Sustainable Energy Solutions for Islands

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION

Bioenergy. Anaerobic Digestion of Organic Waste to Energy Solutions

SIDS DOCK in cooperation with PCREEE, CCREEE and ECREEE.
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SIDSDOCK SMALL ISLAND DEVELOPING STATES ISLAND ENERGY FOR ISLAND LIFE
UNIDO
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Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
MINISTERIO DE ASUNTOS EXTERIORES Y DE COOPERACIÓN
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Austrian Development Agency
CCREEE CARIBBEAN CENTRE FOR RENEWABLE ENERGY & ENERGY EFFICIENCY
PCREEE Pacific Centre for Renewable Energy and Energy Efficiency
SE4ALL Centre of Excellence to Promote Sustainable Energy Markets, Industries and Innovation
ECREEE TOWARDS SUSTAINABLE ENERGY

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Bioenergy. Anaerobic Digestion of Organic Waste to Energy Solutions

Aimed at Small Island Developing States (SIDS)

Module Objectives

The module aims to train professionals in the field of Biogas so that, in the development of their profession, they can help to disseminate knowledge among society in order to achieve excellence in the field of energy and environment, in the global context of a circular economy being friendly to the environment.

The general objective is to provide a global perspective of Biogas in the energy and environment context in the framework of Small Island Developing States (SIDS). The module presents the theoretical foundations concerning the anaerobic digestion process and technical aspects needed to obtain a broad understanding of this renewable energy, from the source of production to final use, in its different areas such as: resource characteristics, available technologies, composition and production, current applications and new developments. In addition, information on projects that have been carried out related to Biogas will be provided. The students will perform two case studies where they can apply the knowledge gained.

The ultimate aim of the module is to equip students with the basic knowledge and skills required to be able to carry out the assessment and definition of sustainable projects and activities on biogas as an energy source in SIDS.

The most important specific objectives of this module are:

- To introduce the students to the knowledge and the importance of biogas in order to stimulate the implementation of this renewable energy in SIDS.
- To make the students aware of different types and characteristics of existing biodegradable wastes (agro-industrial waste, livestock waste, organic fraction of municipal solid waste, sewage sludge), as a resource for biogas production and its current importance as an energy source, so that they can evaluate, based on its characteristics and generation, the biogas potential in their respective islands countries and territories.
- To introduce students to the environmental and energetic benefits that can be obtained with appropriate management of biodegradable wastes.
- To study the fundamentals of the process to produce methane, microbiology, factors that influence the operation and control of the process, and the final products.
- To inform on the different types of existing anaerobic digesters, and the selection of the most appropriate ones depending on the characteristics of biodegradable waste to be treated.
- To show the most suitable anaerobic digesters for application in rural areas in developing countries. Students will complete a case study that will aim to determine the design of a

digester for livestock waste treatment in rural areas and calculate the biogas that can be obtained, and its possible applications.

- To study the biogas generation process that occurs in landfills, extraction infrastructure and requirements of use, and the benefits of its removal. The application of landfill biogas production model LandGEM EPA version 3.02 to a sanitary landfill, whose details will be provided, will be conducted by the student.

- To raise awareness on the bioreactor landfill concept and exhibit the research carried out, mainly in the U.S., in order to take it into account as a possible future implementation in SIDS.

- To study the composition and characteristics of biogas by showing the current applications and the new developments that are taking place. To analyze the possible uses in SIDS.

- To inform on successful experiences in different countries on the production and use of biogas, through case studies of currently operating plants. Also, to report about PROBIOGAS, a unique and strategic project that took place in Spain, in order to promote agro-industrial biogas.

In short, this module is intended to provide the student with global perspective of biogas in an energetic and environmental context, oriented towards SIDS.

1. Introduction

There is greater recognition in both industrialized and developing countries on the need for technical and economic efficiency in the exploitation of resources. The systems for the recovery and utilization of waste are becoming more prominent in the global community. Currently a new environmental awareness is emerging, which is drawing attention to policy makers and the general public.

The problems arising from the expansion of deserts, forest loss, soil erosion, the growth of human population and animal factory farming, destruction of the ecological balance, and the accumulation of waste have resulted in the implementation of new policies needed to meet these new challenges. In a world increasingly complex and with economic interdependence, the economic and security interests of developing countries must be understood in a broader global context.

These relatively new problems in the world come either from poverty and excessive population growth in developing countries, or by the careless and excessive use of natural resources in developing countries, with more cumulative impact on poor countries than on the rich ones. There is growing awareness that environmental precautions are essential for the continuity of long-term economic development. Global objectives are necessary to achieve economic and environmental benefits through sustainable projects for the recovery and utilization of resources and programs for developing countries.

SIDS are among the most vulnerable human and natural systems due to their small size, geographic isolation, rapid population growth, limited capacity and limited natural resources, as well as exposure to natural disasters (cyclones, hurricanes, earthquakes and eruptions). volcanic) and the variability of climate and climate change. Their economic difficulties are often related to the small size of national markets and their heavy dependence on few remote markets, the high costs of energy, infrastructure, transport and communication systems, the great distances that separate them from export markets and import resources, and the great instability of economic growth.

For more than a decade, the Global Environment Facility (GEF) has collaborated with SIDS and their networks in addressing global environmental issues through action-oriented projects, which also foster sustainable livelihood opportunities for the residents of the islands. The restoration and protection of marine and coastal environments, the revitalization of river basins, the preservation of biological diversity, the protection of lands against degradation, and the adaptation of all sectors to changes in the climate regime are important objectives of projects (GEF, 2005).

Recently, the draft work plan and budget for the subprogram for evaluation and management of environmental pollution for 2017-2018, issued by the UN (UN, 2017), indicates that the challenges faced by SIDS, due to their small masses of land, vulnerable economies, strong dependence on external energy resources and growing populations, means that concerted efforts must be made to transform the concept of sustainable development into a realistic practice. It is widely accepted that SIDS will be more directly affected by climate change than other regions in terms of the scope and intensity of the impact. Therefore, governments must continue to accelerate the process to safeguard the natural resource base so that communities and ecosystems can be more resilient to the impacts of climate change.

Despite the progress that has been made on several fronts, there are still many barriers with respect to water, land and resource management, and for the implementation of relevant multilateral environmental agreements. Likewise, it is said that SIDS have specific needs and problems in relation to sustainable development and the environment. The objectives approved through the United Nations Conference on Sustainable Development, RIO + 20, (twenty years after the historic Earth Summit in Rio in 1992), in relation to the document with the results of SAMOA's trajectory and the Sustainable Development Goals, which are most relevant to this project include:

a. The need to accelerate the implementation of the Barbados Program of Action and the suit of SAMOA;

b. The need to provide support for the development and implementation of freshwater programs and work in marine and coastal biodiversity;

c. The implementation of the GPA (Global Programme of Action for the Protection of the Marine Environment from Terrestrial Activities) in SIDS to prevent, reduce and control waste and pollution;

d. The need to provide support for capacity building to reduce and manage waste and pollution and maintain and manage systems to deliver water and sanitation services;

e. The need to address the objectives of the Integrated Management of Water Resources;

f. The need to develop and implement management approaches based on ecosystems, including integrated plans for land management and water use, and strengthen the capacity of governments, local authorities and communities to monitor and manage the quantity and quality of resources terrestrial and hydric;

g. The need to promote programs to sustainably improve the productivity of the land and the efficiency of water resources in agriculture, forestry, wetlands, artisanal fisheries and aquaculture, especially through approaches based on local and indigenous communities; Y

h. The need to provide direct support to countries to achieve the Sustainable Development Goals (SDGs) in water and sanitation, climate change, oceans and terrestrial resources, while contributing to several other SDGs, including poverty reduction and better quality of life.

In this context, the use of anaerobic digestion in a system of integrated resource recovery in these countries is important to address both environmental and economic problems.

The anaerobic treatment is the use of biological processes to degrade the organic matter in the absence of oxygen and transform it into biogas, constituted mainly by methane (50-70%) and carbon dioxide (30-40%), and in a digestate more stable with high concentration of organic matter and nutrients. Methane, combustible gas, gives biogas an energetic value easily exploitable.

Already in the seventeenth century was known anaerobic degradation process of organic matter. In the mid-nineteenth century, it was shown that anaerobic bacteria were involved in the degradation process. But it was in the twentieth century when anaerobic digestion was applied at industrial scale for the treatment of wastewater and organic waste in general. Since then, research on anaerobic digestion has increased steadily, in both microbiological and chemical aspects.

Environmental issues and the need for renewable energy have led to biogas having a great interest in both developed and developing countries, and expanding the research and application in these directions. This technology offers possibilities and solutions of interest to global problems such as the production of alternative energy, the management of wastes (human, animal, municipal and industrial) and pollution control. Other benefits of anaerobic digestion are the reduction of odors, the reduction or elimination of bacterial pathogens (depending on the temperature treatment) and the use of an environmentally acceptable sludge.

Throughout the different chapters of the module, we will learn more in depth the theoretical and technical aspects needed to gain a broad understanding of this renewable energy. Also, we will present practical examples of projects that have been carried out will be presented in this area.

1.1. Sustainable development

Probably, the most serious problem of environmental conservation facing developing countries is rural developmental delay. In the struggle for food and fuel, large areas of vegetation, trees and shrubs have been cleared. The consequence is the alteration of ecological processes in these countries, and the permanent destruction of resources, normally renewable. There is an urgent need of rural development, which combines short-term measures for the survival and long-term measures to protect the resource base and improve the quality of life, while ensuring the future. Many rural communities lack the financial flexibility that allows them to defer consumption of resources that need restoration. Therefore, conservation measures are needed to, at least, maintain the standard of living of these communities, or improve it, taking into account their own knowledge of the ecosystem, and finding effective ways to ensure that these resources are sustainably used.

Depending on the global strategy for sustainable development, recognizing the need for international action to implement it, and to encourage and support national action, it is necessary an integrated approach to many of the problems that arise. The cooperation between nations and organizations can facilitate the deployment of scarce resources and, thereby, improve the prospects for conservation and sustainable development.

A joint international action can do much to restore the environment, to fight against poverty, and to get countries make the best use of their resources. The first objective is to maintain essential ecological processes, such as regeneration and soil protection, nutrient recycling and water purification, from which human survival depends. Part of this goal can be achieved through a rational use of organic matter in developing countries, to help rural communities retain their basic living resources.

One of these processes is the production of biogas from organic waste. These materials are biodegradable and can produce a large sustainable profit, for example, on a farm. In order to achieve the strategy in this particular field, it is necessary to increase the number of people trained and greater awareness, as well as research-oriented management with the necessary background information. The conservation and sustainable development in rural communities, whose only fuel is wood, dung and crop residues, are basic. Biogas production combines short-term economic needs of these communities and the end of ecological degradation.

Biogas as a renewable energy source has aroused great interest in recent years, and is perhaps one of the easiest implementation technologies, especially in rural areas. Its potential development, not only considering the production of biogas, but also obtaining biofertilizer and treatment of health problems in some cases, make very attractive its applicability and dissemination in areas with an abundance of waste with high concentrations of organic matter. On the other hand, in the process in addition to producing energy in the form of biogas, an important environmental benefit is produced by reducing the organic load of a waste and by producing a digest with fertilizing properties because it has a high content of nutrients.

FAO has highlighted to biogas as an energy source for agriculture in developed and developing countries. It asserted that the use of unconventional energy sources, such as biogas, contributes to meet three basic needs: improve sanitary conditions through the control of organic waste, generate renewable energy and supply biofertilizer for crops. It is therefore a source of renewable energy that can contribute significantly to the production and conversion of animal and vegetable waste into different forms of energy, which can be used for the generation of electricity, heating and cooking, among others, boost agricultural activities of small producers and reduce the emission of greenhouse gases (FAO, 2012).

On the other hand, the generation and elimination of urban waste is becoming a major issue due to the increase in urbanization and population growth. According to forecasts, 99% of this population growth, as well as 50% of urban growth, will occur in developing countries (Chu and Majumdar (2012), Curry and Pillay (2012)). If municipal waste could be used for the production of biogas, and thereby reduce the demand for landfills, it would be possible to produce renewable and sustainable energy, together with a beneficial by-product of biolode potentially usable as fertilizer (UN, 2015). In a study by Curry and Pillay published in the magazine Renewable Energy, it was found that the number of biogas producing plants was increasing between 20% and 30% each year, which shows that anaerobic digestion is becoming an important sustainable energy source (Curry and Pillay, 2012). In turn, the UN indicated that in recent years, energy and biofuels have become a priority due to the volatility of oil prices and the need for countries to acquire greater energy independence (FAO, 2012).

Experts highlighted the waste potential that is generated in the food production chains. Farmers can treat waste from its production, solving an environmental problem and at the same time generating energy for their own consumption or to sell the surplus to specialized companies. This will reduce the costs of production and energy will become a new product in the rural economy. However, this potential to convert agricultural waste into biogas will be only realized if governments encourage clean energies and support their research and dissemination.

Nevertheless, things are changing. There is a growing interest in renewable energies and in particular about biogas in most countries and specifically in SIDS. An example is the creation of the First Operational Phase of the Caribbean Center for Renewable Energy and Energy Efficiency - CCREEE.

Currently, the Department of Economic and Social Affairs of the United Nations lists 57 small island developing states. These are divided into three geographical regions: the Caribbean, the Pacific, and AIMS (Africa, Indian Ocean, Mediterranean and South China Sea). Each of these regions has regional bodies to which the respective SIDS may belong for purposes of regional cooperation. These are the Caribbean Community (CARICOM), the Pacific Islands Forum (PIF) and the Indian Ocean Commission (IOC).

The biogas can be an excellent opportunity for the sustainability of both the farming industry and, especially, small-scale SIDS farmers. Organic waste can be treated with appropriate technology and good training, solving an environmental problem and, at the same time, producing energy, electrical and / or thermal, and a natural fertilizer.

Anaerobic digestion is widely used as a source of renewable. Currently, there are millions of digesters in China and India the millions that exist in India and China. In Germany there are about 9,000 working digesters, which generate more than 10,000 million m^3 which are fully used. In Mexico there are 721 and Chile, for example, generates 132 million m3 / year of biogas, of which only 15 percent is harnessed as energy, according to the Renewable Energy Center of CORFO (Hurtado M.E., 2012).

1.2. Characteristics of the Small Island Developing States (SIDS)

Currently, the Department of Economic and Social Affairs of the United Nations lists 57 Small Island Developing States (SIDS). These are divided into three geographical regions: the Caribbean, the Pacific, and AIMS, which encompasses Africa, the Indian Ocean, the Mediterranean and the South China Sea. **Table 1** shows the distribution of SIDS in these geographic regions. Each of them has regional bodies to which the respective SIDS can belong to the effects of regional cooperation. These are the Caribbean Community (CARICOM), the Pacific Islands Forum (PIF) and the Indian Ocean Commission (IOC).

Table 1: SIDS made up of the Caribbean, Pacific and AIMS regions

Caribbean	Pacific	Africa, Indian Ocean, Mediterranean and South China Sea (AIMS)
Anguilla[a][b][c]	American Samoa[d][e][c]	Bahrain[a][e]
Antigua and Barbuda	Cook Islands[c]	Cape Verde[e]
Aruba[a][f]	Federated States of Micronesia	Comoros[g]
Bahamas	Fiji	Guinea-Bissau[g][e]
Barbados	French Polynesia[a][b][c]	Maldives[f]
Belize	Guam[d][e][c]	Mauritius
British Virgin Islands[a][b][c]	Kiribati[g]	São Tomé and Príncipe[g][e]
Cuba[e]	Marshall Islands	Seychelles
Dominica	Nauru	Singapore[e]
Dominican Republic[f]	New Caledonia[a][b][c]	
Grenada	Niue[c]	
Guyana	Northern Mariana Islands[a][e][c]	
Haiti[g]	Palau	
Jamaica	Papua New Guinea	
Montserrat[a][c]	Samoa	
Netherlands Antilles[d][f][c]	Solomon Islands[g]	
Puerto Rico[a][f][c]	Timor-Leste[g][a][f]	
Saint Kitts and Nevis	Tonga	
Saint Lucia	Tuvalu[g]	
Saint Vincent and the Grenadines	Vanuatu[g]	
Suriname		
Trinidad and Tobago		
United States Virgin Islands[d][e][c]		

Notes [edit]

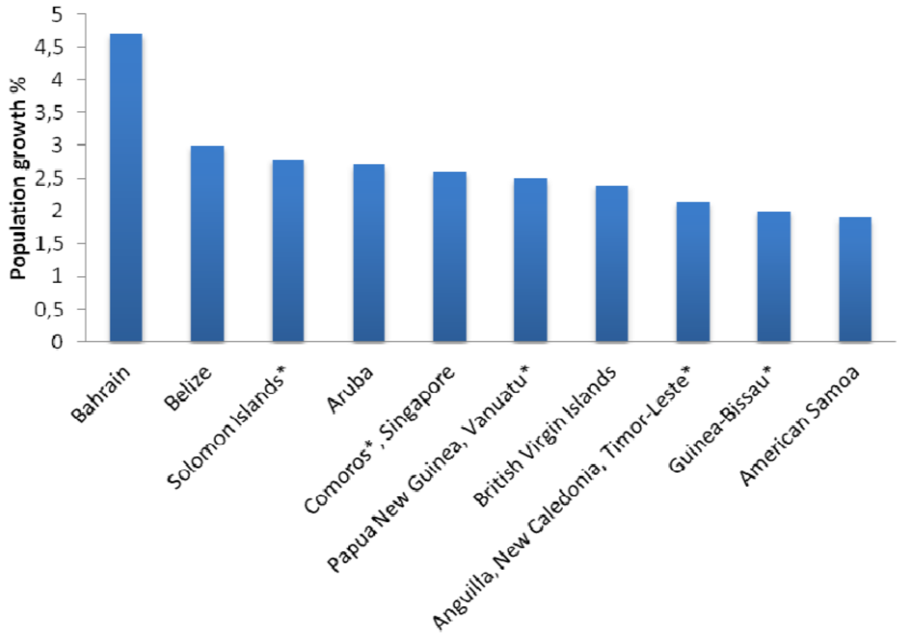
a. ^ a b c d e f g h i j Neither member nor observer of the Alliance of Small Island States
b. ^ a b c d Associate member of regional cooperation body
c. ^ a b c d e f g h i j k l m Not a member of the United Nations
d. ^ a b c d Observer of the Alliance of Small Island States
e. ^ a b c d e f g h i j Neither member nor observer of regional cooperation body
f. ^ a b c d e f Observer of regional cooperation body
g. ^ a b c d e f g h i Also a least developed country

Source: https://en.wikipedia.org/wiki/Small_Island_Developing_States, February , 2019.

