negotiating.
In this paragraph is reported a summary of the agreement in order to better understand the Colombian political and social situation which is reflected then in rural area.

The agreement is divided in six parts, that try not only to guarantee the peace in the country, but also to create social development. This agreement touch different important topics such as: the women rights, the small farmer rights, the end of drug traffic, ensure political rights for the FARC-EP in order to guarantee the democracy (Government of Colombia 2016).

1) **Comprehensive rural reform:**
   This part of the agreement aims to create the conditions to ensure the health and well-being of the rural population, close the gap between the rural and urban areas and protect the environment.
   I. Land access and use: creation of a Land Fund for the free distribution of land to rural people without land. This part aims to guarantee land for the poor people and for all the people that lost their land during the conflict. Also, try to promote a proper land use, offering loans and technical assistance for the farmer, and to protect the environment, better defining the agricultural frontier.
   II. Implementation of National Plans for completely eradicate the extreme poverty, reduce the rural poverty by 50% and reduce the overall inequalities within 10 years. In order to do that will be implemented plan for expand the coverage and quality of power services in rural area, for implement healthcare, education, housing and drinking water services and for ensuring greater rural inclusion in the national economy.

III. Specialized programme for the gradual realisation of the right to food for the rural population, for dealing with hunger and malnutrition and the adoption of good eating habits.
IV. Development Programmes for the territories most affected by poverty, the conflict and illegal economies in order to speed up the execution and founding of national plans.

2) **Political participation:**

This part aim to promote the participation of the population to the political life of the country, in order to strength the pluralism and take advantage of a democratic opportunity to build peace. It organized in four points:

I. Guarantees the right for exercising political opposition;
II. Guarantees security for the exercise of politics;
III. Guarantees the democratic rights for the citizens: the right of organization, of social protest and demonstration, freedom of press and expression, promoting respect for differences, criticism and political opposition;
IV. Effective measures to promote a greater citizen participation in politics, promoting the access of small political parties and guaranteeing a transparent and participative electoral system.

3) **End of the conflict:**

This part of the agreement put the rules for the end of the conflict between the state and the FARC-EP and for the reincorporation of the rebels in the social and economic life of the country in a safe way. It is organized in three parts:

I. Agreement on the bilateral and definitive ceasefire and cessation of hostilities and laying down of arms: this part will be done with the help of United Nation (UN). FARC-EP have six months in order to gives all the weaponry to the UN, after that all the fighter have to pass six months in the Transitional Local Zones for Normalisation, to recognize their crimes and start the reintegration process.
II. Reincorporation of the FARC-EP into civilian life (in economic, social and political matters) in accordance with their interests. The reincorporation process is a transitory process that aim to promote the social coexistence and reconciliation between the fighter and the population. It guarantees the reincorporation of FARC-EP in the political life as a political party and the reincorporation in the economic life giving them loans and technical support to start their own enterprises.
III. Agreement on security guarantees and the fight against criminal organizations, in order to protect the reintroduced fighters against paramilitary group.

4) **Solution to the problem of illicit drugs:**

Clarification of the relationship between the armed conflict and the cultivation, production and commercialisation of illicit drugs. The problem of illicit drugs is deeply present in Colombia in all its aspects: cultivation, production and consumption. With this agreement, the farmers that cultivate crops made for illicit use and the users are recognized as victims of the criminality. The solution is organized in three part:

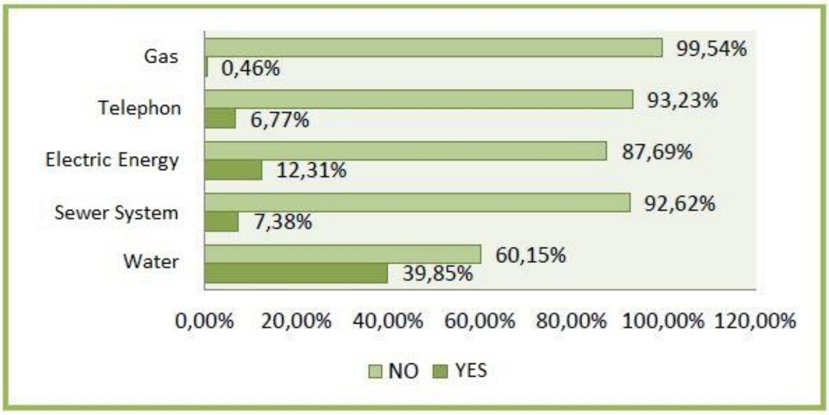
I. Solution to the problem of crops made for illicit use: proposing different alternative cultivation and technical solution to the poor farmer that are forced to cultivate crops for illicit use for survive;
II. National Programme for Comprehensive Intervention into Drug Use. Due to the fact that the drug consumption is a health problem, this program aims to give help to all those people that are drug addicted.
III. Solution to the phenomenon of production and commercialisation of narcotics, increasing the effort in the fight against criminal organization and against corruption associated with drug trafficking.

5) **Agreement regarding the victims of the conflict:**
It is a comprehensive system that try achieve the maximum possible realization of victim's rights, guarantees the non-repetition and promote the coexistence across the country. A Special Jurisdiction for Peace will be created to investigate and judge the crimes committed during the armed conflict. If, during the period of reconciliation, the FARC-EP members will recognize their crimes, they will receive a restricted sanction. This restriction is excluded in case of war crimes and crimes against humanity.

6) **Mechanism of Implementation and Verification:**
Will be created different commissions in order to guarantee compliance with the agreement, monitor and verify the right implementation of the agreement in respect of the law and in respect of the different actors' rights and duties.

4.2 The problem of gas supply in ZRC-VRC rural area

As mentioned before, the ZRC-VRC is characterized by a very low presence of infrastructures, such as electricity, gas and drinkable water supply, and even where are present the services are affected by a low reliability. Nowadays the situation is pretty improved from what is reported on the chart by the ACVC in 2011:



Graph 4.1 Services presence in the ZRV-VRC.

The project of the biodigester was performed in the "*Finca Comunitaria de RecrÍa de Bufalo"* in the ZRC-VRC, a community farm that is located 2km far away from the small village of Puerto Matilde. The project was managed by the ACVC and Ingegnieria Senza Frontiere Milano (ISF-MI) as technical partner. In this paragraph, will be explained the issues that mainly affect the gas supply in the rural area and especially that affect the farm above mentioned. All the problematics are reported by a direct observation and investigation in field.

The village of Puerto Matilde is connected to the main city (Yondò) by a diary service that enter and exit the village once a day. The travel takes approximately four hours on an unpaved road using four-wheel drive pick-up and other quarter of hour by boat on Cimitarra river.

As mentioned before, the farm is 2km far away from the village port and the connection road is unpaved. All the materials are generally transported to and from the port in back horse or, in case of heavy weights, with a tractor. The main problem is that during the rainy season the mud and the high level of the water that burst from the river, ensure the transportations. In that season, it is possible that the village remain disconnected from the city for days or weeks.

Even if the service is quite constant, according to the season, remain quite expensive for the population in the rural area.

Figure 4.3 Typical road transportation system.

Figure 4.4 River transportation made with boat.

Due to the total absence of a gas pipeline, the families have two possibilities:

- Gas tank: usually the gas used is methane or propane. The tanks are available at different size: 40 lb, 30 lb or 25 lb. The tank duration strictly depends by the size of the family and not by the season, because it doesn't affect the nutritional habits. The tanks are recharged in the nearby city Yondò and are transported to and from it thanks to the diary transportation service.
- Firewood: collected in the nearby forest.

Figure 4.5 Gas tank solution.

Figure 4.6 Firewood cook-stove usually used.

The firewood has the advantages that is free and always available, but has also the problem that generate internal pollution, because not always the kitchen has a good ventilation, waste of time for the person that have to collect it, generally children or women, and increase the deforestation problem. It is useful to underline that the deforestation is a huge problem in Colombia, especially in the cultivation area, because the farmers, in order to obtain land for cultivation, burn part of virgin forest, stealing, in this way, land to the protect area.

On the other hand, the gas tank has a high, and not always affordable, cost related both to the recharge and to the transportation. Due to the problems of transportation, related to the road conditions, it is not a reliable solution. Even without road problem, in order to recharge a gas tank, 2 or 3 days are needed for go to the city, recharge the gas tank and come back to the village. In that days, if the family doesn't have another tank, have to use firewood or other solution.

In the following table are resumed all the problematic related to the cooking fuel solution nowadays used in the rural area:

Gas Tank:

- Not reliable;
- Not always affordable by the families;
- Not always available;
- Availability strictly related with weather conditions.

Firewood:

- Not environmental sustainable;
- Generates problem of internal pollution;
- Time wasting;
- Socially unfair.

Facing this problem, the biodigester emerge as an appropriate technology thanks to the following characteristics:

- *Proved technology:* the low cost biodigester for rural area is a technology already tested that present good results in its application, has a wide range of application, is reliable and available in different size according to the application needed. The absence of moving part and heating system reduce the possibilities of fail;
- *Easy to use:* a low skill level is required in order to use this technology, so it could be used even in that area where the education level is lower;
- *Environmental sustainable:* this technology respect the ambient under different point of view: avoid the consumption of wood and so helps to prevent deforestation and internal

pollution, avoid the fuel consumption for the transportation of gas tanks, avoid the releasing in the ambient of methane due to the biomass decomposition;

- The biogas is produced using substances otherwise wasted in the ambient that could pollute water and soil;
- *Horizontal integrated technology*: if properly designed, the biodigester maintenance doesn't steal time to the farmer activities. If is fed with dung in that farm where is also used as fertilizer, thanks to the properties of the digestate, doesn't generate competition for the primary resource use. The dung could be used for fed the biodigester and the digestate could be used as fertilizer, in this way the farmer doesn't have to choose if use the dung for gas production or for fertilizing the field.
- *Affordable:* due to the low cost of initial investment and for the low cost of maintenance.

5. Case study

In this chapter will be explained the design and the construction of the biodigester implemented in the farm “Finca Comunitaria de Recría de Bufalo” in the town of Puerto Matilde in the Peasant Farmer Reserve of Cimitarra river valley (ZRC-VRC), department of Antioquia, Colombia.

The paragraphs will follow the design process, based on the *Standard Design Procedure* previously explained, and realization of the digester, focusing on these three aspects:

- Study of the resource available in the farm and the energy demand of the kitchen in order to obtain the daily quantity of biomass entering the digester;
- According to the context characteristics and farm needs, choice of the biodigester model and design of its volume;
- Realization phases.

The biodigester was implemented with the purpose of:

- Reduce the farm cost related to the cooking fuel;
- Reduce the environmental impact of the new pigsty built in the farm;
- Use the biodigester as a pilot project in order to study the technology and improve it;
- Promote it among the other farmers as an alternative to the common cooking fuel.

The biodigester was realized during a mission of three month from March to June 2017 and monitored during first month of working from the beginning of June till the end of August 2017.

The whole project was realized thanks to a partnership between the *Asociación Campesina del Valle del Río Cimitarra* (ACVC), as on-site partner with the economic and logistic responsibility, and *Ingegneria Senza Frontiere Milano* (ISF-MI), as technical partner.

5.1 Demand and resource

In order to properly design the biodigester following the rules proposed in the Standard Design Procedure, as first step, must be evaluate the on-site parameter required by the higher level of the procedure.

5.1.1 Farm organization

In the previous chapter “Context Analysis” were explained the social characteristics of the area and the general aspect of the climate and the infrastructures, now the focus is on the farm and on the characteristics that could influence the biodigester operation and realization.

In the following list are reported, and analysed, the most important aspects for the *Context Characteristics* according to the *SDP*:

- <u>Altitude</u>: the farm is located in the Tropical region at the border of the rain forest at an altitude of 68m above sea level. The mean temperatures are within 29,2°C, during March, and 27,9°C, during October; the precipitation reach the maximum value of 436 mm during the rainy season in October and the minimum value of 64 mm during the dry season in January. The biodigester doesn’t need a greenhouse in order to rise the temperature and reduce the temperature fluctuation between day and night, but could be useful a protection against the strong precipitations during the rainy season.

- <u>Season and climate</u>: the mission was performed during the rainy season. The precipitation, during the rainy season, are stronger in the middle of the period, so was planned to transport the whole material in the begging of the season, in order to avoid the problem for the road condition, and to proceed with the digging phase during the first half of the season. This choice was made according to the characteristics of the soil that is mainly made of sandstone and rock. Thanks to the rain the soil become easily to dig, during the dry season the soil is too hard to be dug and so it would be necessary more time or more workers.
- <u>Transportation and connection</u>: as underlined in the previous chapter, in order to reach the village of Puerto Matilde are necessary three hours and a half of dirt road and a quarter of hour of boat. To go from the village to the farm there are 2km of dirt road. The transportation of the great part of the material, the heaviest one, was done with private transportation with the ACVC’s pick-up for what concern the first part, then a private boat was used to reach the port of village. The material was transported from the village to the farm with help of the tractor present in the farm. Thanks to the daily connection that the village has with the city of Yondo was possible to send the missing material during the mission without problem.
- <u>Location</u>: the biodigester location was identified on the side of the pigsty. Was choose this place for different reasons:
  - It is near to the exit pipe of pigsty cleaning water, in this way a direct connection between the biodigester and the pigsty could be done;
  - It presents the necessary dimensions, length and width, for the biodigester construction;
  - It is near enough to the biogas tanks location.
- <u>Water</u>: the area is rich of water, so it is not a problem. It was decided to use for the biodigester the same water used for clean the pigsty boxes in order to avoid the use of additional water. The water used is potable, so it not generates problem of inhibition of bacteria in the biodigester. The water arrives to the farm, thanks to a pipe, from a river located in the nearby forest. In case of supply problem, a river is present near the farm and the quality of water is quite good to be used.
- <u>Technical skills</u>: in the farm are present workers with different tasks and ability. The technical level is quite good for what concern the digging phase and the piping connection, but the professional skills aren’t enough for high level carpentry, such as the construction of the digestion chamber. For the construction of a Fixed Dome digester or a Floating Drum digester a professional bricklayer is needed.

From this first analysis emerges that the characteristics of the context are favourable for the implementation of a biodigester:

- The mean temperatures are quite high and can guarantee a good operating point of the biodigester;
- The season is favourable for the construction, even if, due to the strong rain, days of stop could occur;
- Good transport connection;
- Presence of water;
- Optimal location;
- Technical skill good for the implementation of a Tubular digester, but not enough for the other models.

To better understand the decisions took for what concern the biomass use, it is better to describe the farm organization and topography. The following picture is an aerial photo of the farm:

Figure 5.1 Aerial view of the farm.

The most important buildings of the farm are:

1) *The House*: this building is composed by 3 bedrooms, 2 toilets, a shower, a washtub and the kitchen. It is positioned on an elevated point in order to see all the ranch. In the back of this building, near to the kitchen, will be positioned the biogas tanks.
2) *The Pigsty*: it is located 30m away from the house, at a lower level with a difference of 5m. In the back, not visible in the photo, is presents the location chosen for the biodigester. It measures 15m of length and 5m of width, is divided into 6 boxes but only four are occupied by the pigs. The animals present at the beginning were 14. They are used for the meat production and so their number is not constant but change in time. The boxes are cleaned once a day and the cleaning water flow out to the pigsty thanks to a pipe directly in the back woods.

3) *The Stall*: is the place where the buffalos and the cows stay during the milking period, that takes approximately 1 hour and half. During the day and the night all the animals are free to move in the pasture, so the milking period is the only moment when the biomass is collected. The stall is cleaned thanks to a pressurized water jet every day after the milking. The water is discharged directly on the backyard. In the farm are present 80 buffalos and 5 cows. The animals are used for the milk production and, at the end of life, for meat production.
4) *The Poultry*: is a small building made with wood and iron net, but present some problem so chickens, hens and rooster are free to move everywhere in the farm. The animals are used for the self-production of eggs and meat. There is no cleaning plan, their biomass cannot be used.

It is important to notice that the pigsty is very near to the biodigester location, while the stall is far away and in between a hill is present. In order to make the biodigester operation more comfortable for the farmer, was decided to used only the swine biomass for the daily filling. Due to the fact that the buffalos produce a great amount of biomass, was decided to use their biomass for the start-up process, also because is easier to collect a great quantity in a small time.

5.1.2 Calculation of resource available

Let's proceed with the calculation of the biomass available in the farm. It is better to clarify that these calculations were made during the design phase and data available from literature were used. During the construction and operating phase the swine manure production was controlled in order to see if there are relevant variation among the literature data and the real production.

Animal biomass

As already mentioned in the *Farm Organization* there are three kind of breeding animals in the farm, but only two are useful for the biomass production and present the possibility to collect the biomass in an efficient way.

Swine biomass

Initially, in the pigsty, were present 14 pig with a weight in between the 10 and the 20 kilograms. As mentioned before, the pigs are used for meat production, so their number can vary during the time, also the weight change during the time. Knowing that the animal can reach the weight of 90kg, that the pigsty can contain at maximum 3 pigs of that dimension per box and that the boxes used for the pig are 5, it is possible to estimate the maximum quantity of biomass producible by the animals:

$$Q_{DS} = N_i \cdot m_i \cdot sp_i$$

Where:
Q_{DS}= daily swine biomass production [kg/day];
N= number of animal [-];

m= animal weight [kg];
sp= specific production of manure [kg_{manure}/kg_{animal}/day];
i= weight value band.

The results are summarized in the following table:

Animals		sp [kg_{manure}/kg_{animal}/day]	Tot Production [kg/day]
Initially present:	14 per 10-20 kg	0.080	**16.80**
Maximum possible:	15 per 90 kg	0.065	**87.75**

Table 5.1 Swine biomass production related to the weigth.

It is possible to plan the number of animals present in pigsty and generate a synergy between the biodigester and the swine breeding.

Buffalo biomass

From the literature is difficult to find specific production value for the buffalo but, due to the fact that it belongs to the ruminant family, it is possible to use the same value used for the dairy cow (sp=0,08 *[kg_{manure}/kg_{animal}/day]*). Among cows and buffalos, in the farm are present 85 animals with an average weight of 500 kg. It is also important to consider that the biomass is collected only during the milking phase. To consider this, the total daily biomass production was constant during the day and is allocated with an hourly base, knowing that the milking takes 1 hour and half.
The calculation produce the following result:

$$Q_{DB} = N \cdot m \cdot sp \cdot \frac{1{,}5}{24} = \mathbf{212,5}\ \frac{kg}{day}$$

Where:
Q_{DB}= daily buffalo biomass production [kg/day];
N= number of animal [-];
m= animal weight [kg];
sp= specific production of manure [kg_{manure}/kg_{animal}/day].

Vegetable Biomass

In the farm are not present energy crops cultivations and the kitchen waste is used for feed the animals (pig and poultry).

The total biomass available in the farm is resumed in the following table:

Biomass resources		Daily production [kg/day]
Animal	Buffalo and Cow	212,5
	Swine	16,8

Vegetable	Energy crops	-
	Kitchen waste	-

Table 5.2 Biomass quantity available in the farm.

5.1.3 Kitchen energy needs

Usually in the kitchen is used a methane tank of 40 pound connected to a gas stove. The tank is recharged or changed ones every 20 days. When the gas is over, a mud stove fed with firewood is used.