To these 52 SIDS have added another 5 from the Caribbean Community that are not members of the United Nations: Bermuda, Martinique, Turks and Caicos Islands, Cayman Islands and Guadeloupe (UN, 2015).

With respect to the size of its population, SIDS are quite small countries. Cuba is the most populated island with 11.3 million inhabitants and Niue the least populated with 1,500 inhabitants. SIDS have a combined population of around 65 million, which is a little less than one percent of the world's population.

The average annual growth rate of the population is 1.3 percent. Most SIDS experience less than 1 or 2 percent population growth per year. However, there are significant differences between individual countries. For example, while Bahrain has a growth rate of almost 5 percent per year, Niue experiences negative growth (-2.3 percent) due to the high level of emigration to New Zealand. **Figure 1** shows the SIDS with the highest annual population growth.

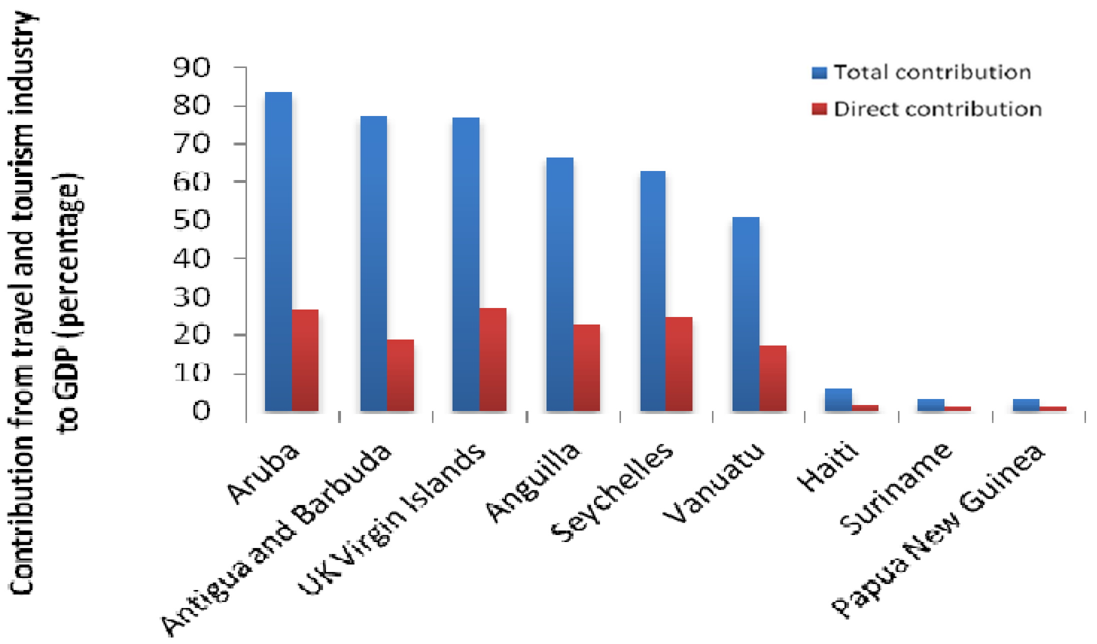


Source: SIDS, 2013.

Figure 1: SIDS with the highest annual population growth (1990-2010)

The growth rates of the urban population vary significantly in SIDS. As in the case of population growth in general, Bahrain dominates the growth of the urban population with almost 5 percent average annual growth.

The tourism industry, according to SIDS statistics, has contributed greatly to the development of many SIDS. The contribution of the travel and tourism industry to GDP (Gross Domestic Product) and employment is indicative of the importance of this industry. For example, in 2012 the travel and tourism industry of Aruba made a total contribution of 26.5 percent to GDP and if the total contribution (direct and induced) is taken into account, the contribution amounts to 83.8 percent. Similarly, Antigua and Barbuda, the Virgin Islands of the United Kingdom, Anguilla, Seychelles and Vanuatu (**Figure 2**) depend to a large extent on the travel and tourism industry (the total contribution is over 50%). Regarding employment, in 2012 the Virgin Islands of the United Kingdom topped the list with a direct contribution to employment of 32.8 percent and a total contribution (direct and induced) of 89.3 percent. On the contrary, the travel and tourism industry in Haiti, Suriname and Papua New Guinea makes relatively small contributions to GDP and employment.



Source: SIDS, 2013; FAO, 2013

Figure 2: Travel and tourism: total and direct contribution to GDP.

Other important industries are fishing and mining. Depending on the island, industries can be more or less relevant. For example, fisheries contributed only 0.07 percent of Trinidad and Tobago's GDP in 2006, 2007 and 2008, while for Tuvalu the contribution amounted to 7.2 percent in 2011 and for the Federated States of Micronesia (FSM) was 10.1 percent in 2010. In terms of mining, the mining industry in Trinidad and Tobago contributed 45.8 percent of the island's GDP in 2008; however, many other islands have less significant mining industries, with contributions of less than 1 percent (for example, Barbados, Belize, Dominica, according to 2007 data). The island of Nauru used to be highly dependent on mining; however, it exploited virtually all of its phosphate reserves.

There are no data on the percentage of population living in poverty for 40 out of 57 SIDS. When looking at the remaining 17 countries on which the data are available, it can be said that there are significant differences among the SIDS. For example in Jamaica, Maldives and Seychelles less than 2 percent of the population has to live with less than $1.25 a day. In stark contrast to this, in Haiti there are almost 55 percent of people living below $1.25. In general, the largest share of population living in poverty can be found in low-income and lower-middle income countries.

As mentioned, SIDS are a group of developing countries that face unique challenges in this process as a result of factors such as their relative isolation or remoteness, the small size of their market, their limited resource base and export, their susceptibility to external economic shocks, their vulnerability to environmental threats and the effects of climate change, and their exposure to frequent and intense natural disasters.

The SIDS are a very heterogeneous group, which, together with the lack of budget to carry out the National Statistical Systems (NSS), makes it extremely difficult to obtain data.

The NSS for SIDS vary considerably in terms of size and budget levels, and the profile of the National Statistics Institute (NSI) differs from one island to another. The smallest in numerical terms are in these States. They face specific constraints linked to their vulnerability and this is frequently reflected in their NSI. Not surprisingly, the most vulnerable are found in smaller countries with fewer financial resources.

For example, acquiring sufficient resources to conduct an agricultural census is a major challenge for many countries. For SIDS, the resource challenge is often both financial, institutional and human. With the importance of the agricultural sector declining in many small island developing States, agriculture no longer enjoys the same high priority that it used to have and obtaining the necessary funds to conduct an agricultural census is increasingly difficult.

External financing is also an option for some SIDS, but there is a growing demand for such funds across the spectrum of government activity and agriculture, and statistics do not always have a high priority. Many agricultural censuses are carried out, therefore, with a level of financing less than optimal. This may have an impact on the methodology for the agriculture census that must be adjusted to accommodate the level of funding available, which often results in a reduction in the scope and coverage of the data collected and, if sampling is used, in a reduction of the available geographic area and the range of articles.

Census methodology, field coordination, data processing, analysis and dissemination are difficult to find in most SIDS. Given the relatively infrequent nature of census taking (every ten years), it can be argued that SIDS can not afford to create and maintain a capacity in all these skill areas. Hence the difficulty in finding information on biodegradable waste, raw material for the generation of biogas.

Likewise, the heterogeneity of SIDS is also evident with respect to the use of per capita energy. Trinidad and Tobago has, with more than 15 tons of oil equivalent, the highest rate of all SIDS and, at the same time, one of the highest rates worldwide. On the contrary, per capita energy consumption in Timor-Leste, which is one of the least developed SIDS, is only 58 kilograms of oil equivalent. The average energy consumption per capita for SIDS is 1,520 kg, but only 7 countries exceed this value. Most SIDS do not come close to this value. In addition, average energy consumption in small island developing States per capita remains significantly lower than the average for middle and high income countries, which is 1,848 kg and 4,944 kg, respectively.

Summary of Chapter 1

Environmental issues and the need for renewable energy have led to biogas having a great interest in both developed and developing countries, and expanding the research and application in these directions. This technology offers possibilities and solutions of interest to global problems such as the production of alternative energy, the management of wastes (human, animal, municipal and industrial) and pollution control.

FAO has highlighted to biogas as an energy source for agriculture in developed and developing countries. It asserted that the use of unconventional energy sources, such as biogas, contributes to meet three basic needs: improve sanitary conditions through the control of organic waste, generate renewable energy and supply biofertilizer for crops. It is therefore a source of renewable energy that can contribute significantly to the production and conversion of animal and vegetable waste into different forms of energy, which can be used for the generation of electricity, heating and cooking, among others, boost agricultural activities of small producers and reduce the emission of greenhouse gases (FAO, 2012).

On the other hand, the generation and elimination of urban waste is becoming a major issue due to the increase in urbanization and population growth. According to forecasts, 99% of this population growth, as well as 50% of urban growth, will occur in developing countries (Chu and Majumdar (2012), Curry and Pillay (2012)). If municipal waste could be used for the production of biogas, and thereby reduce the demand for landfills, it would be possible to produce renewable and sustainable energy, together with a beneficial by-product of biolode potentially usable as fertilizer (UN, 2015). In a study by Curry and Pillay published in the magazine Renewable Energy, it was found that the number of biogas producing plants was increasing between 20% and 30% each year, which shows that anaerobic digestion is becoming an important sustainable energy source (Curry and Pillay, 2012).

In turn, the UN indicated that in recent years, energy and biofuels have become a priority due to the volatility of oil prices and the need for countries to acquire greater energy independence (FAO, 2012).

Anaerobic digestion is a technology widely used as a source of renewable energy. Currently there are millions of digesters in operation. Biogas can be an excellent opportunity for sustainability, both in the agricultural industry and, especially, small-scale SIDS farmers.

Currently, the Department of Economic and Social Affairs of the United Nations lists 57 Small Island Developing States (SIDS). These are divided into three geographical regions: the Caribbean, the Pacific, and AIMS (Africa, Indian Ocean, Mediterranean and South China Sea). Each of these regions has regional bodies to which the respective SIDS may belong to the effects of regional cooperation. These are the Caribbean Community (CARICOM), the Pacific Islands Forum (PIF) and the Indian Ocean Commission (IOC).

SIDS are a group of developing countries that face unique challenges in this process as a result of factors such as their relative isolation or remoteness, the small size of their market, their limited resource and export base, their susceptibility to external economic shocks, its vulnerability to environmental threats and the effects of climate change, and its exposure to frequent and intense natural disasters. They are a very heterogeneous group which, together with the lack of budget to carry out the National Statistical Systems (NSS), greatly hinders the collection of data.

Throughout the different chapters of the module, the different aspects related to the theoretical foundations of anaerobic digestion and biogas will be more thoroughly understood, as well as the precise technical aspects to obtain a broad knowledge of this renewable energy focused on the Small Island Developing States (SIDS).

2. Biodegradable Waste

The biodegradability is the faculty of some products or substances to decompose in chemical natural elements in a short period of time and with the work of organisms (bacteria, microorganisms, fungi, worms, insects, etc.) which are used to produce energy and to create other substances like amino acids, new tissue and new organisms. The biodegradability can happen by aerobic way, in oxygen presence, or anaerobic way, when there is not oxygen. The anaerobic process has the advantage that besides treating the wastes, it produces a gaseous combustible, renowned like biogas for its biological origin, which can be easily useable.

The biodegradable wastes encompass subproducts and organics wastes, they can be found in solid or liquid phase, they are susceptible to be subjected to biological process of via biomethanisation treatment. It is considered as potentials biodegradable wastes, i.e. susceptible of being treated by an anaerobic digestion to obtain energy (biogas), mainly the following: wastes and discharge of livestock farming (manures and purines), agro-industry wastes, as those are generated in distilleries, sugar industry, coffee industry, dairies, slaughterhouses, canneries, etc., the organic portion of the urban solid wastes and the anaerobic effluents of the wastewater treatment plants (WWTP).

2.1. Waste Characterization Parameters

When a wastes treatment Project begins, it is necessary to carry out an initial phase when the wastes are characterized; this must be outlined as an analysis campaign and compile all the information about the different characteristics which can affect the waste. A waste is defined by different physic-chemical parameters, these parameters will determinate the process to be chosen for their treatment. The most important parameters for the characterization of the biodegradable wastes are the following:

Flow: The correct determination of the effluent flow of an exploitation or industry is very important to define the Project. It is usually expressed in m^3/day for the liquid wastes and in t/day for the solid wastes.

Moisture content: Is the measure of the water quantity which is contained in the sample of waste when it is collected. To determinate this parameter, the sample is weighed when it is collected (m_1) and is kept during 24 hours in an oven, the temperature of the oven is 105ºC. After this, the sample is weighed again (m_2). The humidity percentage is calculated replacing the values in the following equation:

$$\text{Moisture percentage} = \frac{m_1 - m_2}{m_2} \times 100$$

Where: m_1 = mass of the sample when it is collected.
m_2 = mass of the sample after the oven

Moisture percentage is determined also to know the total solid content (TS) of a waste because:
The moisture percentage = 100 – TS.

Solid concentration: The nature and the content of the solids define physically a waste and they influence greatly in the selection of the process and the equipment. There are different types of solid according to their characteristics:

Total Solids (TS): This parameter is widely used and influential in the selection of treatment and equipment used. As said, the total solids are determined by drying the sample at 105ºC, to constant weight. The total solids are calculated by substituting the values into the following equation:

$$\text{Total solids (\%)} = \text{TS (\%)} = \frac{\text{weight}_{105^{\circ}C} - \text{tare}}{\text{sample weight}} \cdot 100$$

Figure 3 shows the different types of solids which may contain a waste. The total solids are divided into suspended solids and filterable. Suspended solids are separated by filtration and finally determined at 105 °C. By difference between total solids and suspended solid the dissolved solids are calculated.

The first group consists of solids sedimentable and no-sedimentable, and the second group colloidal and dissolved solids. However, in practice this division is often simplified considering the total solids distributed between suspended solids and dissolved solids. Normally, suspended solids are determined solely and the dissolved solids are calculated by difference.

- Total Solids
  - Suspended
    - Sedimentable
      - Organic (volatile)
      - Mineral
    - No sedimentable
      - Organic (volatile)
      - Mineral
  - Filterable
    - Colloidal
      - Organic (volatile)
      - Mineral
    - Dissolved
      - Organic (volatile)
      - Mineral

Figure 3: Types of solids

- *Suspended solids (SS)*: The intimate mixture solids-water does not exist, preserving both their own characteristics. They can be separated by decanting. It is important to stand out that the contents of suspended solids, their size and chemical composition, affect to the biodegradability, abrasiveness and fluidity of the waste.

- *Dissolved Solids (DS)*: Dissolved Solids (DS): They are intimately mixed with the water. The properties of the mixture are completely different to the properties of the components. It is impossible to separate them by decanting.

- *Volatile solids (VS):* They are those that volatilized during calcination at 550 ± 50 ° C and they are determined by difference of weight with the mineral solids, following method 2540E (aqueous samples) or 2540G (solid and semisolid samples) of Standard Methods (1992 and 1999). They are calculated by substituting the values into the following equation:

$$\text{Volatile solids (\%)} = \text{VS (\%)} = \frac{\text{weight}_{105^{\circ}C} - \text{weight}_{550^{\circ}C}}{\text{sample weight}} \cdot 100$$

- *Volatile Suspended Solids (VSS):* They are also an interesting parameter because it is assimilated to the concentration of microorganisms which are presented in digesters of dispersed phase (Metcalf y Eddy, 1995). The determination is performed according to the methods 2540D y 2540E of the Standard Methods (APHA, 1992 and 1999).