In order to calculate the quantity of biogas to supply to the kitchen energy needs, it is mandatory to make some assumption:

- The methane use is considered constant during in time;
- The biogas production occurs at constant pressure, equal to the ambient pressure, and at daily mean temperature;
- The percentage of methane in the biogas is assumed equal to 60%;
- A safety factor of 1,25 is assumed in order to overdesigning the biogas demand.

In the following table are reported the calculation results:

Data		
Duration	20	[day/tank]
Methane mass	40	[lb/tank]
	18,1436	[kg/tank]
Assumptions		
% methane in biogas	60	[%]
Operating temperature	29,2	[°C]
Operating pressure	101325	[Pa]
Safety Factor	1,25	[-]
Result		
Daily biogas volume need	**2,865**	[m^3/day]

Table 5.3 Daily biogas volume need: data and assumptions.

It is important to notice that the calculation was performed with strong assumption, for example the constant gas use, so it is possible that, in reality, not always the quantity of biogas produced is not sufficient to supply to the kitchen needs. During the design phase is important to think about a support system in order to avoid discontinuing operation.

5.2 Biodigester design

Once calculated the daily biogas volume need it is possible to proceed with the "*Matching*" and the technology selection and design. It is important to underline that all the decisions made during the design and technology selection must be discussed with the farmer. The biodigester is an instrument in the hands of the farmer and must be integrated with its activity and don't waste time, otherwise, after an initial phase, could be abandoned.

5.2.1 Biomass enters the biodigester

Before to continue with the biomass flow rate calculation it is better to do some considerations about the biomass collecting point locations, how they are collected and transported to the digester:

- The swine biomass is collected in the nearby of the biodigester, while the buffalo biomass is collected in the stall that is on the other side of the hill;
- The swine biomass, thanks to a piping system, when the pigsty is cleaned go directly outside in the backyard where the biodigester is located. The buffalo biomass must be collected, after the milking and before the stall cleaning, with a shovel, put it in a bucket and transport it till the biodigester.

Due to the proximity to the biodigester, the easy collection and the possibility to directly connect the pigsty to the biodigester was decided to use the swine biomass for the biodigester daily filling. The direct connection between the pigsty and the biodigester allows to save time because the substrate directly enter in the digester during the boxes washing, in this way there are no additional activities for the farmer. It was decided to use the buffalo biomass for the initial filling because it is produced in great quantity and in small amount of time.

Let's now calculate the overall amount of biomass needed to supply to the kitchen energy needs:

$$\dot{V}_{bio}^{need} = Q_{DA}^{need} \cdot TS \cdot VS \cdot BY \rightarrow \; Q_{DA}^{need} = \frac{\dot{V}_{bio}^{need}}{TS \cdot VS \cdot BY}$$

Where:
Q_{DA}^{need}= daily swine biomass need [kg_{bio}/day];
$\dot{V}_{bio}^{need}$= daily biogas volume need [m^3/day];
TS= Total Solid concentration for swine biomass [kg_{TS}/kg_{bio}];
VS= Volatile Solid concentration for swine biomass [kg_{VS}/kg_{TS}];
BY= Biogas Yield for swine biomass [m^3_{bio}/kg_{VS}].

From the calculation is obtained a quantity of swine biomass need equal to: **33,13** kg/day.
Confronting this value with the biomass available in this moment in the farm what is obtained is:

$$Q_{DS} < Q_{DA}^{need} < Q_{DS}^{max}$$

The daily biomass required in order to produce the desired amount of biogas is higher than the daily swine biomass produced, but is lower than the maximum biomass that will be available in the future. This means that in this moment is not possible to face the kitchen needs only with the biogas plant but, due to the fact that the pigs are growing, it will be possible to obtain the desired value in

certain months. It was decided with the farmer to proceed in this way and to let the biodigester working even if doesn't satisfy the whole needs.
In conclusion, the biodigester will be designed with the quantity of biomass required for satisfy the kitchen energy needs even if for a starting period the biodigester will be filled with a lower quantity of substrate.

5.2.2 Biodigester selection and design

Looking at the context characteristics and the application of the biodigester it was decided to build a *Tubular* model. The low initial investment cost, the high level of adaptability and the low skill level required make the Tubular digester the right choice for a familiar digester application. In addition, the construction of a Floating Drum digester is too expensive and required a level of skills too high due to the presence of the steel drum. Also, its transportation could be problematic and its construction required too much time. For what concern the Fixed Dome digester, it was excluded due to its problem related to the impossibility to adjust in case of failure, the risk was considered too high for a first application. Also, the transportation, due to the fact that the bricks are not available on site but must be transported, could be a problem.

Once decided the model and calculated the quantity of biomass enter the digester, the design process must tackle with the following point:

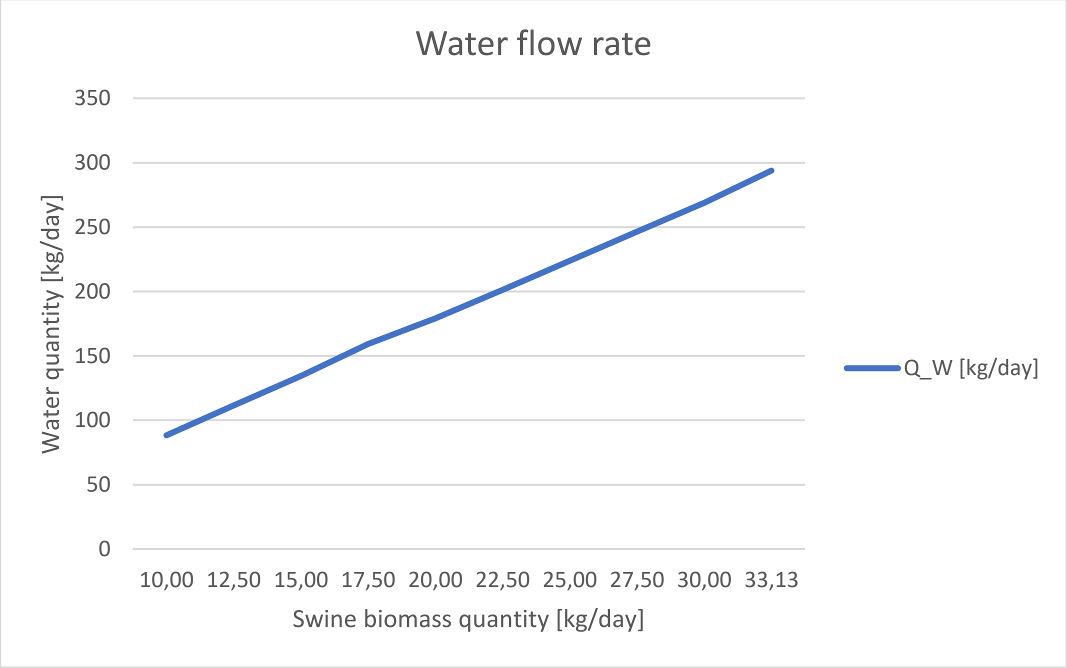
- Calculate the quantity of water to dilute the entering biomass;
- Calculate the volume of the digester chamber;
- Calculate the optimal dimension of the dig where the Tubular digester will be put.

Water flow rate
From the literature was found that for the Tubular digester model a value of 1/3 of Waste to Water ratio it is suggested. In this case, due to the fact that the swine biomass that it's going to be used present a quantity of Total Solid higher than the one present in the literature, was decided to proceed in a different way. The Tubular digester is a digester model that need an entering substrate very dilute in order to avoid clogging, so it was decided to calculate the amount of water maintaining the value of total solid entering the digester equal to 3% (Kinyua et al. 2016).
The quantity of dilute water is calculated as follow:

$$TS_{need} = \frac{Q_{DS} \cdot TS}{Q_{DS} + Q_W} \rightarrow Q_W = \frac{Q_{DS} \cdot (TS - TS_{need})}{TS_{need}}$$

Where:
Q_W= daily quantity of water enters the digester [kg/day];
Q_{DS}= daily quantity of swine biomass enters the digester [kg/day];
TS_{need}= Total Solid need by the digester technology [kg_{TS}/kg_{bio}];
TS= Total Solid concentration for swine biomass [kg_{TS}/kg_{bio}].

The quantity of water was calculated for the biomass quantity nowadays available and for the biomass quantity necessary for face the whole energy needs. The last one was used for the dimensioning of the digestion chamber. In order to follow the biomass production growth in was also calculated for quantities of biomass included in the two value. In this way, it is possible to change the quantity of water supplied according to the biomass production.
The values obtained are reported in the following chart:



Graph 5.1 Water flow rate related to the quantity of swine biomass.

The quantity to supply are reported in the following table:

Quantity of biomass		Dilute water
Nowadays:	16,80 kg/day	**149,06** kg/day
Designed quantity:	33,13 kg/day	**293,87** kg/day

Table 5.4 Quantity of dilute water for nowadays and designed scenario.

These quantities of water are quite high for a biodigester, but this is due to the high value of Total Solid of the swine biomass. Also, the quantity of water used nowadays is only a bit higher to the quantity used by the farmer to clean the pigsty's boxes, so there is a good integration within the farmer activity.

Digestion chamber volume

In order to calculate the volume of the digestion chamber, the value of the HRT must be decided. According to the climate area and to the high mean temperature it was decided to use:

HRT= ***30*** *days*

Once the HRT is decided it is possible to continue with the volume calculation. As already mentioned, the entering substrate present a high quantity of water, so it is possible to consider the density of the entering flow equal to the water density, and obtain in this way a volume flow rate:

$$\dot{V}_{mix} = \frac{Q_{DS} + Q_W}{\rho_W} = \mathbf{0{,}33}\ \frac{m^3}{day}$$

Where:
$\dot{V}_{mix}$= daily volumetric flow of mix [m^3/day];
Q_W= daily quantity of water enters the digester [kg/day];
Q_{DS}= daily quantity of swine biomass enters the digester [kg/day];
ρ_w= water density [kg/m^3].

Knowing that for the Tubular digester the gas volume ratio is equal to 1/5, it is possible to calculate the final volume of the biodigester as follow:

$$V_{tot} = \frac{HRT\ \cdot\ \dot{V}_{mix}}{1 - x} = \mathbf{9{,}90}\ m^3$$

Where:
V_{tot}= digestion chamber volume [m^3];
$\dot{V}_{mix}$= daily volumetric flow of mix [m^3/day];
HRT= Hydraulic Retention Time [day];
x= gas volume ratio [m^3_{gas}/m^3].

Once the digestion chamber volume is obtained it is possible to proceed with the design of the trench dimensions, the last step of the biodigester design.

Trench dimensions

From the total volume equation, it is possible to notice that there is a relation between the HRT and the liquid volume of the digestion chamber. The PVC digester bag is flexible so it adapts to the trench shape. It is a common error to consider the volume occupied by the liquid phase as cylindrical volume. In the reality, the liquid phase, fill the trench and so the liquid volume must be designed on the trench shape and not on the PVC bag shape. If not properly designed this lead to a decreasing of the HRT and, in this way, to a reduction of the biogas production (Martí-Herrero 2011).

In order to avoid this problem, the trench design was based on the new methodology proposed by J. Martí-Herrero in *"Design methodology for low cost tubular digester" (2011)* a novel and universal methodology that aims to calculate the optimal dimensions of the trench in relation with the length of the biogas bell, the length of the trench, the diameter of the PVC bag, the angle of the trench cross-section and the top width of the trench.

A circular shape is difficult to be obtained during the dig, so the trench it usually made with a trapezoidal shape as showed in the image:

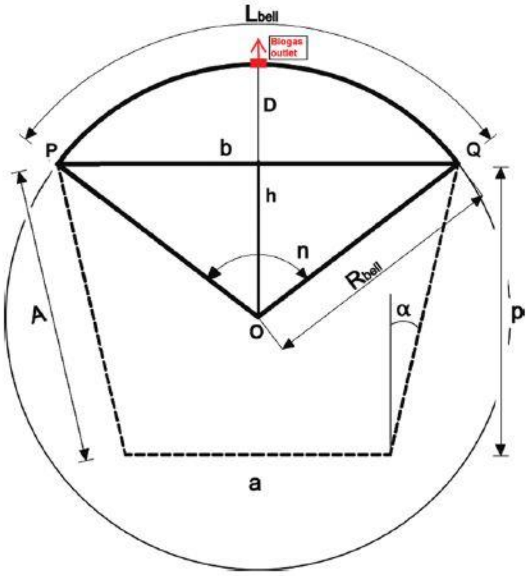


Figure 5.2 Trench dimension parameters.

The PVC bag adapts to the form of the trench in the lower part, where the liquid phase is contained, and form a circular shape, called bell, in the upper part, where the biogas is contained. The methodology aims to find the trench dimensions that maximize the ratio between the gas volume and the liquid volume.

To proceed with the optimization process the following input data are needed:

- c= the PVC bag circumference. The bags are sell in different length but with standardized circumference values (2, 4, 5 or 8 meters). Pay attention that, in order to have an optimal behaviour of the digester, the ratio between the length and the diameter of the bag must be lower than 10;
- α= the tilt angle of the trench wall. It depends by the terrain characteristics and by the gas volume ratio;
- V_{tot}= total digester volume;
- x= gas volume ratio.

The optimization process is performed as follow:

1. The biodigester total volume is expressed as follow:

$$V_{BDG} = (CS_{bell} + CS_{tr})L$$
$$CS_{bell} = \pi R_{bell}^2 \frac{n}{360} - \frac{bh}{2}$$
$$CS_{tr} = \frac{p(b+a)}{2}$$

Where:
V_{BDG}= total volume of biodigester [m^3];
CS_{bell}= cross section area of the biogas bell [m^2];
CS_{tr}= cross section area of the trench [m^2].

2. Dimensionless parameters are proposed in order to obtain parametric equations independents by the PVC bag circumference:

$$f_a = \frac{a}{r}$$
$$f_p = \frac{p}{r}$$
$$f_b = \frac{b}{r}$$
$$f_{bell} = \frac{L_{bell}}{b}$$

Where:
r= PVC bag radius [m];
f_a= dimensionless parameter for the bottom width;
f_p= dimensionless parameter for the depth;
f_b= dimensionless parameter for the upper width;
f_{bell}= dimensionless parameter that takes into account the relation between the bell length and the upper width. It is equal to 1 when there is no place for gas storage.

3. Substituting the parameters into the dimensional equation, it is possible to obtain the following dimensionless parameter that represent the relation between the tubular section and the bell cross-section:

$$\frac{CS_{bell}}{CS_{tubular}} = \left(\frac{f_b^2}{4\pi}\right)\left[\frac{360 f_{bell}^2}{\pi n} - \sqrt{\left(\frac{360 f_{bell}}{\pi n}\right)^2 - 1}\right]$$

The angle *n* could be approximated by a 6th degree polynomial equation in function of f_{bell}:

$$\mathrm{n} = -25{,}085 f_{bell}^6 + 333{,}75 f_{bell}^5 - 1835{,}2 f_{bell}^4 + 5352{,}7 f_{bell}^3 - 8787{,}9 f_{bell}^2 + 7829{,}3 f_{bell} - 2823{,}45$$

This parameter represents the volume occupied by the gas in respect to the tubular digester volume. It is possible to notice that the parameter depends only by f_b and f_{bell}.

4. Substituting the parameters into the dimensional equation, it is possible to obtain the following dimensionless parameter that represent the relation between the tubular section and the trench cross-section:

$$\frac{CS_{tr}}{CS_{tubular}} = \frac{f_b^2 - f_a^2}{4\pi \tan \alpha}$$

Where f_a could be expressed as function of f_b, f_{bell} and the angle α:

$$f_a = \frac{[f_b - (2\pi - f_b f_{bell}) \sin \alpha]}{1 - \sin \alpha}$$

This parameter represents the volume occupied by the liquid in respect to the tubular digester volume. It is possible to notice that the parameter depends only by f_b, f_{bell} and the angle α.

5. Thanks to the trigonometry and substituting the dimensionless parameters it is possible to obtain an expression of f_p in function of f_b, f_{bell} and the angle α:

$$f_p = \frac{f_b - f_a}{2 \tan \alpha}$$

6. It is now possible to calculate the parameter that express the gas percentage inside the digester:

$$\%gas = \frac{{CS_{bell}}/{CS_{tubular}}}{{CS_{tr}}/{CS_{tubular}}} = \frac{CS_{bell}}{CS_{tr}}$$

It is possible to notice that all the parameters that were calculated depend only by f_b, f_{bell} and the angle α. For every couple of value of f_{bell} and α it is possible to obtain an optimal value of f_b that guarantees the maximization of the ratio CS_{bell}/CS_{tr}.

In a Tubular digester, the biogas volume is one-fifth of the total volume, this means that from the whole values of f_b and f_{bell} that were found it is possible to accept only the ones that guarantee: %gas= 25%.

In the following table are reported the results for the optimized values of f_b and f_{bell} in function of the angle α:

		Dimensionless parameters						
		f_{bell}	f_b	f_a	f_p	${CS_{bell}}/{CS_{tubular}}$	${CS_{tr}}/{CS_{tubular}}$	%gas
α	1.00°	1.35	1.36	1.31	1.57	0.17	0.67	25.00%
	2.50°	1.31	1.43	1.29	1.56	0.17	0.67	25.00%
	5.00°	1.26	1.53	1.26	1.55	0.17	0.68	25.00%
	7.50°	1.22	1.62	1.21	1.54	0.17	0.69	25.00%
	10.00°	1.18	1.71	1.17	1.52	0.17	0.70	25.00%
	12.50°	1.16	1.79	1.12	1.51	0.18	0.70	25.00%
	15.00°	1.13	1.87	1.07	1.49	0.18	0.70	25.00%

Table 5.5 Dimensionless parameters for trench design.

		Dimensional parameters			
		P	a	b	L
		[m]	[m]	[m]	[m]
α	1.00°	1.00	0.83	0.87	9.35
	2.50°	0.99	0.82	0.91	9.23
	5.00°	0.99	0.80	0.97	9.08
	7.50°	0.98	0.77	1.03	8.98
	10.00°	0.97	0.74	1.09	8.92
	12.50°	0.96	0.71	1.14	8.90
	15.00°	**0.95**	**0.68**	**1.19**	**8.90**

Table 5.6 Dimensional parameters for trench design.

Due to the characteristics of resistance of the soil it was decided to choose a trench angle equal to 15°. Once this parameter is decided all the trench dimensions are obtained.

In order to verify if the digester shape is properly designed, the ratio between the length and the diameter of the digester must be lower than 10:

$$\frac{L}{d} = \frac{8,900}{1,273} = 6,988 \ < 10$$

The digester is properly designed.

In the following table are reported all the characteristics of the Tubular digester:

Parameter		*Value*	
Biomass quantity:			
	Nowadays value	16,80	[kg/day]
	Designed value	33,13	[kg/day]
Water quantity:			
	Nowadays value	149,06	[l/day]
	Designed value	293,87	[l/day]
Biodigester dimensions:			
	Volume [V_{tot}]	9,90	[m^3]
	Circumference [c]	4,00	[m]
	Length [L]	9,90	[m]
	Depth [P]	0,95	[m]
	Bottom width [a]	0,68	[m]
	Top width [b]	1,19	[m]
	Wall angle [α]	15	[°]

Table 5.7 Project parameters: mass flow rate and biodigester dimensions.