- *Minerals Solids (MS) or ashes*: They are the solids which remain after calcination of the sample at 550±50°C to constant weight, and they are determined by direct weighing. That is to say, they are determined by the following equation:

$$Ashes\ (\%) = Total\ solids\ (\%) - Volatile\ solids\ (\%)$$

- The methodology for the determination of various types of solids in wastewater is taken up in the different sections of Method 2540 described in Standard Method (APHA, 1992 and 1999).

Chemical Oxygen Demand (COD): Is the quantity of oxygen necessary to oxidize the reducing compounds capable of being oxidized by the dichromate and the permanganate in an acid medium. In the case of the residual biomass, the COD is a measure of total organic material, without distinguishing between matter assimilable by microorganisms and non-assimilable. The procedure generally used for its determination is the oxidation by potassium dichromate in an acid medium and subsequent titration with ammonium ferrous sulphate (Mohr's salt). The test is carried out according to the Method 5220 described in Standard Methods (APHA, 1992 and 1999).

Biological Oxygen Demand (BOD_5): It is the only analytical parameter which quantifies in a global way the contamination caused by biodegradable substances, and it is expressed in mg O_2/l. It is the quantity of oxygen used by the microorganisms to assimilate the organic matter, which is contained in the waste. The BOD_5 informs about the contents in materials which can be assimilated biochemically. BOD_5 determination is based on the biochemical oxidation of the organic matter. It is the measure of dissolved oxygen that is consumed by aerobic microorganisms to metabolize biodegradable organic matter present in the sample. The most standardized method used to calculate the BOD_5 is the method of the solutions, which corresponds to the Method 5210 of Standard Methods (APHA, 1992 and 1999). This is a slow reaction because, at 20°C, it needs 20 days to complete the 95-99% of reaction. For operating purposes, analytical determination that lasts 20 days is unreasonably long, so the general approach has been adopted to perform the BOD5, i.e. the measure of oxygen consumed after 5 days at 20°C because at this time over 90% of the reaction is completed.

The difference between the COD and BOD_5 lies in the type of compounds identified in each case. The COD value is always higher as it covers all oxidizable compounds while the DBO corresponds to the fraction of these compounds that are assimilated by microorganisms.

Total Organic Carbon (TOC): It is the quantity of carbon-containing organic compounds. Often it is used as a non-specific indicator of water quality. It gives an idea of the organic matter content but not of its biodegradability. It is determined by measuring the amount of carbon dioxide that is released after treatment with chemical oxidants or combustion, depending on the method used, according to Method 5310 of Standard Methods (APH A, 1992 and 1999).

Nitrogen: This element is found as a part of the organic matter, as ammoniacal nitrogen and as nitrate. The importance of nitrogen is due to its character as essential element to the nutrition of microorganisms, which are responsible of the biological process. The most popular method for determining nitrogen is the Kjeldahl method. Kjeldhal nitrogen is the sum of the organic nitrogen and the ammoniacal. The analysis consists in the valuation with acid of the nitrogen, which has been transformed, through a mineralization process, in ammonium. The determination is performed according to the method 4500 of Standard Methods (APHA, 1992 and 1999).

Carbon/Nitrogen ratio: The C/N ratio is a value of the susceptibility of a material to be biologically degraded. The microorganisms need a substrate which contains carbon and nitrogen in an equilibrated relation to their development. If the C/N relation is high, it will not have enough nitrogen and the bacteria will not be able to produce the necessary enzymes to assimilate the carbon. If the relation C/N is too low, an excessive growth of microorganisms is produced. Generally, the optimum value in the relation C/N to star the biological process is between 20 and 30, and never it can be higher than 35.

Temperature: All biological processes have an optimum temperature range, so it is necessary to know the temperature at which the residue originates and daily and annual changes in order to adapt to the optimum value.

pH: The pH is essential to characterize a waste; it reports on the type of compounds which can contain and possible reactions that can be performed as precipitation of salts and oxidation of metals. In general, when the pH is outside the range 6.5-8, which is the suitable for biological processes, it is necessary to correct it.

Alkalinity: Indicates the ability of the spill to neutralize acids or for buffering. Alkalinity is due to the presence of hydroxides, carbonates and bicarbonates of calcium, magnesium, sodium, potassium and ammonium. It is determined by titration with standard acid expressing results as $CaCO_3$, according to the method 2320 of Standard Methods (APHA, 1992 y 1999).

Phosphorus: Like nitrogen, phosphorus is an essential element for the growth of microorganisms. In some particular cases it is necessary to add phosphorus to a residue so that bioconversion can take place. Phosphorous is determined as orthophosphate by forming a colored complex with ammonium molybdate, according to Standard Method 4500-PC (APHA, 1992 y 1999).

Sulfur: The determination of sulphate content is necessary when it is required to foresee the formation of hydrogen sulphide in the digestion gas. Such determination consists in a turbidimetry, adding a barium salt to the sample, according to the method 4500 of Standar Merhod (APHA, 1992 y 1999).

Inhibitor Compounds: Are all those that adversely affect biological processes, preventing or slowing the reactions. His nature is varied. They can be organic compounds displayed as a result of the waste generator process, as in the case of detergents, pesticides, antibiotics, etc. Inhibition can also be caused by heavy metals or high concentrations of elements which are not toxic themselves as sodium or when nitrogen is in ammonium form.

2.2. Livestock Waste

We could define Livestock, in its simplest basic concept, as the group of animal species that have been domesticated by man with the primary purpose of using their products better. From the environmental point of view, until relatively recently, livestock could not be said as to cause major pollution problems. Waste generated on livestock farms have been traditionally used as fertilizer and organic amendment in agricultural fields, due to its mineral content and organic matter. Its balanced dispersion, its permanent contact with nature, the type of operation and reduced herd size could not produce significant impacts on the environment, since the same depurative power of natural systems was able to eliminate the problem.

However, in recent years, in a short period of time, it has gone from traditional extended farms to intensive due to the demands of the market, i.e. the large consumption of products, which involves a massification of animals and strong genetic selection. This fact has caused the generated wastes to be so numerous and localized in specific zones that the self-purification capacity of the receiving medium is not sufficient to absorb such production. This produces the consequent impact and incidence on the physical environment, which leads to its deterioration preventing further use and causing a serious environmental problem.

These changes have not only affected the production of waste, but also have effects on the composition, due to the use of products that accelerated growth inducing, medicines, and heavy metals such as copper and zinc, whose presence in the waste can cause unforeseeable damages at the time of their use and application for agricultural purposes. These circumstances have caused the livestock farm waste, formerly regarded as byproducts of agricultural application to constitute at present, and with ever greater incidence, a serious environmental problem because of its strong pollutant load and the large volumes generated around producing cores.

In this regard, anaerobic digestion offers the possibility of greatly solving the environmental problem and, at the same time, producing a readily usable energy. Also, small farms, where the environmental problem is not as severe, biogas generated from waste can solve many energetic problems and help improve the quality of life of its users, as indeed it has been happening for years in some countries.

2.2.1. Production

Unable to establish a general and theoretical livestock waste production since this is highly variable, as is obvious not only from one species to another, but also within the same species. The bibliographical reviews are abundant and highly variable data since the production of animal waste depends on numerous factors including livestock species, animal size, and physiological status and feeding, basically.

It can also find variations in the volumes of waste produced by the type of accommodation and the frequency of washes as well as by disposal form and use of water as a means of propulsion whose volume should be considered. It is therefore essential, when undertaking a study of the treatment to be applied to these residues, to determine their real production, using the literature as indicative data only, because of the importance of this parameter in the design of a treatment plant.

As a guide, **Table 2** shows, as average values, the waste produced by different animal species. As it can be seen, the amount of waste produced per animal varies from 50 kg/d in dairy cow to 0.1 kg/d in broilers.

Table 2: Waste produced by different animal species (fresh manure)

Livestock species	Animal weight (kg)	Quantity (kg/d)	Live weight (%)
Beef cattle	200-250	15-30	5,3-7
Dairy cow	450-600	30-50	6-9
Ovine	45-50	1,5-5	3-10
Adult pigs	160-250	5,8-25	2,5-10
Fattening pigs	45-100	3-9	5-10
Post weaning pigs	8-40	1,3-4,5	7-17
Broilers	1-2,5	0,10-0,17	6-8
Hens	2-2,5	0,15-0,25	7-12

Source: AEE, 2010.

2.2.2. Composition

The biochemical composition that these residues present allows the development and the microbial activity of anaerobic process. The microbiological process, as discussed below, requires carbon and nitrogen sources, as well as a number of other nutrients such as phosphorus, potassium, calcium and sulfur, among others. Normally, organic substances such as cattle manure have these elements in appropriate proportions. **Table 3** shows the chemical composition of various animal wastes on a dry basis. The water content of these raw materials may range between 40 and 90% of the fresh weight of the waste.

Table 3: Chemical composition of various animal waste (average values on a dry basis)

Animal waste	Lipids (%)	Proteins (%)	Cellulose Hemicellulose (%)	Lignin (%)	Ash (%)
Bovine	3,23	9,05	32,49	35,57	19,66
Porcine	11,50	10,95	32,39	21,49	23,67
Poultry	2,84	9,56	50,55	19,82	17,23
Equine	2,70	5,00	40,50	35,00	17,80
Ovine	6,30	3,75	32,00	32,00	25,95
Caprine	2,90	4,70	34,00	33,00	26,40

Source: Varnero, 2011.

2.2.3. Livestock waste characteristics

Table 4 shows the total solids and volatile solids (depending on the total solids) for different livestock species.

Table 4: Percentage of total solids and volatile for different livestock waste

Livestock waste	TS (%)	VS (%)
Pig slurry	3-8[1]	70-80
Cattle manure	5-12 [1]	75-85
Poultry manure	10-30[1]	70-80

[1] Depending on the dilution. Source: Steffen et al (1998).

Also, **Table 5** shows some characteristics of production with respect to livestock waste the.

Table 5: Characteristics of livestock waste depending on the production

Animal	TS (kg/d)	VS (kg/d)	COD (kg/d)	Nitrogen (kg/d)	Total waste (kg/d)	Moisture (%)
Beef cattle	2,353	1,895	1,961	0,163	29,412	92
Dairy cow	8,900	7,500	8,100	0,450	68,000	87
Broilers	0,022	0,016	0,018	0,002	0,088	75
Hens	0,027	0,020	0,022	0,001	0,102	74
Javelin in pregnancy	1,200	1,000	1,100	0,085	12,000	90
Wild pig	0,380	0,340	0,270	0,028	3,800	90

Source: ASAE (2003-2005).

2.2.4. Livestock in SIDS

Although there are differences between the different SIDS and there is a lack of statistical data, it could be said that, on the whole, the most abundant herds are the coil, the pig, the sheep and the goat.

In CARICOM, livestock production is distributed in very varied climatic and agro-ecological conditions. Livestock is carried out under a range of very different technical conditions. At one extreme are the subsistence production systems, characterized by low indicators of production and use of raw materials. In the other, there are the intensive production systems, with high use of raw material, where production is destined to satisfy demands of well established or growing markets. Livestock production is mainly based on small farms where a few animals are raised, usually of dual purpose (milk and meat), intended for family consumption or for sale at local auctions. There are also larger livestock farms aimed at commercial activity to meet the demand for livestock products from the domestic or export markets.

FAO has a long history of partnership with SIDS, providing policy advice, analysis and technical assistance in agriculture, livestock, fisheries, forestry, natural resources management and food security in its commitment to support resilient livelihoods and enhance food security. As an example, FAO has worked to establish a commercially viable and environmentally sustainable domestic egg production sector in the Maldives that increases family income and improves food security and nutrition.

A project jointly managed by the Government of Saint Vincent and the Grenadines and the Food and Agriculture Organization of the United Nations (FAO) has been carried out so that Saint Vincent and the Grenadines can begin the innovative concept of field schools for farmers (FAO, 2013).

The project, the first of its kind specifically aimed at farmers in the Caribbean, was officially launched with a workshop attended by local farmers, Ministry officials, representatives of CARDI, IICA and the FAO Development Officer, Dr. Cedric Lazarus.

This was motivated because in 2011, Saint Vincent and the Grenadines imported 8.6 million kilograms of meat and meat products from Australia and New Zealand for an approximate value of 47.6 million USD, according to data from the Ministry of Agriculture. These imports represent more than 90% of total meat consumption. The objective of the project has been to contribute to the reduction of this excessive dependence on imported meats by helping the country's sheep and goat farmers, most of whom run small family farms, to increase production, productivity and efficiency.

2.3. Agro-industrial waste

Biodegradable agroindustrial waste source is usually identified with waste and wastewater from agro-food, for debugging, which are treated by biological processes. There are also other industrial discharges, such as from paper factories, pharmaceutical industries, among others, depending on the type of industrial process that generates them, that can be treated biologically. The following section describes the characteristics of biodegradable waste produced in some of the most agro LAC region.

2.3.1. Agro-industrial waste characteristics

Coffee Industry: The ripe coffee has a composition in which the grain, which is the important part for consumption, accounts for about 20% of the total volume of the fruit. The extraction process of the fruit (benefited) generates approximately 80% of the volume remaining as waste processing (Orozco et al., 2005). The wastewater characteristics vary greatly depending on the procedure followed, finding values of 2,000 (mg O_2 L^{-1}) and 15,000 (mg O_2 L^{-1}) for COD (Guardia, 2012). They offer excellent conditions for agroindustrial waste biodegradability from the standpoint of relationship BOD/COD (above 0.5) (Guardia, 2012).

Distilleries: The wastewater generated in distilleries is called vinasse; its characteristics depend on the type of liquor to be distilled. In cane sugar molasses or beet stillage amount generates between 10 and 15 liters per liter of alcohol with a COD between 60,000 and 100,000 mg O_2/l (Wilkie et al., 2000; López et al., 2010; Del Toro, 2001; Perez y Garrido, 2008).

Breweries: In the brewing industry wastewater originates from washing bottles, barrels and vats, which are the most charged, and water from cooling and condensation which provide low-polluting high volumes. Reference values are: waswater volume/beer volume= 3.5-8, BOD/COD= 0.58 – 0.66, BOD_5= 0.2-0.4 kg O_2/hl of beer, nitrogen= 30-100 mg/l, phosphorus= 30-100 mg/l. (UNEP, 1996).

Sugar: The wastewater from beet and sugar cane derive mainly from transport and washing, and vapor condensation. Depending on the technology used, a part of the water can be recycled and the water is enriched with organic matter throughout the campaign and reaches values of BOD_5= 700-5,000 mg O_2/l and COD=1,800-10,000 mg O_2/l (Tanksali, 2013; Morales, 2011, Ainia, 2007). Discharges are seasonal because factories work for four or five months a year.

Canning industries Fruits and vegetables: The wastewater from these industries comes from the washing of raw materials and processing them. They tend to generate large volumes since the consumption of these industries are high (tomatoes, peas, spinach, beets, peach, apricot, etc.). Its characteristics are: pH = 4.5-8, BOD_5 = 200-3,000 mg O_2/l, SS = 250-1,600 mg/l DS = 1,700-6,000 mg/l (WBG, 1998; Nelson y Dasgupta, 1998)**.**

2.3.2. Agriculture and agro-industry in SIDS

As commented, SIDS is a very heterogeneous group, both because of their geographical location and because of their economic level. The group includes countries that are relatively wealthy developing national standards, but also some of the poorest countries in the world. Common traits include smallness, abundance of marine resources, and remoteness. With some exceptions, the bulk of the population in SIDS is concentrated in rural areas, often at or near the coast. Traditionally, SIDS are highly dependent on fishing for food and income, especially for the poor. The land is limited which restricts the area for agricultural production, resulting in a low diversity of crops and food products, and significantly increasing the dependence on imports. The great distances to important import and export markets and the high sensitivity to external shocks, in particular to the volatility of the price of food, make it even more difficult to feed and ensure nutrition. In addition, these countries are threatened by rising sea levels, coastal erosion and declining availability of fresh water for agriculture as result of both climate change and the overexploitation of natural resources (FAO, 2017).

As indicated, there are not enough statistical data to know the agriculture and the agroindustry of all the SIDS. The importance of the agricultural sector varies from country to country. For example, Papua New Guinea had a contribution of 36 percent to GDP in 2012, while the Bahamas and Puerto Rico had a dependency of 2 and 1 percent, respectively. Agriculture includes forestry, hunting and fishing, crop cultivation and livestock production.

Among the most important trading partners for more than half of all SIDS are the European Union, the United States and China, as shown in **Table 6.**

Table 6: The most common top 5 trading partners of SIDS

	Trading partners
33 SIDS	EU (27x), US (23x), China (21x), Singapore (12x)
17 Caribbean SIDS	US (16x), EU (15x), Trinidad and Tobago (8x), Venezuela (4x), Canada (3x)
9 AIMS SIDS	EU (9x), China (5x), US (5x), India (4x)
7 Pacific SIDS	Australia (6x), Singapore (6x), Japan (4x) New Zealand (3x)

Source: SIDS, 2013.

In the Caribbean region, it can be quote the sugarcane agroindustry in Cuba and the sugar beet in the Dominican Republic for rum production. Likewise, the citrus industry is a great source of income in several of the countries of the region. Since October 2009, it has been under threat from Citrus Huanglongbing (HLB) or green disease. In a regional project covering Central America and the Caribbean, FAO is providing technical support to Antigua and Barbuda, Bahamas, Barbados, Belize, Grenada, Guyana, Haiti, Jamaica, Saint Vincent and the Grenadines, Saint Lucia, Suriname and Trinidad and Tobago. Its objective is to control the health of plants in countries and subregions, organizations with fundamental technical tools and trained human resources to implement efficient systems and coordinated regional measures to respond to the HLB.

In the Pacific Region, it is worth mentioning the coffee production of Papua New Guinea (PNG). With the assistance of donors and the private sector, coffee producers sought to capitalize on the market trend of third party certification (TPC) by increasing the coffee sold in this market niche by 25 percent. It was a challenge to achieve the levels of quality consistency and sufficient supply volume to provide a positive return on this investment. Eighty-five percent of the coffee produced in PNG is produced by small farmers in less than 2 hectares, with poor transport and communication infrastructures. Only relatively large groups of farmers (1,000 or more) located in areas easily accessible by road or near purchase stations, provided a positive net return on investment and in 2013, only 10 percent of coffee production was certified. of PNG.

Tables 7, 8 and **9** show the economically active population in agriculture and the percentage with respect to the total, in the Caribbean, AIMS and Pacific regions, respective

Table 7: Economically active population in agriculture and percentage of total in the Caribbean Region.

Caribbean	Economically Active Population in Agriculture	% of Total
Anguilla	1000	7,1
Antigua and Barbuda	8000	8,9
Aruba	9000	8,7
Bahamas, The	5000	1,3
Barbados	4000	1,4
Belize	33000	9,9
Bermuda	0	0
British Virgin Islands	2000	7,1
Cayman Islands	5000	8,6
Cuba	551000	4,9
Dominica	6000	8,3
Dominican Republic	432000	4,2
Grenada	9000	8,5
Guadalupe	3000	0,6
Guyana	52000	6,5
Haití	2323000	22,5
Jamaica	208000	7,5
Martinique	3000	0,7
Montserrat	NA	NA
Puerto Rico	13000	0,4
Saint Kitts and Nevis	6000	11,1
Saint Lucia	18000	9,5
Saint Vicent and the Grenadines	11000	10,1
Suriname	33000	6,1
Trinidad y Tobago	45000	3,4
Turks and Caicos Islands	3000	9,1
Virgin Islands (U.S.)	9000	8,4

NA: Not Available.
Source: FAO, 2014_b.

Table 8: Economically active population in agriculture and percentage of total in the AIMS Region.

AIMS	Economically Active Population in Agriculture	% of Total
Bahrain	4000	0,3
Cabo Verde	30000	6
Comoros	222000	30,2
Guinea-Bissau	498000	29,2
Maldives	23000	6,7
Mauritius	41000	3,3
Sao Tome and Principe	38000	19,7
Seychelles	32000	34,4
Singapore	2000	0,04

Source: FAO, 2014_b.

Table 9: Economically active population in agriculture and percentage of total in the Pacific Region.

Pacific	Economically Active Population in Agriculture	% of Total
American Samoa	6000	10,9
Cook Islands	2000	9,5
Fiji	128000	14,5
French Polinesia	31000	11,2
Guam	18000	10,9
Kiribati	11000	10,8
Marshall Islands	6000	11,3
Micronesia, Fed. Sts.	11000	10,6
Nauru	1000	10
New Caledonia	31000	12,1
Niue	NA	NA
Northem Mariana Islands	6000	11,1
Palau	2000	9,5
Papua New Guinea	2247000	30,7
Samoa	18000	9,5
Solomon Islands	157000	28
Timor-Leste	358000	31,6
Tonga	11000	10,5
Tuvalu	1000	10
Vanuatu	39000	15,4

NA: Not Available.
Source: FAO, 2014_b.

2.4. Municipal Solid Waste

The Municipal solid waste (MSW), commonly known as "garbage”, was not a particular concern until a few years ago. At present, due to economic growth and the accumulation of population in specific areas, such increased quantities reached have to be managed properly; otherwise it would become a major problem.

2.4.1. Production

Knowledge of production is essential for all aspects of urban waste management. This depends essentially on the number of inhabitants. However, per capita production is very heterogeneous and varies according to different elements It depends mainly on: the standard of living of the population, the time of year, the geographical location and the way of life of the inhabitants and new methods of packaging the products with a tendency to use disposable packaging and packaging, among others. It is a certain fact that the higher the level of life, the greater the generation of waste. Thus, the more developed a country, the greater the amount of waste generated.

2.4.2. Composition

It is essential to perform studies in composition and characterization of urban waste if you plan the application of a particular treatment system, regardless of it being quantitative. The knowledge of the composition of solid waste has been of increasing importance, especially with the development of different recovery processes. Urban waste is essentially heterogeneous. Overall, the number of categories depends on the objective pursued and more complete classification could be the division in 10 categories: 1. Paper and cardboard, 2. Fabrics, 3. Plastics, 4. Metals, 5. Glass, 6. Organic matter, 7. Bones, 8. Fuel remains unclassified, and 9. Fireproof unclassified remains and fines below 20 mm. This classification is necessary if you want to make a study of the different valuation processes waste.

2.4.3. Municipal solid waste in SIDS

The production of municipal solid waste (MSW) in a country depends on the number of inhabitants and production per capita. At the same time, as mentioned, the production of MSW per inhabitant depends on different factors such as the population's standard of living, time of year, geographic location and the way of life of the inhabitants, among others. Therefore, given the heterogeneity of the SIDS, their different populations and their different economic levels, it leads to the production of urban waste in them being very diverse. Also, the influx of tourists should also be taken into account, given the importance that this sector has in many of these SIDS.

Tables 10, **11** and **12** show the SIDS populations of the Caribbean, Pacific and AIMS regions, respectively.

Table 10: Populations of the SIDS of the Caribbean Region.

Caribbean	Total Population	Rural population	% of Total
Anguilla	14000	NA	NA
Antigua and Barbuda	90000	63000	70,0
Aruba	103000	55000	53,4
Bahamas, The	377000	58000	15,4
Barbados	285000	155000	54,4
Belize	332000	185000	55,7
Bermuda	65000	NA	NA
British Virgin Islands	28000	17000	60,7
Cayman Islands	58000	NA	NA
Cuba	11266000	2804000	24,9
Dominica	72000	23000	31,9
Dominican Republic	10404000	3034000	29,2
Grenada	106000	64000	60,4
Guadalupe	466000	7000	1,5
Guyana	800000	572000	71,5
Haití	10317000	4527000	43,9
Jamaica	2784000	1331000	47,8
Martinique	404000	45000	11,1
Montserrat	5000	4000	80,0
Puerto Rico	3688000	33000	0,9
Saint Kitts and Nevis	54000	4000	7,4
Saint Lucia	182000	153	80,5
Saint Vicent and the Grenadines	109000	55000	50,5
Suriname	539000	159000	29,5
Trinidad y Tobago	1341000	1150	85,8
Turks and Caicos Islands	33000	2000	6,1
Virgin Islands (U.S.)	107000	5000	4,7

NA: Not Available. Source: FAO, 2014_b.

Table 11: Populations of the SIDS of the Pacific Region

Pacific	Total Population	Rural population	% of Total
American Samoa	55000	3000	5,5
Cook Islands	21000	5000	23,8
Fiji	881000	414000	47,0
French Polinesia	277000	135000	48,7
Guam	165000	11000	6,7
Kiribati	102000	57000	55,9
Marshall Islands	53000	14000	26,4
Micronesia, Fed. Sts.	104000	80000	76,9
Nauru	10000	NA	NA
New Caledonia	256000	99000	38,7
Niue	1000	1000	100
Northem Mariana Islands	54000	4000	7,4
Palau	21000	3000	14,3
Papua New Guinea	7321000	6400000	87,4
Samoa	190000	153000	80,5
Solomon Islands	561000	441000	78,6
Timor-Leste	1133000	803000	70,9
Tonga	105000	80000	76,2
Tuvalu	10000	5000	50,0
Vanuatu	253000	188000	74,3

NA: Not Available. Source: FAO, 2014_b.

Table 12: Populations of the SIDS of the AIMS Region.

AIMS	Total Population	Rural population	% of Total
Bahrain	1332000	149000	11,2
Cabo Verde	499000	179000	35,9
Comoros	735000	528000	71,8
Guinea-Bissau	1704000	932000	54,7
Maldives	345000	195000	56,5
Mauritius	1244000	725000	58,3
Sao Tome and Principe	193000	69000	35,8
Seychelles	93000	42000	45,2
Singapore	5412000	NA	NA

NA: Not Available. Source: FAO, 2014_b.

Among several issues faced by SIDS over the years, increasing waste generation is becoming one of the major problems. Consequently, with this rapidly increasing waste generation, SIDS are faced with a serious issue of solid waste management (SWM). In addition, the problems of land scarcity, lack of economic resources and lack expertise in the field of waste management considerably reduces the waste management potentials in these islands (UNEP, 1999).

Solid waste management is a major issue affecting both developed and developing economies due to the increasing amount of wastes generated annually. Increases in waste generation are often associated with economic growth, higher industrialisation, rise in population and higher standards of living (Kothari et al., 2014). Thus, waste generation differs between economies. Developed countries generally have higher waste generation rates than less developed ones. **Table 13** presents a summary of average municipal solid wastes (MSW) generation rates for the different geographic SIDS regions.

Table 13: MSW generation rate per capita in SIDS

SIDS	MSW kg/inhab/d
Caribbean region	1,61
Pacific region	0,82
AIMS region	1,56
Average value	1,29

Source: Mohee el al, 2015.

Comparing MSW generation rates between SIDS, it can be observed that Caribbean SIDS possess higher generation rates as compared to the other SIDS. This can be explained by several factors such as standards of livings and economic growth.

Human development index (HDI) is a measure of the standard of living of a citizen. Having a higher HDI means higher standard of living therefore higher good consumption and more waste generation. In Caribbean SIDS, the average HDI is 0.70 followed by 0.69 in AIMS SIDS and 0.63 in Pacific SIDS (Mohee et al., 2015). Therefore, the higher HDI in Caribbean SIDS corresponds to a higher MSW generation rate in Caribbean SIDS followed by AIMS and Pacific SIDS respectively. Besides, the GDP per capita is also higher in Caribbean and AIMS SIDS (US$ 11,732 and US$13,853 respectively) as compared to US$ 9,076 in Pacific SIDS (Refer to Table A.1). With higher GDP per capita, more goods and services are produced and this causes a much larger volume of wastes to be generated. Although the GDP per capita is higher for AIMS SIDS than for the Caribbean region, the latter possesses a high MSW generation rate. The GDP per capita for AIMS SIDS is anomalously high due to the inclusion of the GDP per capita of Singapore which stands at US$ 55,182 (The World Bank, 2014). Another reason behind the low MSW generation rate for Pacific SIDS as compared to Caribbean and AIMS SIDS is the amount of tourists visiting the different SIDS. Due to the low number of tourists visiting Pacific SIDS relative to Caribbean and AIMS SIDS (UN, 2010 cited by Mohee, 2015), the amount of wastes generated and consequently, the MSW generation rate is considerably lower as compared to Caribbean and AIMS SIDS.

As a reference, in 2015, the production of MSW in Spain and the average production in the European Union (U28) was 434 kg / inhabitant and 476 kg / inhabitant, respectively (Eurostat, 2017).

Besides waste generation, waste composition is an important parameter in the development of adequate strategies for waste management. Based on the composition of the MSW generated in the SIDS, appropriate technologies for their treatment can be implemented. **Table 14** shows the average composition of the MSW in the different geographical regions of the SIDS and the average value. As can see, waste compositions differ only slightly between the three regions, due to possible similarities in consumption patterns adopted by people living in the different geographical regions of SIDS (Chandrappa and Das, 2012 cited by Moheer et al., 2015). The main fraction of the MSW in the three regions is the corresponding one for the organic matter, being higher in the Aims region (48%) and lower in the Pacific region (41%). The average value indicates that major fraction of MSW comprises of organics (44%) followedby recyclables namely paper, plastics, glass and metals (43%), although some SIDS generate more recyclable materials.

Table 14: Average composition of MSW in SIDS

SIDS	Paper and cardboard	Metals	Glass	Plastics	Organic matter	Other
Caribbean region	15 %	7 %	7 %	13 %	46 %	12 %
Pacific region	17 %	10 %	6 %	14 %	41 %	12 %
AIMS region	11 %	7 %	2 %	12 %	48 %	20 %
Average value	16 %	8 %	6 %	13 %	44 %	13 %

Source: Mohee el al, 2015.

As for the waste management system, collection and transport are important functional elements. In many SIDS there is no adequate collection system.The absence of a proper waste collection system disrupts the waste management, and the waste generators resort to illegal and unwanted practices such as throwing them in prohibited sites and burning them without any control. These practices result in harmful effects to health due to the release of toxic emissions during burning and the spread of diseases caused by illegal discharges (ADB, 2014 cited by Mohee et al, 2015). Waste collection rates in SIDS vary from high to very low and there are several reasons for this difference (ADB, 2014). While in some SIDS the infrastructure is well developed, the same is not true in others where the roads are too narrow or inaccessible (ADB, 2014, Medina, 2011 cited by Mohee et al., 2015). As a result, collection vehicles can not access these areas and the waste remains in its generation source. Another factor responsible for low waste collection is the lack of sufficient funds to provide suitable containers and to buy proper collection vehicles (Al Ansari, 2012). The effectiveness of the collection and transport processes is greatly reduced. Therefore, waste generators turn to illegal burning or dumping at sea as their closest disposal option (UNEP, 1999).

Regarding waste management technologies, there are several technologies that can be employed, from recycling, composting, anaerobic digestion, thermochemical processes and ultimate disposal in landfills (Perla, 2010). Considering the high organic nature of the waste in the SIDS (Table 14) and the lack of landfill space in most SIDS, the recycling of the organic fraction for its treatment by anaerobic digetion seems to be one of the most appropriate technologies for the management of

MSW in SIDS. However, before implementing any waste management technique, it is of paramount importance to carry out an adequate characterization of the waste for the waste management process to be finally effective.

It's important to note that a major problem in SID is the lack of knowledge from waste generators, namely general public, amplifies the complications and difficulties already present in solid waste management (SWM) in SIDS (Thaman et al., 2003 cited by Mohee et al., 2015; Prasertsan and Sajjakulnukit, 2006, Wangi, 2013 and ADB, 2011 cited by Mohee et al. 2015). Squires (2006) discussed that the effectiveness of a SWM system can be affected by social risks due to insufficient public participation (Mohee et al., 2015). Consequently, the general public must be sensitised and encouraged to participate in waste management programmes through appropriate waste management awareness campaigns developed by the government or non-governmental organisations (UNEP, no date; Wangi, 2013). The local citizens must be made aware of existing regulations that will deter them from resorting to practices like illegal dumping or backyard burning of wastes. Sensitisation and environmental awareness campaigns at educational and community level can eventually help in having an efficient waste management system.

2.5. Wastewater treatment plant sludge

The wastewater from urban areas is mainly domestic-origin, existing in some cases industrial contributions. The volume of wastewater generated by a population estimated in terms of the provision of water per capita per day depending on the degree of development of the country and the size of the city. These waters are treated in wastewater treatment plants of urban waste water treatment plant (WWTP) so that, once they are treated, they can be reused, thereby achieving reduced pollution caused by human activity. These facilities, more or less complex, allowing waste water purifying aid of chemical physical and biological processes, with the end result of these different stages of treatment quality effluent suitable for incorporation into the public channels and sludge generation. The sludge or biological sludge is the product of the removal of excess biomass synthesized in aerobic biological reactor as result of the assimilation of the pollutant load (substrate) influent wastewater removed in secondary treatment. This treatment plants sludge is concentrated in polluting products which separate in the debugging process. The sludge must undergo certain processes in order to reduce organic load. One of the most commonly used systems for stabilization is anaerobic digestion.

2.5.1. Sludge production

The determination of sludge production is complex and depends on many factors. Next, for orientation purposes amounts of sludge produced in various treatment processes that correspond to the water line are given. The most significant values are: primary decantation 110-170kg/1000 m^3, typical value 150; activated sludge (excess) 70-100 kg/1000 m^3 , typical value 85; trickling filters (excess) 55-90 kg/1000 m^3, typical value 70; extended aeration (excess sludge) 80-120 kg/1000 m^3, typical value 100 (assuming no primary treatment); aerated lagoon (excess sludge) 80-120 kg/1000 m^3, typical value 100 (assuming no primary treatment). In general terms we can say that the amount of sludge generated is about 1% of treated water flow.

2.5.2. Characteristics

The parameters that characterize urban wastewater are BOD_5, the TS and the SS. On average they generate 70 g BOD_5/inhab.d, and 90 g SS/inhab.d. TS percentage between 2% and 8% of those between 60 and 80% are volatile. These values, together with the provision of water, allow estimating the volume and concentration of discharges of the population knowing the number of inhabitants.

The average concentration of BOD_5 ranging from 250 to 350 mg/l and SS about 300 mg/l. Being discharges diluted with low organic matter content, processes that apply to these waters have one cleansing purpose only and not re-use. However, in the process of waste water purification, muds with a higher concentration and subject to anaerobic digestion are originated, thus yielding methane from whose energy may be benefited.