5.3 Biogas plant realisation

It is possible to divide the biogas plant realization phase in four different moments:

- Location individuation and land works: in this phase are identified the locations for the biodigester and for the biogas storage tanks. Also, the channels for the piping system and the trench for the biodigester are dug;
- Components construction: in this phase are prepared all the valves and filters, the biodigester and the storage tanks;
- Biodigester plant connection: in this phase the biodigester is connected with the alimentation system, the storage tanks are installed in their dedicated place and all the features are connected each other thanks to the piping system;
- Start-up: the biodigester is filled with the starting mix and a bacteria cultivation.

Usually the whole construction phase takes from 5 to 7 days in order to be accomplished, with an average effort of 6-10 people. In our case, it took more than a month, because was not realized in one go, but the different phases were divided and accomplished in different moments due to logistic problems. Another fact that influenced the realization time was the presence of only 2 workers or, in the best cases, 4. In addition there was a delay in the PVC bag delivery due to the supply company.
The biogas plant present the following scheme:

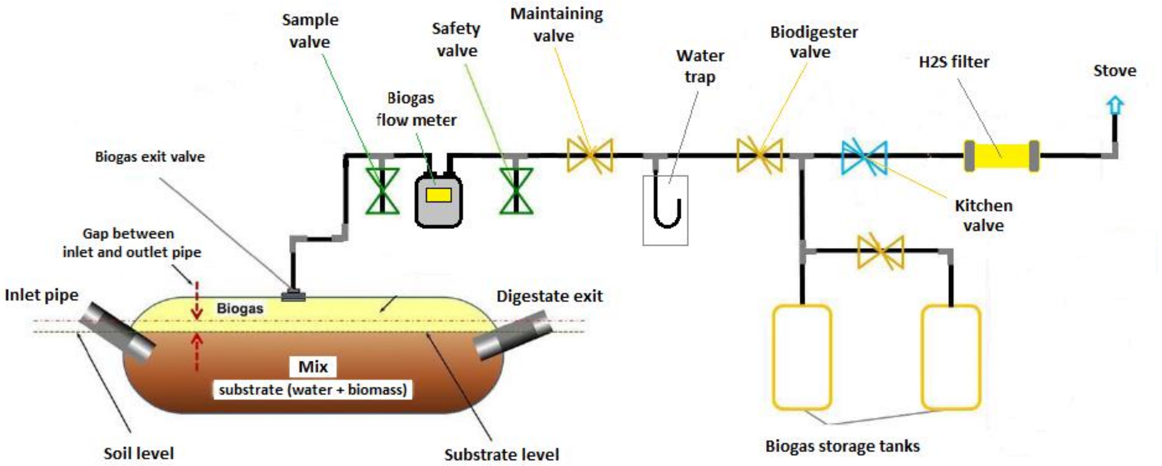


Figure 5.3 Distribution system organization and valves positioning.

In the following paragraphs will be explained the different construction phases of the biodigester implemented in the farm “Finca Comunitaria de Recría de Bufalo” in the town of Puerto Matilde in the Peasant Farmer Reserve of Cimitarra river valley (ZRC-VRC), department of Antioquia, Colombia.

5.3.1 Plant location and land work

Biodigester location
As already mentioned, the location for the biodigester was individuated on the side of the pigsty. This place was evaluated as optimal due to the proximity to the pigsty and due to the space characteristics: it was wide enough and long enough in order to contain the biodigester. Also, due to the proximity to an orchard, it is possible to directly use the digestate as fertilizer, without any additional infrastructure.

The site presents a surface that is not flat and this could be a problem during the digging phase because make difficult to understand the real dimension and could false the measurements. Also, this inclination concentrates the rain in the biodigester direction, the continuous flowing of water could generates erosion problems, leading to a digester structural problems.
It was decided to use the farm tractor for make the soil plane and, after the biodigester positioning, the channels for drain the water were dug.

Figure 5.4 Location before the work.

Figure 5.5 Location after the work.

Once the site was ready, it was possible to proceed with the excavation. Thanks to the tractor was dug the main part of the trench, then the desired shape was achieved manually. The trench dimensions were not exactly the designed one, due to the fact that is impossible to achieve such level of accuracy working with sandstone. In the following table are reported the real trench dimensions and how this change in dimensions affect the digester HRT:

Biodigester parameters	Designed value	Real value
Length [L]	9,90 m	10 m
Depth [P]	0,95 m	1,00 m
Bottom width [a]	0,68 m	0,70 m
Top width [b]	1,19 m	1,20 m
Wall angle [α]	15°	15°
Volume [V_{tot}]	9,90 m^3	11,87 m^3
HRT	30 days	36,3 days

Table 5.8 Trench designed dimensions and real dimensions.

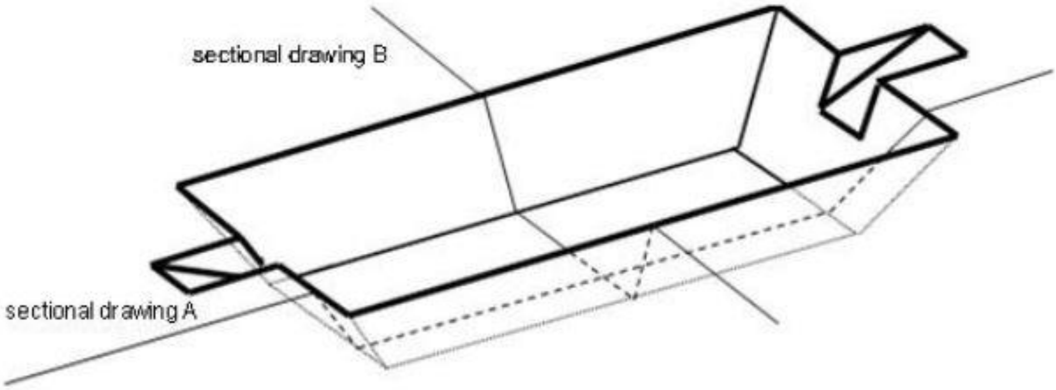


Figure 5.6 Prospective view of the trench.

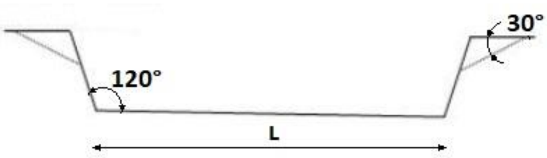


Figure 5.7 Sectional drawing A.

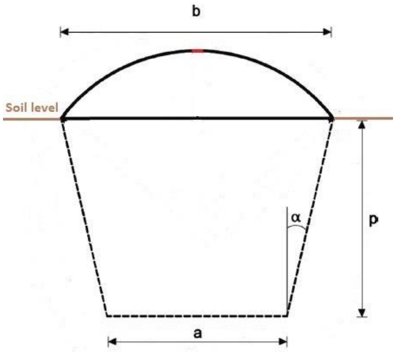


Figure 5.8 Sectional drawing B.

The daily quantity of biomass entering the digester remain the same, so increasing the digestion chamber dimensions, the HRT grows. A higher HRT value means a higher biogas production because the substrate needs more time in order to cross the digester.

Figure 5.9 Final trench realisation.

Within the biodigester trench were dug the channels for the biogas distribution system, from the digester to the biogas storage tanks location. The channels must be deep enough in order to avoid that the passage of person or weights could damage the pipes. In order to protect the pipes, an iron pipe was used to cover them in the section that cross the road suddenly used by the tractor.

Biogas storage tanks location

The optimal location for the biogas storage tanks was individuated in the back of the kitchen. This site is near to kitchen and not too far from the biodigester (less than 30 meters), in this way the biogas could arrive to the stove with the right pressure. The site is protected on a side by the house, it is far away from heat source and it is naturally shaded for half day. Also, it is in a place where people don't pass, this could avoid accidental damage.

In order to protect the storage tanks by the animals and possible damages, a structure was built with recycled wood present in the farm.

5.3.2 Components construction and connection

In this section are reported the construction technique adopted for built the different plant components and the material choice.

Biodigester construction

For the digestion chamber was decided to buy a digester bag ready to use from a company of Itaguí, Antioquia department, Colombia. The digester bag presents the following characteristics:

Material	Geomembrane, 20µm
Colour	Black
Diameter	4 m
Length	14 m
Features	Already equipped with biogas exit valve

Table 5.9 PVC digester bag characteristics.

It was selected this model due to its good characteristic of resistance, in fact the geomembrane is more strength than the PVC and present a longer a degradation over time lower than the other plastic. Even if it cost a bit more than the other digester bag present in the market it can guarantee a longer lifetime.

Subsequently the digester bag was equipped with the inlet and outlet pipe. It was selected a 4-inch pipe for the inlet and a 6-inch pipe for the outlet. To build the biodigester structure, it is necessary to insert the pipe for 80 cm in the digester bag and then ties it with rubber strips, previously obtained by car tyres. The strips must be 5 cm width in order to guarantee good performance against the leakage. This procedure must be done on both sides. At the end, connect to the biogas exiting valve a rubber pipe that will be after connected with the distribution system.

Figure 5.10 Construction of the inlet pipe.

Figure 5.11 Inlet pipe.

The trench was covered with a PVC sheet in order to protect the biodigester from eventual damages during the positioning phase and for isolate it from the ground.