2.5.3. Situation of wastewater in SIDS

In recent years, the economic and demographic growth of SIDS has been increasing, causing disturbances in the natural environment. Most of these states have a small, but dense and growing population, which usually totals between 100,000 and 700,000 people, who settle mainly in areas of rapid development along fragile coasts; 30% of the population of the Pacific islands and 60% of the population of the Caribbean islands currently live in towns and cities, which puts pressure on resources and increases pollution. The cities in expansion, the new urbanizations, the agriculture and the elimination of remainders are disputed the earth increasingly scarce, which causes the impoverishment of these and the desertification. Waste and pollution are becoming serious problems. Industrial growth is causing an increase in the proportion of toxic solid waste and non-biodegradable waste; Untreated urban wastewater discharged into the sea, along with agricultural runoff, is destroying coral reefs and other environments of critical importance to tourism.

Pacific SIDS face growing challenges to efficiently protect and manage their limited freshwater resources. There are several facets to ensuring the safety of fresh water in SIDS. Among these, the intrusion of salt water in aquifers caused by climate change and causes related to human activities, becomes a critical challenge. Although it is widely acknowledged that the lack of data avoids the reliable and detailed assessment of the country's current vulnerability to this problem and its scope, the integrated water management and governance frameworks are being improved. However, a complex environment where traditional and legal structures are intertwined and a fragmented water drift, hinders the decision-making process. The magnitude of the future challenges related to water resources will depend on how well the current commitments included in the legislation and national strategy documents are translated. Key priorities in this process include investment and improvement of human and technical capacities related to water science and evaluation of resources and maintaining national public awareness campaigns.

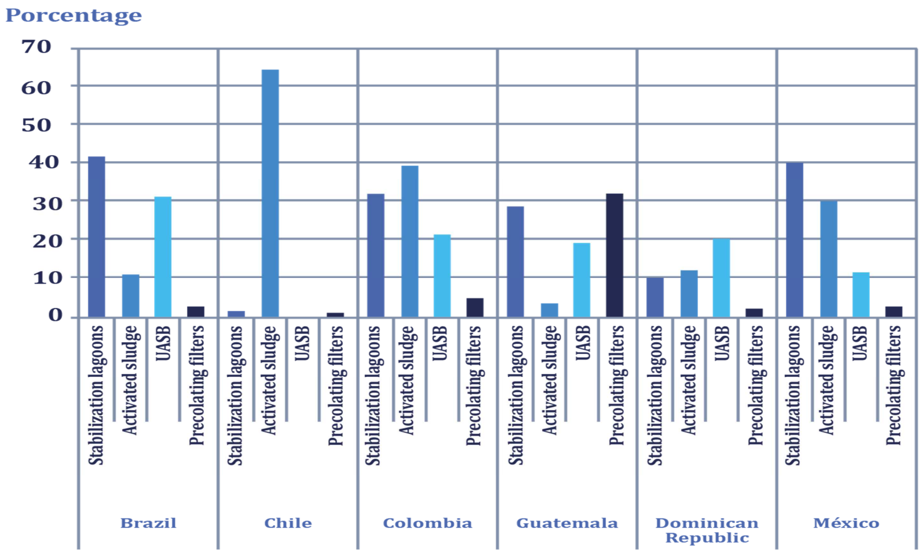
Several projects of the Global Environment Facility (GEF) provide for the integrated management of coastal zones to protect the fisheries on which the economy of many SIDS depends, ensure maritime transport that is vital to their economies, and protect the reefs of coral by treating sewage and other measures.

In 1999, the GEF financed the project Demonstration of innovative approaches for the rehabilitation of highly contaminated bays in the Greater Caribbean, as a continuation of a pilot project executed in the Bay of Havana (Cuba), Puerto Limón (Costa Rica), the bay of Cartagena (Colombia), and the port of Kingston (Jamaica). The pilot project resulted in investment and institutional strengthening plans, and identified sources of financing for the application of corrective measures, which eventually resulted in a contribution of more than US $ 250 million

Through the entire project, co-financing is being raised at the national level to help Cuba and Jamaica overcome several important obstacles to the adoption of best practices to reduce the pollution of national waters and adjacent international waters. The project aims to reduce the entry of nitrogen and phosphorus to the Havana Bay and Kingston Harbor and the adjacent waters of the Greater Caribbean, by constructing, at an intermediate point on the banks of the Luyanó River, a demonstration plant on Integrated wastewater treatment.

It is worth noting the pilot projects carried out in the province of Cienfuegos (Cuba) on the protection of water supply basins and the reduction of the effects downstream of the discharge of wastewater; reduction of pollution from industries in the lower basin of the Haina River in the Dominican Republic; improvement of the management of the catchment area of Fond d'Or in Santa Lucía; reduction of pollution and sediment from the Courland watershed, in Trinidad and Tobago, and protection of the water supply from the basseterre valley aquifer in Saint Kitts and Nevis.

There is no specific information regarding the treatment of urban wastewater in SIDS. In Latin America and the Caribean, less than 20% of municipal wastewater is treated, which reflects the need for investment in the Wastewater Treatment Plants (WWTP) sector in this region and more specifically in the SIDS. The selection of treatment technologies must take into account the environmental impacts generated and not only technical and economic aspects. In this sense, Greenhouse Gas (GHG) emissions constitute one of the relevant environmental impacts of the sector (Noyola, 2012). **Figure 4** shows the most used technologies in LAC in the WWTP in a sample of six countries analyzed (Noyola, 2012).



Source: Noyola, 2012.

Figure 4: Distribution by number and country of various treatment techr ılogies for municipal waste water.

2.6. Waste mixture: Codigestion

Under the term "anaerobic codigestion" we understand an anaerobic treatment of organic waste from different origin and composition in order to make the complementary compositions to allow processing profiles more efficient. Besides improving the process, it has other advantages such as sharing treatment facilities, unifying management methodologies, buffering temporal variations in composition and production of each residue separately, and reducing investment and operating costs. For some time the co-digestion of different co-substrates has been investigated, for instance, livestock waste with industrial waste (Ahring et al., 1992) or algae (treated or untreated) with energy crops (Ramos and Carreras, 2011 y 2012).

The main advantage of the co-digestion lies in harnessing the synergy of mixtures, compensating for the shortcomings of each of the substrates separately. In addition to increasing the potential for biogas production, the addition of co-substrates readily biodegradable confers additional stability to the system. Also, it unifies the management of this waste treatment facilities sharing, reducing investment and operating costs. The anaerobic "co-digestion" allows complementarity taking advantage of the composition of the waste for more efficient processes. For instance, the carbon content of cattle manure is excessive, as the content of nitrogen in pig manure; hence the possibility and advantage to feed the digester with several animal species mixed manure, allowing balancing their nutrient content and thus increasing the efficiency of biogas production process (Marañón, 2009).

As co-substrate many organic materials can be used, using much agricultural waste such as straw, or energy crops such as corn silage.

The anaerobic co-digestion has been a great development in recent years, especially in Germany where in the past 10 years the number of biogas plants has been multiplied by five. There are currently more than 9,000 plants (see Figure 27, Chapter 5) dealing mainly with pig slurry in co-digestion with maize silage.

Summary of Chapter 2

Biodegradable waste encompasses subproducts and organic waste which may be present in solid and liquid phase, which may be subject to biological treatment processes via biomethanation.

A waste is defined by a set of parameters that indicate the degree of pollution they produce and they determine the type of process to be followed for treatment.

Those wastes likely to be treated by anaerobic digestion to generate energy (biogas) are considered as potential biodegradable waste, mainly the following: waste and discharges from livestock (manure and slurry), discharges of agribusiness, as well as those generated by the coffee industry, distilleries, sugar refineries, breweries, etc., the organic fraction of municipal solid waste and anaerobic sludge from wastewater treatment plants (WWTP).

Also, anaerobic co-digestion of waste, or combined treatment thereof, may be an alternative to consider. Its viability has a number of advantages such as sharing treatment facilities, unifying management methodologies, buffering temporal variations in composition and production of each residue separately, and reducing investment and operating costs.

In recent years, the economic and demographic growth of SIDS has been increasing, causing disturbances in the natural environment. Solid waste management is a major issue affecting both developed and developing economies due to the increasing amount of wastes generated annually. Increases in waste generation are often associated with economic growth, higher industrialisation, rise in population and higher standards of living (Kothari et al., 2014). Thus, waste generation differs between economies. Developed countries generally have higher waste generation rates than less developed ones.

Several shortcomings were noted in the process of waste collection, transfer and transport namely the fact of having outdated collection vehicles and narrow roads which are inaccessible. Among the waste management practices in SIDS, waste disposal via landfilling, illegal dumping and backyard burning were favoured most of the time at the expense of sustainable waste treatment technologies such as composting, anaerobic digestion and recycling.

The effectiveness of a solid waste management system can be affected by social risks due to insufficient public participation (Mohee et al., 2015). Consequently, the general public must be sensitised and encouraged to participate in waste management programmes through appropriate waste management awareness campaigns developed by the government or non-governmental organisations (UNEP, no date; Wangi, 2013). The local citizens must be made aware of existing regulations that will deter them from resorting to practices like illegal dumping or backyard burning of wastes. Sensitisation and environmental awareness campaigns at educational and community level can eventually help in having an efficient waste management system.

Besides waste generation, waste composition is an important parameter in the development of adequate strategies for waste management. Based on the composition of the MSW generated in the SIDS, appropriate technologies for their treatment can be implemented. The main fraction of the MSW in the three regions is the corresponding one for the organic matter, being higher in the Aims region (48%) and lower in the Pacific region (41%).

Considering the high organic nature of the waste in the SIDS and the lack of landfill space in most SIDS, the recycling of the organic fraction for its treatment by anaerobic digetion seems to be one of the most appropriate technologies for the management of MSW in SIDS.

3. Anaerobic Digestion or Biomethanation

Biological degradation of the biodegradable organic matter is a process that occurs in the natural environment due to the action of different microorganisms. Depending upon the environment in which they grow, they may be aerobic, anaerobic or facultative. This classification is based upon the presence of air or, more specifically, oxygen in the environment. Thus, aerobic microorganisms need oxygen to survive, anaerobes grow in the absence of oxygen and facultative microorganisms have the ability to survive in both environments.

Currently, among the various treatment technologies that reduce contaminant organic load from the waste, one of the most widely used processes is anaerobic digestion or biomethanation. This is a biological process whereby organic matter in the absence of oxygen and by means of a specific group bacteria (anaerobic) is degraded in a number of gaseous products, known as biogas, and a byproduct known as digestate. This treatment is of particular interest because, in addition to reducing pollution, it gives rise to the production of biogas, with significant energetic value for being constituted mainly of methane (55-65%).

Compared to aerobic processes, the anaerobic treatments have the advantages of not requiring aeration and generating biogas which can be recovered and used for energy purposes, allowing in many cases, the sufficiency or autonomy of processing plants. Another aspect to consider is the reduction of sludge generation, thereby also reducing the costs.

However, we must keep in mind that anaerobic digestion is a complex process, which requires some control to ensure proper operation. An example of this is the sensitivity to organic overloads that can even lead to destabilization of the process. The degradation rate is low compared to aerobic treatment, and therefore requires high retention times and, consequently, larger digesters.

This process can occur in anaerobic digesters forcedly or naturally in MSW landfills. Both the generation of biogas in anaerobic digesters as the extraction and use of biogas generated in landfills solid waste (MSW) are processes of interest in the area of the energy production and will be discussed in later chapters. Also in both cases there is a significant environmental improvement because, biogas extraction of landfill offers the possibility of reducing methane emissions, gas that contribute significantly to the greenhouse effect, and anaerobic digestion significantly reduces the contaminant power of the wastes.

Analyzing all the factors, it can be concluded that anaerobic digestion constitutes a good alternative to treat effluents and / or waste with a high concentration of biodegradable organic matter, which, on the other hand, as it has seen in the previous chapter are numerous and problematic in SIDS.

This chapter provides an historical overview of the discovery of the biogas, discusses the stages of anaerobic biological process and the different microorganisms involved in each of them. It also outlines the basic parameters affecting the performance of the process and the energetic potential of some wastes.

3.1. Historical Review: The Finding of Biogas

The biogas generation from anaerobic digestion is one of the most common processes used by nature to degrade organic matter. It has been known for centuries that the degradation of organic waste produced fuel gas. Ancient sources indicate that the use of waste and "renewable resources" for the energy supply are not new concepts, as they were already known and used long time before the birth of Christ.

The beginnings of the biogas are fixed based on historical facts that say the story of biogas begins in Assyria, in the tenth century BC, indicating that there is evidence that it was used to heat water for the public baths (Brakel, 1980; Lusk, 1998). Other authors establish the beginning around 3000 BC, indicating that the Sumerians were already practicing the anaerobic treatment of the wastes (Deublein and Steinhauser, 2008). There is also data stating that are based on the story of Marco Polo's journey to China (Cathay) (1278-1295) in the book "divisament du monde" (later known as "The Book of the Wonders of the World"), which describes covered tanks where wastewater was stored in ancient China, but it is unclear whether the gas was captured or given any use; in this book it is said that this fact is mentioned in Chinese literature of the third millennium BC. Much more recently, in the sixteenth century in Persia, there is written evidence of the use of biogas (Brakel, 1980; Lusk, 1998).

Apart from these facts, more or less anecdotal, the science of biogas production process is as old as scientific research can be and includes the names of most of the world's most famous researchers. The first scientific notation on biogas is attributed to Jan Baptista Van Helmont, in the first half of the seventeenth century (1630), who found that in the decomposition of the organic matter some flammable gases were obtained (Abbasi et al, 2012) and Boyle, in 1682, announced the possibility of obtaining gas from animal waste and decaying plant (Pine, 1971; Stafford, 1974). The scientific interest of energy production process dates from 1776, when Alessandro Volta identified the relationship of the decomposition of organic matter in an environment without oxygen with the presence of fuel gas (Staffford and Hawkes, 1980), which had been described years before as "gas of the swamps" by its discoverer, Shirley, in 1659.

In 1804, John Dalton described the chemical structure of methane, and associated it with biogas, thus was the one who discovered the presence of methane gas. It was Humphry Davy, in 1808, who generated methane from livestock manure in closed containers laboratory; this event is taken as the beginning of research on biogas (Tietjen, 1975). This work was continued, in part, by his student and then famous English physicist Faraday, performing some experiments with the swamp gas and the hydrocarbon identified as part of it. The end chemistry structure of methane, however, was elucidated by Avogadro in 1821.

Antoine Béchamp (student of Pasteur), in 1866, concluded that the formation of methane during the decomposition of organic matter was produced by a microbiological process. Louis Pasteur was the first to discover the anaerobic microorganisms (Clostridium type) to carry out a study on the butyric fermentation. Also, he got to check that small amounts of oxygen were toxic to these microorganisms. In 1884, he obtained 100 liters of biogas per cubic meter of manure by mixing manure and water at 35 ° C, without the presence of oxygen.

Van Senus, in 1890, studied the relationship between the activities of various microorganisms. Later, in 1906, Sohngen wrote his doctoral thesis on "Microbiological Process of Anaerobic Digestion”. He showed that the hydrogen reacted with carbon dioxide to form methane. Also, he assumed that, the acetic acid formed methane via decarboxylation. This assumption was controversial and remained for decades, but now it is known to be essentially correct (McCarty et al. 1982).

During the decade of the 20s and 30s many experiments were carried out in the laboratory and pilot plant. In many cases the sewage sludge was already used as food for digesters (Acharya, 1958;

Summers and Bousfield 1976). In 1927, Castellini was one of the researchers who studied the symbiotic relationships between different microorganisms involved in methane production process.

Between 1927 and 1950 various experimental studies of gas production from livestock waste were performed and it was from the 40s onwards when a greater interest in anaerobic digestion was developed in Europe, in the wake of the Second World War, because energy sources were scarce. However, this interest was waning by the increasing consumption of fossil fuels. It was from the oil crisis of 1973 when renewed interest in the mechanization of European countries raised and research and development programs were promoted, and industrial plants were built. All these investigations have led to a better understanding of the process which is summarized in four stages as discussed in Section 3.4.

Currently it is noteworthy the number of digesters in the world, both small size and low cost (Figure 12) and large size and advanced technology (Figure 26).

3.2. Environmental benefits and advantages of Anaerobic Digestion

Anaerobic digestion combines two important characteristics that distinguish it from other technologies: it has the ability to debug and at the same time to produce energy. Below are the environmental benefits and advantages of using this technology.

3.2.1. Environmental benefits of anaerobic digestion

- Reduces the pollution potential of organic waste. These wastes are one of the most contaminant for our environment.
- Reduces contamination of soil and water.
- Reduces emissions of greenhouse gases.
- It has additional benefits in terms of meeting targets under the Kyoto Protocol.
- Low polluting potential of the sludge obtained from the process.
- Nutrients of sludge obtained are more susceptible to being absorbed by plants and thus prevent leachate into the ground.
- Reduces odors from agricultural slurries.
- Allows proper waste management.
- Prevents the proliferation of insects.
- In rural areas, it avoids cutting trees to be used as fuel. The digesters are one of the great opportunities to avoid excessive logging since you can get the energy from biogas.
- Does not produce smoke, as in the burning of biomass, this being one of the evils that affect the health of rural women.

3.2.2. Advantages of anaerobic digestion

- The moisture of the waste is not a problem.
- It can treat various wastes together (co-digestion).
- Its energy consumption is much lower than aerobic processes.
- A combustible gas is produced in the process which can be easily exploited.
- Can be achieved additional revenue from waste management.
- These systems are simple and easy to manage.
- There is a wide range of technologies. The simplest for rural areas of developing countries are low cost.
- In rural areas, family economy is improved because of energy production and investment is low cost to the family. It is an investment for many years and the maintenance is low cost. The repairs

of digester are simple. When there is a basic understanding of how to handle it, it can be managed without problems. Biogas is very fast for cooking. It has a blue flame with a high concentration of heat, which facilitates fast cooking.

3.3. Biodegradability of organic material components

Organic wastes mainly comprise three groups, glucids or carbohydrates, proteins or protids and lipids or fats. Anaerobic digestion is suitable for treatment of these residues since these compounds have very good biodegradability. **Table 15** shows the biodegradability of the main components of the organic matter and the types of wastes that are mostly present.

Table 15: Origin and biodegradability of the main components of the organic waste

Component	Present in	Anaerobic biodegradability
Sugars	Beet or cane sugar Byproducts of sugar and candy factories, etc.	Excellent
Starch	Surplus of grain, potatoes, etc.., subproducts of factories of snacks, etc.	Excellent
Cellulose	Chopped straw, grass, pulp and skins of fruits and vegetables, etc.	Good[1]
Protein	Chopped straw, grass, pulp and skins of fruits and vegetables, etc.	Excellent

[1] Require longer retention times
Source: Ainia (2010).

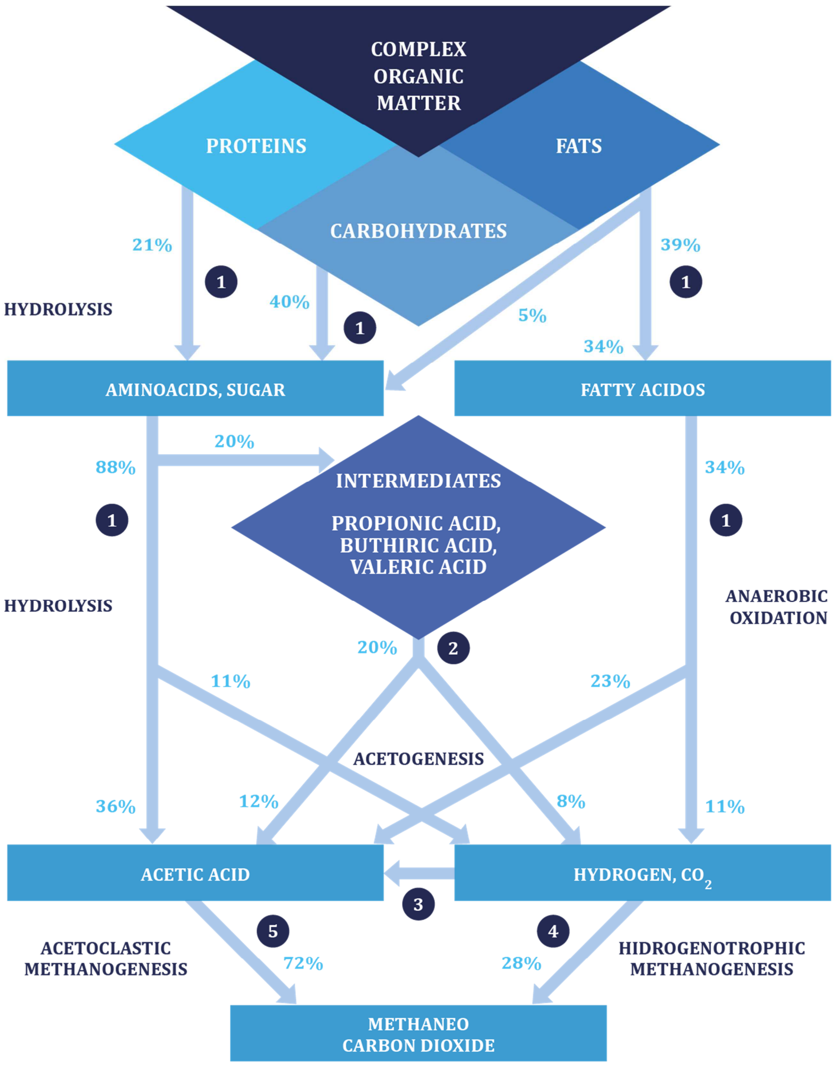
The following describes the steps of the anaerobic degradation of these components.

3.4. Anaerobic process stages

As it has been referred to in the process of anaerobic degradation, the organic matter is transformed by the action of microorganisms in a gas, known as "biogas" for its biological origin, degraded organic materials that remain in solution and novel microorganisms. Degradation of organic matter is performed through a complex series of biochemical reactions that are carried out by different families of microorganisms. It is therefore a complex process because of the number of biochemical reactions that occur as the amount of microorganisms involved in them. In fact, many of these reactions occur simultaneously.
Biochemical and microbiological studies conducted so far divide the anaerobic decomposition process into four phases or stages:

1. Hydrolysis
2. Acidogenesis
3. Acetogenesis
4. Methanogenesis

It must be taken into account that any of these four stages can be the limiting step in terms of the overall reaction rate. The hydrolysis step can be the limiting step in the overall process when dealing with complex substrates, as it is the case for some residual biomass and agricultural residues that present high solids (and Mendez Lema 1997). However, it can be considered that the slowest step in the process is methanogenesis. **Figure 5** shows a diagram of the various steps involved in the anaerobic digestion process, the microorganisms involved in each, and intermediate products generated. The numbers indicate the bacterial population responsible for the process: 1: fermentative bacteria, 2: hydrogen-producing acetogenic bacteria, 3: homoacetogenic bacteria; 4: hydrogenotrophic methanogenic bacteria, 5: acetoclastic methanogenic bacteria.



Source:(Gujer, W., Zehnder, A.J.B., 1983.

Figure 5: Degradation steps of anaerobic digestion process

3.4.1. Hydrolysis phase

Hydrolysis is the initial step in the anaerobic degradation of complex organic substrates, since microorganisms can only use soluble organic matter that can pass through the cell wall. Therefore, the hydrolysis process provides organic substrates for subsequent anaerobic stages. The hydrolysis of these complex molecules is carried out through the action of extracellular enzymes produced by hydrolytic microorganisms and can be the limiting step of the overall process especially when the waste has a high solid content.

The organic material mainly comprises three basic types of macromolecules: carbohydrates, proteins and lipids. During hydrolysis, the bacteria transform the organic substrates in soluble polymers and monomers i.e., proteins, carbohydrates and fats are converted, respectively, to amino acids, monosaccharides and fatty acids.

The rate of degradation of lignocellulose materials composed mainly of lignin, cellulose and hemicellulose is so slow that it is often the limiting step of the hydrolysis process. This is because lignin is highly resistant to degradation by the anaerobic microorganisms and also affects the biodegradability of the cellulose, hemicellulose and other carbohydrates. Hydrolysis rate generally increases with temperature and also depends on the size of the particles, primarily due to the availability of surface for adsorption of hydrolytic enzymes. The physico-chemical pretreatment, whose main effect is the reduction of particle size, produces an increase in the rate of hydrolysis, and if this phase is the limitation of the anaerobic process, it is a benefit to the overall process, producing shorter time retention and smaller reactor sizes.

3.4.2. Acidogenic phase

During this stage, it takes place the fermentation of organic molecules soluble in compounds that can be used directly by the methanogenic bacteria (acetic, formic, H_2) and smaller organic compounds (propionic acid, valeric acid, lactic acid and ethanol, in particular) which will be oxidized by acetogenic bacteria in the next step of the process.

The formation of one acid or another depends on the concentration of H_2 in the middle. When the H_2 concentration in the gas produced is very low (5 to 50 ppm), preferably acetic acid is formed. If the H_2 concentration increases, a decreasing concentration of acetic acid is observed and an increasing of the fraction of acids longer chain such as propionic, butyric, etc.

In this phase also alcohols are produced. The kinetics of the process is relatively fast, the acid producing bacteria are fast growing, because they have a minimum of 30 minutes dubbing. The bacteria involved are facultative.

3.4.3. Acetogenic phase

In the third stage, known as acetogenesis, the other products of the acidogenic phase, namely, propionic acid, butyric acid and alcohols, among others, are transformed by acetogenic bacteria in hydrogen, carbon dioxide and acetic acid (Figure 3). The small organic molecules, especially VFA (volatile fatty acids), are converted into acetic acid. The metabolism of these bacteria is inhibited by high concentrations of hydrogen. The responsible bacteria are facultative and live in close collaboration with the methanogenic bacteria, and can only survive in symbiosis with the genre that consumes hydrogen. These bacteria have slower growth than acidogenic bacteria, with a minimum time dubbing from 1.5 to 4 days.

3.4.4. Methanogenic phase

This phase constitutes the final stage in which compounds such as acetic acid, hydrogen and carbon dioxide are transformed into CH_4 and CO_2. Bacteria involved constitute a single group composed of several species of different shape and cell structure. They are strictly anaerobic. They are found naturally in living organisms (belly of ruminants), and in total absence of oxygen. There are two main types of microorganisms, which degrade acetic acid (acetoclastic methanogenic bacteria) and those that consume hydrogen (hydrogenotrophic methanogens). The main route of formation of methane is the first, with about 70% of the methane produced.

Acetoclastic methanogenic bacteria produce methane from acetate. They have a slow growth (doubling time minimum 2-3 days) and not affected by the concentration of hydrogen in the biogas.

The hydrogen-consuming methanogenic bacteria produce methane from hydrogen and CO_2. This reaction has a dual function in the anaerobic digestion process; on the one hand methane is produced and on the other gaseous hydrogen is removed.

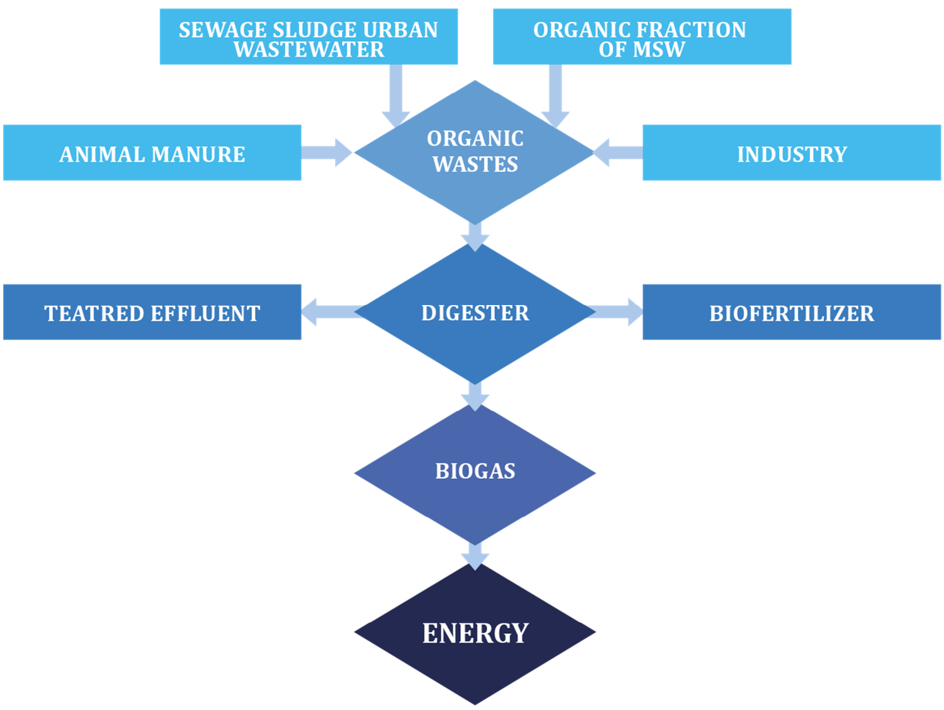
3.4.5. Formation of hydrogen sulphide

In addition to bacteria described above, a group called sulfate-reducing bacteria also exist in the anaerobic digesters, which are particularly important in presence of sulfates (Espinosa-Chavez, 2007). These sulfobacteria are able to reduce sulfate to sulfide. Its importance is great because it can compete with metanobacterias and decrease the formation of methane. Moreover, the sulfobacteria are also able to reduce the sulphates using the hydrogen produced by the acid-forming bacteria. In this case, the hydrogen cannot be used by the methanogenic bacteria. It is therefore important to monitor the presence of sulfates in the middle because, besides affecting the metanobacteria, the presence of hydrogen sulfide in the biogas can affect its corrosivity to energetic use of biogas (Hidalgo and García, 2001).

3.5. End Products of Anaerobic Digestion Process

Anaerobic digestion of organic material give rise to two products, a gaseous compound known as biogas and an effluent stabilized called digestate.

Figure 6 shows a scheme of applications and products that can be obtained in a process of anaerobic digestion.



Source: Prepared by the author based on information collected.

Figure 6: Applications and products of anaerobic digestion.

3.5.1. Biogas

Biogas is known as the gas mixture obtained from the decomposition of organic matter under anaerobic conditions. Therefore, it occurs as a result of degradation of organic material in the absence of air by the action of microorganisms.

The overall equation of the process can be summarized with the following equation:

$$C_6H_{12}O_6 \rightarrow 3\ CO_2 + 3CH_4 + 34.4 \text{ calories}$$

The amount of biogas produced in the anaerobic digestion depends on the composition of the substrate. Simple degradable compounds can be determined with good approximation by the following stoichiometry:

$$C_n H_a O_b + \left(n - \frac{a+2b}{4}\right) H_2O \rightarrow \left(\frac{4n - a + 2b}{8}\right) CO_2 + \left(\frac{4n + a - 2b}{8}\right) CH_4$$

According to this equation it can be deduced that per kg COD removed, i.e. complete anaerobic degradation of 1 kg of COD, theoretically are obtained 0.35 m^3 methane, measured under normal conditions. Knowing the biogas composition, one can determine the volume thereof to generate (Marañón E., et al, 1998).

How much methane gas can be generated through complete anaerobic degradation of 1 kg COD at STP (Standard Temperature and Pressure)?

1.- Calculation of COD equivalent of CH_4

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad \Rightarrow \quad 1\text{ g } CH_4 \sim 4\text{ g } O_2 \text{ (COD)}$$

2.- Conversion of CH_4 mass to equivalent volume:
Considering that 1 mole of any gas occupies 22.4 L at STP:

$$1\text{ mol of } CH_4 \rightarrow 22.4\text{ L } CH_4 \quad \Rightarrow \quad 1\text{ g } CH_4 \sim 1.4\text{ L } CH_4$$

3.- Methane generation rate per unit of COD removed:

$$1\text{ g } CH_4 \sim 4\text{ g } O_2 \text{ (COD)} \sim 1.4\text{ L } CH_4 \quad \Rightarrow \quad 1\text{ kg de COD produce } 0.35\text{ m}^3\ CH_4$$

That is to say, complete anaerobic degradation of 1 kg COD produces 0.35 m^3 CH_4 at STP.
The total biogas production depends primarily on the amount of food consumed by bacteria or, put another way, the amount of substrate removed in the process. This substrate is usually expressed by chemical oxygen demand (COD) and volatile solids.

The following tables of potential production of biogas from different substrates are shown.

Table 16 shows values of potential production of biogas from different wastes depending on total solids content.

Table 16: Potential production of biogas from different wastes

Waste	Potential Production of Biogas (Nm^3/t TS)	Methane (%)
Organic fraction of MSW	400-700	60-65 (%)
WWTP Sludge	380-400	65-75
Pig slurry	250-350	65-70
Dairy sludge	950-1100	75
Paper mill sludge	180-210	55
Newsprint paper	80-100	50
Wheat straw	200-250	65

Sources: Kübler (1999), Abring (1992), Slesser y Lewis (1979), Flotats (2000), Mata (1999), etc.