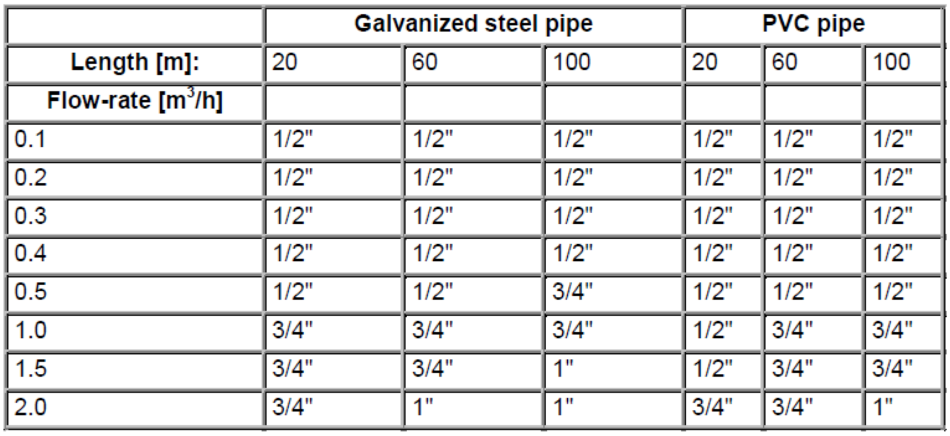
Figure 5.12 Digester bag transportation.

Figure 5.13Digester bag positioning inside the trench.

Biogas distribution system

To contain the cost of the project and for make the transportation easier, it was decided to use PCV pipe for the biogas distribution system.

The pipe diameter was designed as follow:



	Galvanized steel pipe			PVC pipe		
Length [m]:	20	60	100	20	60	100
Flow-rate [m^3/h]						
0.1	1/2"	1/2"	1/2"	1/2"	1/2"	1/2"
0.2	1/2"	1/2"	1/2"	1/2"	1/2"	1/2"
0.3	1/2"	1/2"	1/2"	1/2"	1/2"	1/2"
0.4	1/2"	1/2"	1/2"	1/2"	1/2"	1/2"
0.5	1/2"	1/2"	3/4"	1/2"	1/2"	1/2"
1.0	3/4"	3/4"	3/4"	1/2"	3/4"	3/4"
1.5	3/4"	3/4"	1"	1/2"	3/4"	3/4"
2.0	3/4"	1"	1"	3/4"	3/4"	1"

Table 5.10 Pipe sizing (Sasse 1988).

Making the assumption of constant biogas production during the day, it is possible to calculate the biogas flow rate and then choose the pipe diameter:

$$\dot{v}_{bio} = \frac{\dot{V}_{bio}}{t} = \frac{2{,}865}{24} = 0{,}119\ \frac{m^3}{h}$$

Where:

$\dot{v}_{bio}$= biogas flow rate [m^3/h];
$\dot{V}_{bio}$= daily biogas flow rate [m^3/day].

Knowing that the pipeline is long 40 m, it was selected a PVC pipe with a diameter of ½” [50].

Safety valve

The safety valve is composed by a plastic water bottle, a PVC pipe and 3-way valve. The plastic bottle present an open part to let the gas escape. The PVC pipe is immersed in the water at a certain depth to guarantee an adequate pressure. The maximum pressure of the valve is decided by the maximum pressure that the digester can support and by the distance from the storage tanks. The geomembrane biodigester bag present a high resistance to the pressure, 10 cm of water column is the safety valve pressure suggested by the seller.

Knowing the characteristic of the pipe, its length and the biogas flow rate was possible to calculate the pressure losses over the distribution system. From the calculation results that:

$$\Delta p_{loss,dist} < P_{SV}^{max}$$

It was decided for this reason to maintain 10 cm of water column as pressure for the safety valve.

Figure 5.14 Safety valve during the construction phase.

Figure 5.15 Safety valve applied on the line during a working test.

To avoid the avoid the dispersion of H_2S when the gas escape from the valve, an oxidized iron sponge was put in the pipe.

Water trap

The digestion chamber is mainly fill with water, due to the high temperature that the substrate reach during the day a lot of water evaporate, so it is necessary to eliminate this water from the pipeline to avoid clogging. Two solutions were adopted in the plant scheme:

- The pipe exiting from the biodigester was positioned with a descending inclination, in this way the water that condense I the pipe come back to the digester;
- In the lower point of the distribution system was positioned a water trap made with a bucket and U-shape tube fill with water. The bucket is used for collect the water exiting from the distribution system, the U-shape tube is used to guarantee a continuous operation of the system. The U-shape tube must guarantee a pressure higher than the safety valve pressure, otherwise the biogas could escape. It was designed a U-shape tube 12 cm high.

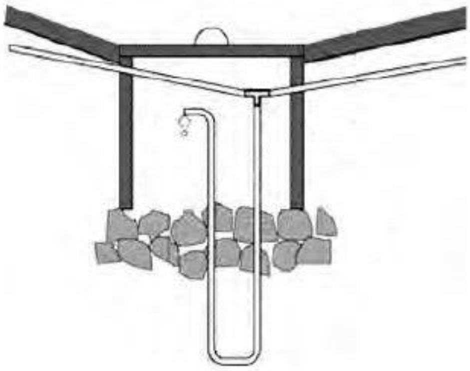


Figure 5.16 Behaviour of the water trap.

Figure 5.17 Water trap applied on the pipeline.

H2S filter

This filter is positioned between the biogas storage tanks and the stove. It introduces a very high pressure losses, for this reason can't be positioned between the biodigester and the storage tanks, otherwise could prevent that the biogas reaches the tanks.

In order to contain the costs, it was decided to build a self-made filter with oxidized iron sponges and a PVC pipe of 2". The iron sponges were wetted with water and put at air in order to oxidize them. After 24 hours, when they were completely oxidized, were put in the PVC pipe.

This filter is the only part of the distribution system that could be open, in this way it is possible to change the sponges and clean the filter when is necessary.

Figure 5.18 H_2S filter applied on the pipeline.

Biogas storage tanks

The biogas storage tanks are the elements that guarantee the constant biogas pressure at the stove and guarantee to decoupling the biogas production and utilization. The storage bags were self-produced using plastic sheet of 4 m width for greenhouse application and material available on site. The volume of the storage was designed in order to guarantee one day of operation with the following characteristics:

Number of storage	2
Volume	1,5 m^3
Height	1,18 m
Diameter	1,273 m

Table 5.11 Biogas storage tanks dimensions.

Figure 5.19 Biogas storage tanks construction phase.

Figure 5.20 Biogas storage tanks applied on the pipeline.

Plant connection

In order to make easy the biodigester daily filling, the pigsty was connected with the biodigester inlet pipe. When the farmer cleans the pigsty, the water, with excrement and urine, go out thanks to a pipe and they are directly discharged into the backyard. The pipe exiting from the pigsty was connected to a 250 litres plastic tank and then the tank was connected, thanks to a system of 4" pipes, to the biodigester inlet pipe. The tank could be open in order to add other biomass or water if necessary.

Once all the components are built it is possible to proceed with the plant connection. All the components are connected each other thanks to the distribution system made with PVC pipes.

5.3.3 Start-up procedure

After the connection, the plant is ready to produce, store and use the biogas, so it is possible to proceed with the biodigester filling.

In the first biodigester filling it is suggested to use cattle biomass because present a higher concentration of anaerobic bacteria and so it could help to accelerate the starting procedure, reducing in this way the activation time. It is also suggested to fill the 10% of the liquid volume with the digestate coming from a digester, in order to supply an additional quantity of bacteria. In the digestate are present the so called "starving bacteria". They are bacteria that have consumed all the nutrient inside the environment where they are and so they are looking for fresh substrate. Due to the fact that these bacteria are already activated, when they get in touch with a fresh substrate they can rapidly start the digestion (Brunetti 2013).

In our case, no biogas plant was present in the nearby, so the digestate was substituted with an anaerobic bacteria cultivation. This bacteria cultivation was made by the Agricultural Engineer E.M. Raquira Garcia, manager of the Biofertilizer laboratory built by the ACVC in the nearby of the farm. The bacteria cultivation is made with microorganisms collected in the forest floor and maintained in an anaerobic environment with rice husk and molasses as nutrient. The microorganisms are in solid matter, so it is not possible to insert them in the biodigester because they could produce clogging. Thanks to a dilution process, 4 kg of bacteria were transferred into a liquid matrix. The process consists in an infusion of bacteria into a solution of molasses, milk whey and water in an anaerobic environment. In this way, the bacteria pass from the solid matter to the liquid matrix. In the following days, the solution is diluted with other water and the bacteria are starved. At the end of the process a solution of anaerobic “starving bacteria” is obtained (Raquira Garcia 2016).

Figure 5.21 Eng. Garcia with the bacteria cultivation.

Figure 5.22 Bacteria filling procedure.

The quantities of the first digester filling are reported in the following table:

		Proportion	**Quantity**
Mix:		2/3 liquid volume	6,33 m^3
	Water	¾ of the mix	4747,5 l
	Biomass	¼ of the mix	1582,5 kg
Water:		1/3 liquid volume	3,31 m^3
Bacteria solution:		2% liquid volume	200 l

Table 5.12 Mix quantities for the start-up procedure.

Due to the great quantity necessary for the first filling, was decided to use the buffalo dung because produced in great quantity and so faster to collect.

6. Results

The biodigester was monitored for four months, starting from the first day after the start-up filling, the 1st of May 2017, until the 7th of September 2017. During the monitoring phase, the daily quantity of biogas produced was observed in order to characterize the *Biogas Yield* of the swine biomass. The data is also useful to understand if there were problems during the operation and, in this way, to adapt the biodigester to the farmer needs.

As previously mentioned, the biodigester was built for different purposes and with the following objectives:

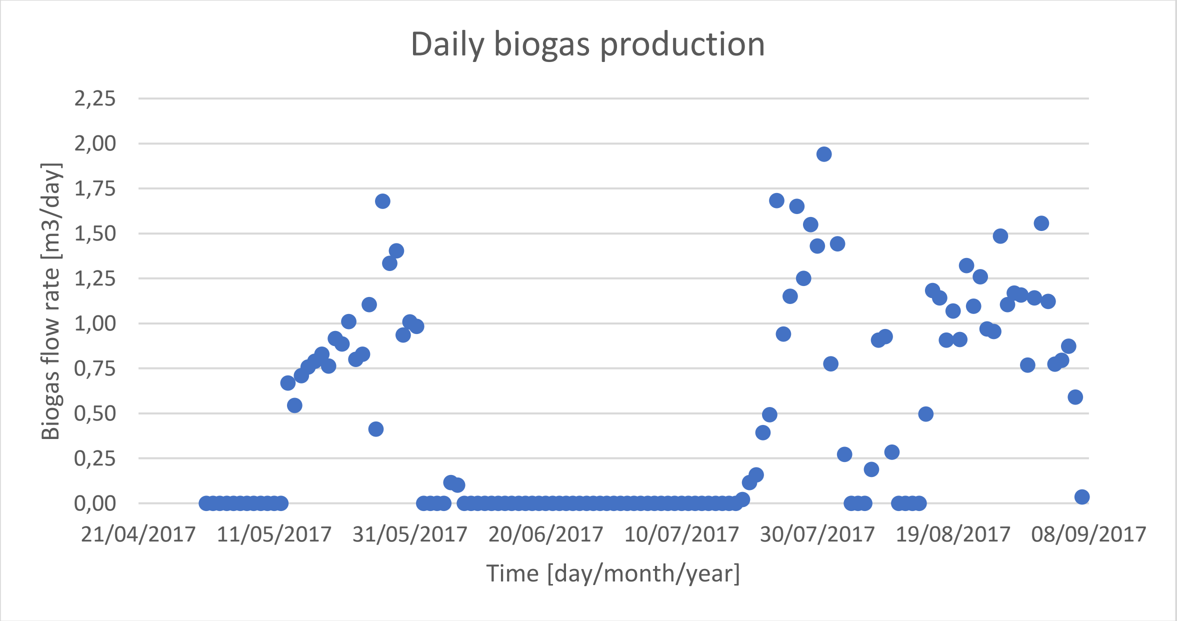
- Reduce the farm cost related to the cooking fuel;
- Reduce the environmental impact of the new pigsty built in the farm;
- Use the biodigester as a pilot project in order to study the technology and improve it;
- Promote it among the other farmers as an alternative to the common cooking fuel.

6.1 Biodigester performances

The paragraph is organised as follow:

- Presentation and analysis of *daily biogas production* data;
- Analysis and comparison of the data between the *Design value at Operating Condition* and the *Present Value*;
- Comparison between *Design value at Actual Condition* of biomass production and *Present Value*;
- Analysis of biomass production and *Biogas Yield* in present condition and in steady state condition.

The data regarding the biogas daily production is reported in the following diagram:



Graph 6.1 Daily biogas production

It is possible to divide the graph into three time intervals according to the biogas production trend:

- *Start-up period*: from the 1st of May to the 1st of June;
- *Breaking period*: from the 1st of June to the 19th of July;
- *Operating period*: from the 19th of July to the 7th of September.

The start-up period is defined as the period of time that passes between the end of the filling phase and the reaching of a steady state biogas production. In this time interval, the bacteria start to acclimatize to the new environment, allowing finally the biological process to take place. Usually the biogas production has a behaviour that could be represented by an S-shape curve, with an initial plateau followed by an increasing phase until the reaching of the steady state production. The initial plateau represents the period of time that the bacteria need in order to get acclimatized and to produce enough biogas to fill the biodigester gas volume. Due to the fact that the gas flow meter is on the pipeline, it sees only the biogas that flows outside the biodigester and not the one that remain inside it. The whole start-up period usually takes one or two HRT, depending on the operating temperature and on the initial filling. If the biodigester is filled with only biomass, without a starter, takes more time in order to start the biogas production, since the bacteria present in the biomass are too weak and need more time in order to get acclimatized. It is possible to notice from the diagram that, even if a real steady state production cannot be identified, the start-up period is very short compared to the time that a biodigester usually needs to start the production. We should underline that the digester bag began to swell only five days after the end of the filling phase.
This behaviour is mainly due to two important factors:

- The biodigester was filled with a bacteria cultivation composed by bacteria that were previously starved and, importantly, had already acclimatized to an anaerobic environment. These bacteria helped to speed up the start-up phase, that was reduced to only 15 days when it usually needs 30;
- The buffalo dung was used as substrate for the initial filling. This biomass presented a small amount of bacteria but a great amount of nutrients, for this reason it was coupled with starving bacteria.

During this initial phase, it is possible to notice a good behaviour of the biodigester, with a biogas production constantly growing.

Due to the fact that the biodigester was built in a place where no one usually passes, no containment was planned. During the 1st of June, the PVC balloon was damaged and the connection between the outlet biogas valve and the distribution pipeline was disconnected. This damage was individuated very late and, in addition, the part necessary for the reparation was difficult to find. This led to a long time of inactivity of the biodigester where all the biogas produced was released in the ambient.

After the biodigester was repaired a cover over the biodigester was built in order to protect it against strong rain fall and pigsty cover was extended.
During the last period of monitoring, it was possible to notice an initial increasing of the biogas production, that led to a two weeks period of stationary production, and then a fall of the production, with an irregular biodigester operation. The discontinuous operation was due to a

breakdown of the biodigester caused by a damage to the PVC bag. During the construction of the cover, some screws were left on the ground and accidentally hit the bag producing small holes. These holes generated a biogas escape too small to deflate the digester bag but great enough to reduce the pressure and prevent the flow of the biogas in the gas meter. In addition, the size of the small holes made them difficult to be identified.

Analysing the daily biogas production data, the following results were obtained:

Monitoring days:		130	*[days]*
Operating days:		66	*[days]*
Biomass quantity:		16,8	*[kg/day]*
Average biogas production:			
	During the operating days	0,909 ± 0,424	*[m^3/day]*
	During the whole period	0,462 ± 0,553	*[m^3/day]*
Biogas Yield (BY):		0,2728 ± 0,1270	*[m^3/kg_{SV}]*

Table 6.1 Monitoring data.

In order to understand how the biodigester is working, it is useful to compare the real quantities measured with the designed values:

	Designed value	Measured value	Difference
Biomass quantity [kg/day]	33,13	16,8	-49,29 %
Biogas daily production [m^3/day]	2,865	0,909 ± 0,424	-68,27 ± 14,80 %
Biogas Yield [m^3/kg_{SV}]	0,4358 ± 0,1261	0,2728 ± 0,1270	-37,40 ± 29,14 %

Table 6.2 Comparison between designed parameters and real parameters.

Starting from the first parameter, it is possible to notice that the daily quantity of biomass enters the digester is the half compared to the designed one. As already explained, the difference is related to the swine's age and weight. They are still too young and small to produce the desired quantity of biomass and this directly affect the biogas daily production. Reducing the quantity of substrate, also the quantity of total solid and volatile solid which enters the biodigester decreases and, in this way, also the biogas production is reduced.

For what concern the *Biogas daily production,* the value is very low compared with the designed value. The quantity of biogas produced by the digester is related to two factors: the quantity of biomass entering the digester and the biogas yield. As already explained, having less quantity of biomass entering the digester led to a reduction of biogas production, but this reduction is greater than the one that can be generated by the biomass reduction, so the reason of this low value has to be related to the biogas yield value. In order to understand how this influence the digester performance, it is useful to compare the biogas quantity produced within the design condition with actual swine's weight and age (*Design value at Actual Condition*) and the measured real value (*Present Value*).

Nowadays in the farm are present 11 pigs with an average weight of 20kg.

	Present Design	**Present Value**	**Difference**
Biomass production [kg/day]	17,6	16,8	-4,54 %
Biogas production [m^3/day]	1,522	0,909 ± 0,424	-40,27 ± 27,85 %

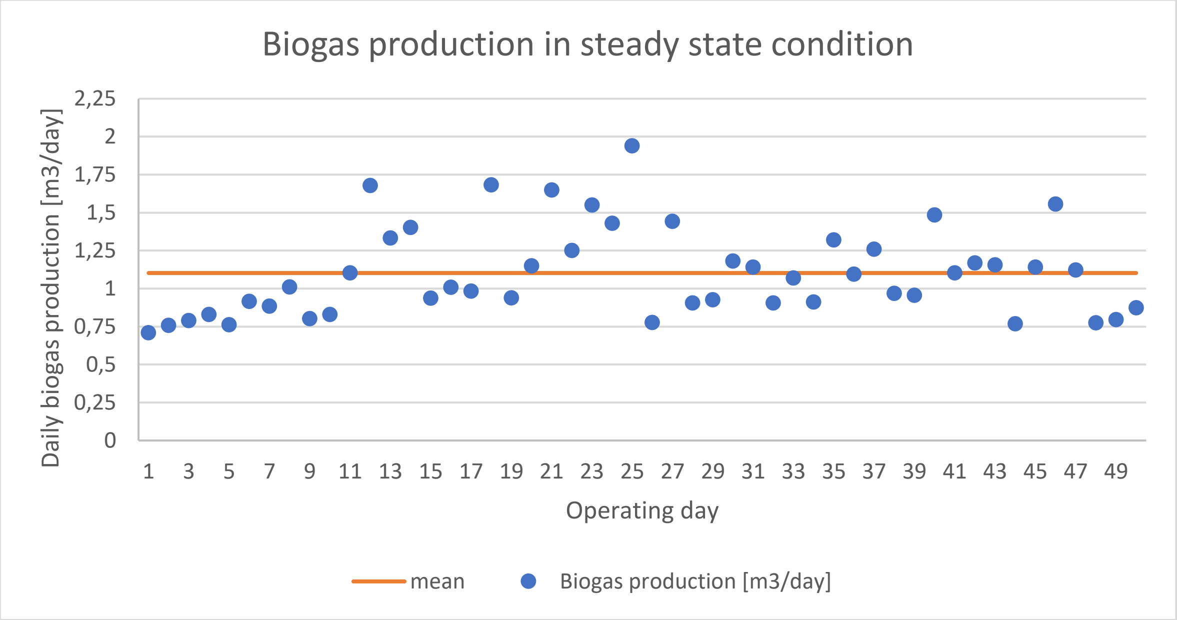
Table 6.3 Comparison between Present design value and Present value.