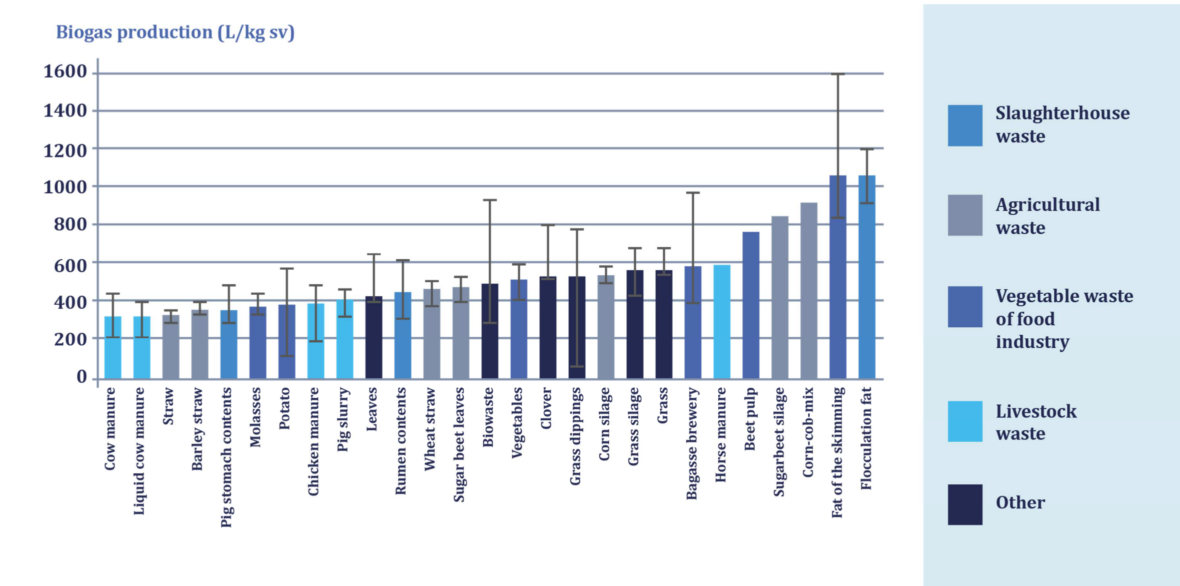
Table 17 shows values of biogas production based on the amount of digested residue as well as features for different agro-industrial wastes.

Table 17: Biogas production from different agro-industrial wastes

Type	Organic Content	Volatile Solids (%)	Biogas production (m^3/t)
Intestines + contents	Carbohydrates, proteins, lipids	15-20	50-70
Fish oils	30-50% lipids	80-85	350-600
Serum	75-80% lactose, 20-25% proteins	7-10	40-55
Concentrated serum	75-80% lactose, 20-25% proteins	18-22	100-130
Meat and bone hydrolysates	70% proteins, 30% lipids	10-15	70-100
Jams	90% sugars, organics acid	50	300
Soybean oil / margarine	90% vegetal oils	90	800-1.000
Sewage sludge	Carbohydrates, lipids, proteins	3-4	17-22
Concentrated sludge	Carbohydrates, lipids, proteins	15-20	85-110
Organic fraction MSW	Carbohydrates, lipids, proteins	20-30	150-240

Source: Angelidaki, I. y Ahring, B.K. 1997

The biogas potential production of some organic waste from food industry and organic fraction of urban waste are shown in **Figure 7**.



Source: Ainia, Probiogás 2010.

Figure 7: Maximum potential of biogas of waste in the food industry

In relation to the production of biogas in Wastewater Treatment Plants (WWTP's), according to Eckenfelder, the maximum biogas production of the WWTP sludge is: 1-1.25 0.30 to 0.42 m^3/kg VS destroyed and COD m^3 CH_4/kg destroyed. Also the production of biogas can be estimated from a per capita basis, according to Metcalf, the normal yield is 15-22 $m^3/10^3$ inhab.d in sewage primary treatment. In WWTP's with secondary treatment, production increases to 28 $m^3/10^3$ inhab. day. **Table 18** shows the potential production of biogas from different livestock wastes depending on SV content and some characteristics of these residues.

Table 18: Potential production of biogas from different livestock wastes depending on SV content and some characteristics of these residues

Waste	TS (%)	VS (%)	C/N	Biogas product. (m^3kg^{-1} SV)	HRT (d)	CH_4 (%)
Pig slurry	3-8[1]	70-80	3-10	0,25-0,50	20-40	70-80
Cow manure	5-12 [1]	75-85	6-20[2]	0,20-0,30	20-30	55-75
Poultry manure	10-30[1]	70-80	3-10	0,35-0,60	>30	60-80

[1] Depending on dilution [2] Depending on presence of straw. Source: Steffen, R. et al (1998).

Table 19 shows the potential production of biogas from different livestock wastes and human waste depending on the amount of waste treated.

Table 19: Potential production of biogas from different wastes

Type of waste	Biogas production (m^3kg^{-1})
Cow manure	0,023-0,04
Pig slurry	0,04-0,059
Poultry manure	0,065-0,116
Human	0,02-0,028

Source: Buxton and Brian (2010).

The biogas composition and its energy properties are discussed in Chapter 7.

3.5.2. Digestate

The anaerobic digestion process produces a byproduct commonly known as digestate, also called "biol" in certain countries. It is another product of anaerobic degradation and, it can be said, it is the mixture of influent stabilized and microbial biomass produced. For a same residue, the type of digester and the operation parameters used determine the quality of the digested sludge relative to the level of contamination and pathogens. As already mentioned, during the anaerobic process part of the organic matter is converted into methane, whereby the organic content of the digestate is lower than in the influent. According to Lindemeyer (2008), reduction of the C / N is beneficial when the end product is for agricultural purposes. The characteristics of the digestate are shown in **Table 20.**

Table 20: Characteristics of the digestate

Parameter	Digestate
Total solids	6%
Volatile solids	69%
pH	7,6 – 8,8
C/N	1,5/1
Nitrogen	15%
Potassium	4,70%
Phosphorus	0,70%
Calcium	0,34%
Sulfur	0,30%
Magnesium	0,19%

Source: WRAP, 2013.

There are different strategies of digestate management and suitability for one or the other will be conditioned by the characteristics of the environment, the objectives and the scale of treatment. The agricultural valuation of the digestates focuses mainly on two aspects: the direct use of the digestate as fertilizer and solid-liquid separation, with use of the solid fraction for the preparation of high value-added fertilizers through composting and the use the liquid fraction as a liquid fertilizer (Bernal, et al. 2010).

a) <u>Using the digestate as fertilizer</u>
Direct use of the digestate in agriculture should be considered as an option of recovery of such products, at profit to the soil and crops. In this sense, there must be a balance between the needs of the crop and annual production of digestate produced in the anaerobic digestion of residues by farmers and agribusiness. The amount of digested should be determined based on parameters such as stability, level of hygiene, presence of contaminants and impurities compounds and nutrient content and organic matter.

b) <u>Independent management of the solid fraction and the liquid fraction, solid-liquid separation</u>
The separation phase process to divide the digestate in two different fractions, a solid (solid digestate) with a solids content of the digested higher than original, and a liquid (liquid digestate), which contains dissolved and suspended elements. The solid-liquid separation does not change the contents of components in the digested, but with this physical treatment a redistribution of the constituents is achieved and, therefore, the management capability of the phases obtained is improved. Thus favoring the application of different processing lines, transport and soil application for each of the two phases obtained (Bernal, et al, 2010).

There are different separation systems such as:

- The natural settling: it is the cheapest option to separate suspended particles, but should only be considered when the separation requirements are low.
- The mechanical systems of separation: which are classified, depending on the force used in the process, in gravity systems, compression or centrifugation.

3.6. Factors influencing the operation and control of anaerobic processes

The basic objective of the digester is to keep the bacterial activity as long as possible. The amount of microorganisms retained depends in large measure on the configuration and design of the digester. The condition how they are and the achievement of a balanced flora is function of the operating parameters. For the process to occur with maximum efficiency is to be achieved: A) Maintaining maximum activity of microorganisms, B) maintaining a minimum concentration of intermediates and C) Increasing the speed-limiting step of the overall process.

A) *<u>Maintaining maximum microbial activity</u>*

This requires controlling both the sludge retention time, because if the digesters operate with very high concentrations of active bacterial biomass it achieves better stability conditions, and physical and chemical parameters such as pH, redox potential, temperature, nutrients and toxicity. The most suitable conditions in anaerobic processes are:

3.6.1. Startup phase. Initial inoculum

For some organic substrates that lack suitable microorganisms, such as some industrial waters, an inoculum of anaerobic bacteria to carry out degradation is required. Moreover, the low rate of growth of microorganisms makes it necessary to use an initial inoculum to provide a sufficient amount of bacteria.

The inocula used are those from another digester, because the use of commercial lyophilized microorganisms up to now is rarely used (Fernandez-Polanco and Garcia, 2000). Because of its larger abundance, sludge anaerobic digesters are used as inoculum, which treat urban waste and / or livestock waste, and sometimes also sludge of industrial anaerobic reactors are used. The microorganisms present in the inoculum must acclimate to the new conditions of operation and the new medium. Initial inoculum concentration of 5% is usually sufficient for achieving the activity of the first stage of the anaerobic process (Balaza et al., 2003).

The start-up of the digester requires working initially with moderate organic loading rates and constantly monitoring operating parameters. The digesters that have been started slowly eventually offer greater stability. The usual starting time is from 1 to 4 months, depending on the substrate and on the technology used, as discussed in the next chapter.

3.6.2. pH

The pH of the digester is yet another important parameter in anaerobic digestion. The different groups of bacteria present in the process have optimum activity levels around neutrality, between the following values:

- Fermentative bacteria: between 7.2 and 7.4
- Acetogenic bacteria: from 6.0 to 6.2

- Methanogenic bacteria: between 6.5 and 7.5

In order for the process to be developed successfully, the pH should not be lower than 6.0 or higher than 8.3 (Banaza et al., 2003). If the pH of the medium is below 6.5, the activity of methanogenic acetoclastic bacteria begins to diminish while with a pH below 5.5, the activity ceases completely. On the other hand, if pH is below 4.5 the activity of all the microorganisms involved stops (Lema and Mendez, 1997). For that whole anaerobic process to be developed properly in a single digester, the pH should be worth about 7, between 6.6 and 7.6. So is the correct development of the anaerobic process in a single digester. One difficulty is maintaining pH above 6.6. During digester start-up, overloading, or instability, organic acids are intermediate products produced by the microorganisms. The presence of too high a concentration of organic acids decreases the pH, decreases methane production, and can cause reactor souring or reactor failure (Rittmann & McCarty, 2001).

pH value not only determines the biogas production but also its composition. One of the consequences of the pH value below 6 is that the biogas produced is very low in methane and, therefore, it has less energy qualities.

3.6.3. Alkalinity

Alkalinity is defined as the capacity of water to neutralize acid (Rittman and McCarty, 2001). Maintaining an optimum value of alkalinity in the digester is very important, since it buffers sudden changes in pH produced by the generation of volatile fatty acids. Bicarbonate alkalinity of at least 500 – 900 mg/l $CaCO_3$ is required for a pH greater than 6.5 (Rowse, 2011). Lime, sodium hydroxide, and ammonia are three of the least expensive chemicals available for the addition of alkalinity. Other authors recommend bicarbonate alkalinity values between 1.500 and 5.000 mg/l $CaCO_3$. Besides those already mentioned, other reagents as calcium carbonate or sodium bicarbonate can also be added to maintain and/or increase the alkalinity. Previous studies have shown that values of bicarbonate alkalinity above 2500 mg/l ensure good control of pH and adequate stability. Volatile acids concentration under stable conditions is usually between 50 and 100 mg/l. By maintaining a constant relationship volatile acid/alkalinity <0.25, the buffering capacity of the system is ensured (Water Environmental Federation, 1998) (Energía de la Biomasa, 2010). CO_2 dissolving also allows increasing original alkalinity of influent, so that the recirculation of portion of the effluent makes possible the treatment without adding reagents.

3.6.4. Volatile Fatty Acids (VFA)

It is a specific parameter of anaerobic digesters control. Volatile fatty acids (VFA) to consider are: formic, acetic, propionic and valeric, although the two most abundant are acetic and propionic acids. VFA accumulation in the digester is an unequivocal symptom of destabilization caused by the decoupling of the production and elimination reactions of these compounds. VFAs act as inhibitors of anaerobic process. In a mature and stable reactor, VFA concentration is below 500 mg/l. Inhibition is not reached until values are close to 5.000 mg/l.

3.6.5. Redox Potential

Because methanogenic bacteria are strict anaerobic, tolerance to changes in the redox potential is less than that of other species involved. In pure cultures, methanogenic bacteria require a redox potential between -300 mV and -320 mV to ensure the strongly reduced environment that these bacteria needed for optimal activity. Dirasian studied digestion process through continuously measuring the redox potential in a digester. From this research, the conclusions reached are shown in **Table 21** (Montes, 2008).

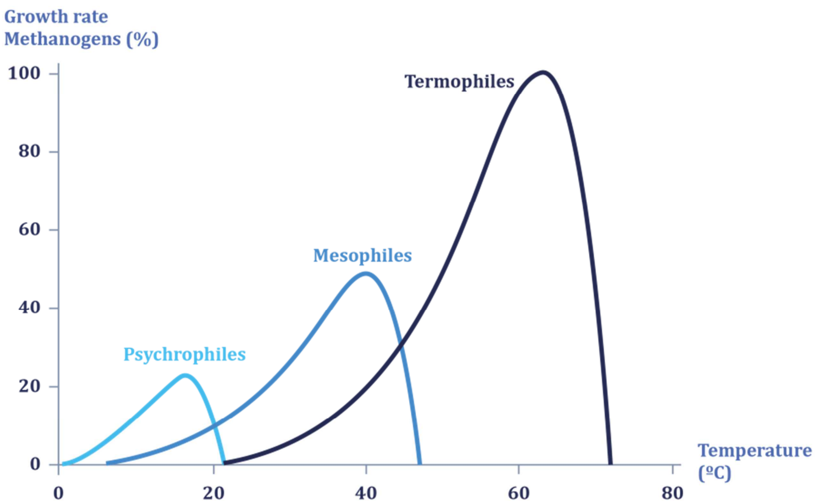
Table 21: Influence of redox potential in anaerobic digestion

Potential (mV)	Anaerobic digestion
-520 a -530	Optimal
-510 a -540	Good
-495 a -555	Allowable limits
Beyond the previous limit	Not possible

Source: Montes, 2008.

3.6.6. Temperature

Temperature is a very important parameter. As a general rule, bacterial growth rates double for each 10°C rise in temperature over a temperature range, which varies on bacterial species. Methanogenic microorganisms are extremely sensitive to temperature. There are three temperature ranges: psychrophilic (5-20°C), mesophilic (25-45°C, with the optimum of 35-37°C, above 40°C can cause denaturation of the enzymes) and thermophilic (45-65°C, being the optimum 50-60°C) (**Figure 8**). The latter range is subdivided in thermotolerant (about 50°C but may live at 35°C) and stringent (> 45°C).



Source: Van Lier, 1993.

Figure 8: Effect of temperature on anaerobic activity.

Specific methane production rates are 50 to 100 percent higher for thermophilic anaerobic digestion than for mesophilic anaerobic digestion (Rittmann y McCarty, 2001).

So far the psychrophilic range has been poorly studied and, in general, it is seen as impractical because it would be necessary to make large digesters. However, stability has fewer problems than other temperature ranges. Most used range is the mesophyll, although currently being employed increasingly thermophilic range for obtaining higher processing speed and a better elimination of pathogens. However, thermophilic range is typically more unstable to any change in operating conditions and also presents greater problems of inhibition of the process by the greater toxicity of certain compounds at elevated temperatures, such as ammonia nitrogen or long chain fatty acids.

3.6.7. Nutrients

One of the advantages inherent to the anaerobic digestion process, compared to aerobic processes is their low need for nutrients derived from their low biomass production rates presented by anaerobic microorganisms. The main nutrients required for growth of microorganisms are carbon, nitrogen and phosphorus, and a series of mineral elements such as sulfur, potassium, sodium, calcium, magnesium and iron should be present at trace levels.

Carbon is the main power source for the bacteria and the main component of biogas. It comes mainly from carbohydrates contained in the biomass (cellulose and sugars), which will be subsequently degraded by the microorganisms for their growth. The problem arises when biomass is combined with lignin, as it is not easily digested as cellulose, since this compound is hardly attacked by microorganisms (although it is also a source of carbon). For this reason the fermentation period should be longer.

Nitrogen is a major source for the synthesis of proteins of living organisms. Nitrogen deficiency disables bacteria to metabolize all the carbon, which would lead to lose effectiveness in the degradation. Conversely, if there is an excess of nitrogen that can't be used entirely, it accumulates in the environment, usually in the form of NH_3 (ammonia), which causes a decrease or inhibition of bacterial growth, especially the methanogenic.

Therefore, the **C/N ratio** is a significant index referred to the digestibility and yield potential of the biomass. Its value varies depending on the quality or origin of the biomass substrate. **Table 22** shows the values of this parameter for different wastes.

Table 22: C/N ratio for different substrates

Substrate	C/N ratio
Pig slurry	18-20
Cattle slurry	15-24
Chicken manure	15
Slaughterhouse waste	2-8
Kitchen waste	25
Fruit waste	35
Sewage sludge	16
Potato skins	25
Barley, rice, wheat	60-90

Source: Flotats, 2008.

Several authors have studied the necessary relationship between majority nutrients, considering appropriate the C / N ratio value between 15-30/1. In the case of **phosphorus**, C / P ratio is between 75-113/1 and with respect to nitrogen a ratio of 1/5 to 1/7 is admitted.

As orientative values, the following ones are provided: (Fernández-Polanco y García 2000):

Aerobic treatment: $DBO_5/N/P = 100/5/1$
Anaerobic treatment: $DBO_5/N/P = 100/0.5/0.1$

Sulfur: requirements are lower than those of phosphorus; the greater part of the biomass contains enough. But an excess of sulfur can promote the development of sulfobacterias, which convert sulfur compounds to hydrogen sulfide (H_2S), gas toxic and foul-smelling, and cause serious corrosion problems when burning biogas.