The difference in the biomass production can explain only a small part of the total difference between the design value, with nowadays conditions, and the present value, so the influence of the biogas yield must be investigated.

The biogas yield is a parameter related to different factors, internal and external, and is difficult to identify which is the cause of its variation. It mainly depends by the operating temperature, the HRT and, of course, by the substrate. The operating temperature influence the digestion process speed, while the HRT identifies the quantity of time that the bacteria have in order to decompose the substrate. Usually, the higher is the temperature lower is the HRT and vice versa. The biogas yield is calculated knowing the biomass characteristics (total solid and volatile solid) and the biogas production trend. If the HRT is properly chosen according to the temperature, the factor that could generate a great difference between the average literature value and the calculated one is the digester operation. When the biogas yield is calculated using laboratory scale reactor, the start-up period does not influence with its value the finale value of average biogas production. As see the chart shows, the continuous breakdown of the digester does not permit to reach a steady state condition of operation. When the average biogas production is calculated, the presence of transitory periods has a negative influence, leading to a decreasing of its value. In order to calculate a more precise value of biogas yield it is necessary a longer period of continuous operation without breakdown. In this particular case, due to the small quantity of data available, the value of biogas yield result underestimated.

It is important to notice that, the digestion process was never stopped and the data was not available in the breakdown period because, due to the damage at the exiting valve, the biogas didn’t pass through the gas flow meter. It is realistic to assume that the digestion continued with a biogas daily production with a trend similar to the one after the start-up period. We can take into account only the production data related to a steady state condition and consequently exclude all the start-up period after the different damaging.

For the steady state production, the following trend is observed:



Graph 6.2 Biogas production in steady state condition.

For the steady state production, the following parameters are obtained:

	Present Design	Steady state	Difference
Biogas production [m^3/day]	1,522	1,103 ± 0,295	-27,52 ± 19,38 %
Biogas Yield [m^3/kg_{SV}]	0,4358 ± 0,1261	0,3308 ± 0,0884	-24,09 ± 20,28 %

Table 6.4 Biogas parameters at steady state conditions.

Comparing the values obtained in steady state conditions with the designed data, we can notice that they start to be comparable and the difference between the two is reduced. With this data is now possible make another comparison in order to understand how much the biogas yield really influence the total biogas production:

	Present Design	Steady state	Difference
Biomass production [kg/day]	17,6	16,8	-4,54 %
Biogas production [m^3/day]	1,522	1,103 ± 0,295	-27,52 ± 19,38 %

Table 6.5 Comparison between Present design value and Steady State value.

From the data, it is possible to notice that the greater part of the difference in biogas production could be caused by the lower biogas yield.

The value obtained in steady state condition is not exactly what was expected, but it was closer than the one calculated in the operating condition. Also, the value of the Biogas Yield is increased coming closer to the designed one.

In order to obtain more significant results about the biodigester performances, one would need a longer period of monitoring and ensure steady state operation.

6.2 Biodigester impact

The biodigester was built in order to offer an alternative to the cooking fuel commonly used. An important aspect of this technology is the impact that produces on the context where is applied, in particular, how its impact is under an economic, environmental and social point of view.

Economic Aspect

The cost of the project was entirely covered by the local association ACVC. In the following table the total cost of the project split in the main voice cost is reported:

Material cost:		458.150 COP	157,50 US$
PVC digester bag:		588.000 COP	202,14 US$
	Specific cost	*42.000 COP/m*	*14,44 US$/m*
	Length	*14 m*	*14 m*
Total cost:		1.046.150 COP	359,64 US$

Table 6.6 Project's cost analysis.

From the table one can notice that the main voice cost is the PVC digester bag, costing more than a half of the total project cost. The "Material cost" includes the cost for: the pipeline distribution system, the biogas storage tanks, the biodigester inlet and outlet system and the all the work tools used for the digester construction. From the Total cost are excluded the cost of the labour force and transportation. For the construction, people available for free in the farm were employed, in addition to ACVC coordinators. The material was transported for free by the ACVC's pick-up which already had to enter the rural area.

To understand the different impacts that the biodigester could have on the farm economy, three scenarios were analysed:

1. Designed Scenario: economic impact with a biogas production equal to the designed one;
2. Steady State Scenario: economic impact with a biogas production equal to the one at steady state condition;
3. Nowadays Scenario: economic impact with a biogas production equal to the nowadays production, taking into account all the breakdowns.

Knowing that a gas tank has a cost of 50000 COP and that one tank every 20 days is used, the following results were obtained:

Parameters	**Scenario 1**	**Scenario 2**	**Scenario 3**
Biogas produced [m^3/day]	2,865	1,103	0,462
% needs covered	100 %	38,49 %	16,12 %
Avoided cost [COP/year]	912.500	351.202,62	147.051,05
PBT	*1,15*	*2,98*	*7,11*

Table 6.7 Project's economyc analysis.

Considering that the average life span of PVC digester bag lasts between 5 and 7 years the first two scenarios produce positive results because the Pay Back Time (PBT) is lower than the PVC bag life span, while the *Nowadays Scenario* presents such a large PBT that the solution is not economically sustainable.

Environmental Impact

From an environmental point of view, the impacts of a biogas plant could be different, from the reduction of GHG emissions, thanks to the capture and burning of methane, to the reduction of soil and water pollution, thanks to the reduction of total solid and BOD in the exiting flow. In order to thoroughly analyse this kind of effects, a long period of monitoring is required, unfortunately not compatible with the length of the mission.

During the monitoring period, an odour reduction was observed in the nearby of the pigsty. The main source of odours was the water used for the box cleaning which was directly discharged in the backyard. Thanks to the biogas plant, the cleaning water is no more directly discharged in the environment, but passed through the biodigester that, through to the digestion process, treated it, eliminating the odours emission.

The photos show the situation before and after the construction of the biogas plant:

Figure 6.1 Pigsty cleaning water directly discharged in the ambient.

Figure 6.2 Pigsty cleaning water is now treated by the biodigester.

Social Impact

The biodigester social impact was investigated during a lesson about the biodigester made in the *Farmer Agro-ecologic Course* (Ecuela Campesina Agroecológica), a three days camp made by ACVC allowing different experts to explain to the farmers the new techniques of breeding, the fundamentals of veterinary and farm management. During the course the biodigester was presented to the farmers who then gave some feedback about the technology. Most of the farmers were surprised by the digestion process and by the possibility to use something that they discharge in the ambient (the dung) to produce something very useful like the biogas. The farmers also underlined the complete absence of odours in the nearby of the plant and, most importantly, having tasted some coffee cooked on the biogas stove, the complete absence of strange flavour or odour. Indeed, the farmers had some prejudice about the use of biogas worrying that it would affect food flavour, seen that the gas come from the dung. After the coffee tasting, they showed a good acceptance of the biodigester and its use.

A problem regarding the heating value of the biogas was underlined by the cook. She told that the flame, made by the biogas, is too weak and she needs more time to cook compared to using the methane in the tank. This problem could be solved, in part, increasing the gas pressure at the cook stove, which would then produce a bigger flame, reducing cooking time.

Conclusion

The study developed inside this thesis led to the creation of Standard Design Procedure for low-cost anaerobic digester for rural area application. This procedure was also applied to the study case of a Tubular digester for the farm "*Finca comunitari de recría de bufalo*" in Puerto Matilde, Colombia.

The Standard Design Procedure was realised thanks to a literature study about the anaerobic digestion process, and the parameters that influence it, and the state of art technologies used in Developing Countries' rural area. Thanks to this study was possible to identify the relationship that exist between the context characteristics and the anaerobic digestion parameters, therefore every technology could be adapted to every context situation.

This new procedure was used to choose and design an anaerobic digester, fed with swine biomass, and used for supply to the farm kitchen's energy needs. It was calculated that in order to face the kitchen's energy needs, 2,865 m^3 of biogas must be daily produced. Due to the context characteristics was decided to build a Tubular digester.

The digester was designed using the biomass characteristics, Total Solid and Volatile Solid, obtained by the laboratory analysis of the swine biomass available on site.

The digester present a digestion chamber volume of 9,90 m^3 and a daily feeing quantity of biomass of 33,13 kg, in *Design Operating Conditions*, that have to be diluted with 293,87 litres of water. Due to the fact that the swine are still young, the real production of biomass is lower than the designed one and this led to a lower biogas daily production. To take this behaviour into account, two different scenarios were developed: *Design at Operating Condition* and *Design at Actual Condition*.

The digester was monitored for four month in order to characterize its performances and to see how closer they are to the designed case. From the data analysis emerged a daily biogas production very far from the *Design at Operating Condition*. As mentioned before, this was due to the lower swine biomass production. To better understand the digester behaviour, the daily biogas production was analysed in steady state condition and compared with the design production at the present swine weight (*Design at Actual Condition*). From the analysis emerged an average daily biogas production of 1,103 m^3. The value is still a bit far from the *Design at Actual Condition*, but nearer than the previous condition. The different is caused by a lower biomass production (- 4,54% compared to the design case) and a lower biogas yield (- 24,09% compared to the design case). To better characterize the biogas yield, a longer period of monitoring is suggested.

The economic impact was also analysed. The Tubular digester had a total cost of 1046150 COP (359,64 US$). If the steady state operation is considered, with the nowadays biomass quantity production, the digester could cover the 38,49% of the kitchen's energy needs and present a Pay Back Time of 2,98 years, a period of time lower than the technology's life span.

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