Usually, the water from the food industry, livestock waste, sewage sludge urban wastewater or organic fraction of municipal waste does not require the addition of these nutrients in anaerobic systems. Some waters are deficient in some of these nutrients, especially phosphorus, which should be added to treatment. This circumstance has a significant economic impact, because the soluble phosphorus is expensive. In some occasions other nutrients (trace elements) may also be needed, such as iron, nickel, cobalt and molybdenum. It has been observed that the addition of these elements in concentrations ranging from 50 to 100 nM have a positive effect on the conversion of acetic acid (Sarasa, 2010).

3.6.8. Toxicity and inhibition

As already mentioned, the main indicators to show inhibition in the process are:

- Decreased production of methane
- Increased VFA concentration in the environment

The anaerobic digestion process can be inhibited by the presence of toxics in the system and affect the development of bacterial activity. Furthermore, a substance can be considered to be toxic depending on its concentration; temperature also plays an important role in the toxic effect of certain compounds (ammonium sulfide, volatile fatty acids, etc.). Methanogenic bacteria are generally the most sensitive, although generally all groups of microorganisms involved in the process are affected.

The most important are:

- *Substances that are generated as intermediates: H_2, AGV, H_2S, etc.* A high level of H_2 is able to block the progress of the reaction. AGVs can cause a decrease in pH, while the presence of H_2S, generated from the sulfate content in the feeding, has inhibitory effects.
- *Substances entering the digester by accident: O_2 and toxic.* To prevent entry of oxygen, digesters work with a slight overpressure. The massive entry of oxygen, because of accidental causes, inhibits the process, which is recovered without difficulty when oxygen is removed by stripping with a gas or by facultative microorganisms.
- *Substances that accompany the food: antibiotics, metals.*

Besides those mentioned, the major toxic compounds are:

- alkali cations and alkaline earth
- ammonia and ammonium (according to pH)
- heavy metal
- compounds with unsaturated carbon-carbon bonds
- chlorinated compounds
- cyanides

Tables 23 and **24** show the effect of ammonia concentration and stimulatory concentrations and inhibitory of certain cations in the anaerobic process, respectively.

Table 23: Effect of concentration of ammonia nitrogen in anaerobic digesters

Ammonia concentration (mg N/l)	Effect
50 a 200	Beneficial
200 a 1000	No adverse effects
1500 a 3000	Inhibitor at pH between 7.4 and 7.6
>3000	Toxic

Source: Water Environment Federation, 1996.

Table 24: Stimulatory concentrations and inhibitory of cations

		Concentration (mg/l)	
Cation	Stimulants	Moderate inhibitor	Strong inhibitor
Calcium	100 a 200	2.500 a 4.500	8.000
Magnesium	75 a 150	1.000 a 1.500	3.000
Potassium	200 a 400	2.500 a 4.500	12.000
Sodium	100 a 200	3.500 a 5.500	8.000

Source: Water Environment Federation, 1996, 1998.

Table 25 shows some common inhibitors (Varnero, 2011), but these values should be taken as approximate, because the bacteria have the ability to adapt to conditions that were initially affected significantly.

Table 25: Most common inhibitors in the microbiological process of the digestion

Inhibitors	Inhibitory concentration
$SO_4^=$	5000 ppm
NaCl	40.000 ppm
Nitrate (according to nitrogen content)	0,05 mg/ml
Cu	100 mg/l
Cr	200 mg/l
Ni	200 - 500 mg/l
ABS (synthetic detergent)	20 - 40 mg/l
Na	3.500 - 5.500 mg/l
K	2.500 - 4.500 mg/l
Ca	2.500 - 4.500 mg/l
Mg	1.000 - 1.500 mg/l

Source: Gene y Owen, 1986.

B) <u>Maintaining a minimum concentration of intermediate products.</u>

The concentration of intermediates is an indicator of the balance between the microorganisms involved in the different phases of the process. To maintain low concentration of these intermediates the following factors should be taken into account: Mixing, Hydraulic residence time, Solids Retention Time, Organic Loading Rate and Production biogas and composition.

3.6.9. Mixing

Mixing is another important parameter to consider in the design of an anaerobic digester. Mixing increases the kinetics of anaerobic digestion speed, accelerating the biological conversion process. Additionally, mixing allows uniform heating of the reactor (Tchobanoglous et al., 2003).

The objectives that are achieved with a suitable homogenization are: mixing means to achieve uniform values of concentration and temperature, facilitating mass transfer processes, because substrate molecules should be adsorbed by the surface of microorganisms -and Intermediates and the end should be transported-, and preventing both dead zones and that part of the original substrate leaves the digester without having contact with the microorganisms.

A good mixing can be done by mechanically through conventional impellers rotating immersed within the digester at low speed, pneumatical recirculation by injecting biogas via spargers at the bottom of the digester (Tchobanoglous et al., 2003) or by recycling the effluent at the bottom of the digester. For large digesters, mixing with gas has major advantages (Baraza et al., 2003).

3.6.10. Hydraulic Residence Time (HRT)

Hydraulic retention time is important to reactor operation and design because it defines the length of time the substrate and particular constituents targeted for removal will be in contact with the biomass within the digester. Hydraulic retention time (HRT) is defined as the average amount of time one reactor volume of actively digesting sludge stays within the reactor. The numeric definition is:

$$HRT = V/Q$$

Where: HRT= hydraulic retention time (d)
V = volume of reactor (m^3)
Q = influent flow rate (Rittmann & McCarty, 2001).

HRT is the parameter that allows us to control the flow of treated effluent. It is essential to determine the optimal time. If there is accumulation of intermediate products, because the substrate feed is greater than its degradation, the residence time properly should decrease.

Hydraulic retention time (HRT) is important to digester operation and design because it defines the length of time the substrate and particular constituents targeted for removal will be in contact with the biomass within the digester. Reaction kinetics ofmethanogenesis and fermentation are the rate-limiting kinetics in anaerobic digestion (Khanal, 2009). Most often, methanogenesis is the rate-limiting step of the process. It is important to design reactors for sufficient retention times so that volatile solids destruction can take place (Vesilind, 1998).

The amount of degraded organic matter increases with increasing HRT, whereas the methane production (output per unit volume of the digester) decreases after passing the optimum. Therefore it is necessary to determine, for each type of waste and digester, the optimal retention time of the process.

HRT are related to two factors, the type of substrate and the temperature thereof. Selecting a higher temperature range would lead to a decrease in the retention times required, thus the needed volume of digester will be lower for a certain material volume. **Table 26** shows values of HRT for different animal waste.

Table 26: HRT for different animal waste

Raw material	HRT
Liquid cattle manure	20-30 days
Liquid pig manure	15-25 days
Liquid chicken manure	20-40 days

Source: Rural Engineering Institute. I.N.T.A. - Castelar (Dela Torre, 2008)

As discussed, the temperature affects the anaerobic digestion process. There are different stages of a microbiological process that are directly affected by the temperature and inversely with HRT as shown in **Table 27.**

Table 27: Temperature ranges and retention times in anaerobic fermentation

Fermentation	Temperature range			HRT (days)
	Minimum	Optimum	Maximum	
Psychrophilic	4-10	15-18	25-30	>100
Mesophilic	25-20	28-33	35-45	30-60
Thermophilic	25-45	50-60	75-80	10-16

Source: Swine Research Institute, 2003 (De la Torre, 2008)

3.6.11. Solids Retention Time (SRT)

Solids retention time (SRT), or mean cell residence time, is defined as "the mass of organisms in the reactor divided by the mass of organisms removed from the system each day" (Rittmann & McCarty, 2001).

Solids retention time (SRT) is important because if SRT is too low, there will be organism washout. If SRT is too long, then the system becomes nutrient-limited. SRT impact which organisms have optimal growth conditions within the reactor, and changes the microbial ecology of the system (see Section 2.1). SRT is equal to HRT when there is no solids recycle (Vesilind, 1998). Increasing SRT increases the extent the reactions involved in anaerobic digestion needs to completion (Vesilind, 1998). A longer SRT stabilizes the process, lowers the amount of sludge produced, and increases biogas production (Rittmann & McCarty, 2001).

3.6.12. Organic Loading Rate (OLR)

Organic loading rate (OLR) is defined as the mass of volatile solids added each day per reactor volume (Vesilind, 1998) or the amount of BOD or COD applied to the reactor volume per day (Tchobanoglous et al., 2003). Organic loading rate is related to hydraulic retention time by the following equation:

$$OLR= (Q)\ (C_{VS})/\ V_{digester} = C_{VS}/\ HRT$$

Where OLR = Organic loading rate
Q = volumetric flow rate (m^3/d)
CVS = concentration volatile solids (kg VS/m^3)
$V_{digester}$ = reactor volume (m^3)
HRT = hydraulic retention time.

In the case of no recycle, HRT = SRT and therefore:

$OLR = (C_{VS})/\ SRT$

OLR thus depends on the waste composition and residence time. It is one of the parameters more used to characterize the treating ability of anaerobic digesters. As basis, either take the digester volume or amount of biomass, being the units: kg COD/m^3.day; kg COD/kg biomass.day or kg COD/kg VSS.day.

The organic loading rate cannot be considered in absolute terms, but relative to the influent organic load (kg COD/m^3). Both are related through the hydraulic residence time

$$\frac{\text{kg COD}/m^3_{digester}.\text{day}}{\text{kg COD}/m^3_{influent}} = \frac{m^3_{influent}}{m^3_{digester}\ .\ \text{day}} = \frac{Q}{V} = \frac{1}{HRT}$$

To each digester and influent a maximum value of the organic loading rate corresponds, which if exceeded the digester becomes unstable and decreases performance debugging. This parameter is very important, because for many wastewaters the determinant factor of the size of the reactor is admissible organic loading rate.

According to Rittmann & McCarty (2001), the recommended organic loading rate for high-rate anaerobic digestion is 1.6 - 4.8 kg $VSS/(m^3.d)$, and the recommended organic loading rate for low-rate anaerobic digestion (digestion with no heat and no mixing) is 0.5 - 1.6 kg $VSS/(m^3.d)$. Speece (1996) recommended organic loading rates of 5-10 kg $VSS/(m^3.d)$. Vesilind (1998) recommended that the peak organic loading rate for high rate anaerobic digestion should be 1.9- 2.5 kg $VS/(m^3.d)$.

If the loading rate in anaerobic digestion is too high for the system conditions, the two methanogenesis pathways can become inhibited, which can result in the accumulation of volatile fatty acids in the digester. The presence of VFA's decrease the pH in the reactor and can lead to reactor souring, or failure. Therefore, it is very important that the design organic loading rate is conservative.

3.6.13. Biogas Production and Composition

The biogas production rates can be used not only as a control parameter, but also as a variable to establish stability of the digester. Variations of CO_2 production in the biogas are symptoms of digester behavior changes, and persistence of the variation is clear sign of instability. As a quick response parameter and easy analysis, the percentage of CO_2 can be taken as an index of stability.

C) Increase the speed of limiting step of the overall process.

The controlling step in the anaerobic degradation corresponds to the methanogenic bacteria. This possibility can be achieved with a separation phase favoring each one independently. Phase separation refers to maintaining digesters in series, in which the hydrolysis steps and acidogenesis are carried out in the first one and methanogenesis in the second. His objective is to get a global retention time lower than for a single digester. Separation is kinetic type, controlling the retention time of each digester, which will be lower in the first, due to higher growth rates acidogenic bacteria. This type of system has been successfully applied to the digestion of wastes with high sugar concentration and low solids content, but not to wastes with fibers and, in general, complex substrates whose limiting step is the hydrolysis. This technology will be discussed in the next chapter. **Table 28** shows the requirements for a biogas production process into two phases.

Table 28: Ideal conditions according to anaerobic digestion phases

Parameter	Hydrolysis/Acidification	Methanogenesis
Temperature	25-35ºC	Mesophilic: 32-42ºC Termophilic: 50-58ºC
pH	5,2-6,3	6,7-7,5
C/N relation	10-45	20-30
Solids content	<40% D.M.	<30% D.M.
Redox potential	+400 -300 mV	<-250 mV
Nutrient demand (C, N, P, S)	500:15:5:3	600:15:5:3
Trace elements	No specific requirements	Essential: Ni, Co, Mo, Se

Source: MAGRAMA, 2010.

Table 29 summarizes the information and the ranges of the main operating parameters of anaerobic digestion.

Table 29: Operating parameters of anaerobic digestion

Parameter	Range	Information
Temperature	35-40ºC Mesophilic 50-60ºC Termophilic	The upper end of the mesophilic range is ideal for maximum production of biogas
pH	6,5–7,6	The ideal pH is neutral at 7.0. Self-adjusting by anaerobic microbes, methanogens are unlikely to grow with pH <6.5
Alkalinity	1 g/l	Regulation by hydrogen in the conversion of waste to bicarbonate
Acidity/Alkalinity	0,3 a 0,5	Easier to measure than VFA or alkalinity
VFA		Higher concentrations inhibit the acetate and the production of biogas
C/N	20 to 30	Higher ratios of C / N give a consumption of nitrogen by methanogenic as a result; production of biogas decreases.
Organic load	Rate of 3-5 kg of volatile solids per cubic meter of digester volume and day	Microorganisms generally are inhibited when the loading rate exceeds 6.4 kg/m^3 day
TRH	9 – 95 days	Varies greatly depending on the substrate, temperature and design of the system

Source: EPA, 2010; NREL, 2013.

3.7. Anaerobic Digestion in SIDS

Anaerobic digestion has been widely researched both for its energy production and for its waste management potential and, as will be seen in the next sections, it has been implemented in many countries. Currently there are millions of digesters in operation in the world, which shows that it is a mature technology, although the process is still being investigated in order to make the best possible design in each case and thus obtain maximum energy, environmental and economic returns.

In principle, anaerobic digestion is a simple technology. No specific knowledge is necessary to generate biogas, anyone can produce it, it is enough to put the biodegradable organic matter in anaerobic conditions (absence of oxygen) to obtain it after a while. However, despite its simplicity, training is required so that the process takes place optimally and efficiently. Experiences have been carried out in some SIDS, as will be seen below, and not always with good results. This could be due to the lack of knowledge, capacity and experience of the people who managed the digesters (UNEP, 1998). A major problem in SIDS is the lack of properly trained personnel. For these biogas plants to be successful, one of the basic limiting factors is the correct management of the technology by the communities where they are implemented (Gómez et al., 2010), which is a challenge for the near future in the case of the adoption of waste management technologies such as anaerobic digestion. The training is therefore of the utmost importance and experts must be recruited to help in the training of the locals to deal with possible waste management technologies such as anaerobic digestion.

This technology was introduced into the SIDS of the English-speaking Caribbean in the 1980s by the Deutsch Gesellschaft für Technische Zusammenarbeit (German Society for Technical Cooperation) (Consigny et al., 2005). In Jamaica, 89 biogas plants were built from 1988 to 1992, but 15 of these plants were phased out and from 1993, another construction phase of biogas plants startedbegan where 120 plants were constructed (Kranert et al., 2012). In Cuba, anaerobic digestion was introduced since the 1940s and currently has around 700 biogas plants (Kranert et al., 2012). Likewise, in 2009, a low-cost polyethylene biodigestor was installed in Belmopan (Belize) for biogas production from livestock waste (IICA, 2009 cited by Mohee et al, 2015). In the Dominican Republic, Brugal has digesters of 1.93 million gallons to treat vinasses and uses biogas in one of its two boilers (Del Toro, 2001). Also, in this SIDS, the potential of capturing methane emissions from agricultural and livestock wastes for use as a renewable fuel through the anaerobic digestion process is being investigated through the global methane initiative (Eastern Research Group Inc. and Tetra Tech, 2011 cited by Mohee et al, 2015). In Haiti, anaerobic digestion is used for the treatment of agricultural wastes, domestic wastewaters and animal manures for the production of biogas (Faculty of Agriculture and Natural Resources, 2015, Toussaint and Wilkie, 2011). In Puerto Rico, Bacardí has anaerobic digesters with which it avoids many emissions of greenhouse gases and, at the same time, uses biogas in its boiler; also in Yauco a biogas plant will be built that will be fed with food waste from residences and school canteens (Figueroa, 2015). A biomass/biogas facility was being developed in United States Virgin Islands for the production of biogas from Giant King Grass (Tibbar Construction Services Inc., 2014).

In Pacific SIDS, the situation is not dissimilar. In Samoa, for instance, biogas plants were built in 1980s but then phased out (Isaka et al., 2013). In 2005–2006, large scale-biogas plants were constructed but these were also ineffective (Isaka et al., 2013). More recently, under the Pacific Island Greenhouse Gas Abatement through Renewable Energy Project (PIGGAREP), the constructions of two biogas plants were expected to be completed and operational by September 2014 (UNDP, 2014). In Fiji, there are nine operational biogas plants (Tudreu, 2011 cited Prasad, 2012) while in Papua New Guinea, pilot scale AD has been investigated by Jenangi (2001). In Tuvalu, a biogas plant treating pig and human sewage was commissioned but the project is currently stalled due to management problems (Rosillo-Calle and Woods, 2003 cited by Mohee, 2015).

In AIMS SIDS, there are few anaerobic digestion plants. In Singapore, the construction of the first biogas plant began in 2008 with the investment of Advanced Environmental Technologies Pte Ltd., a subsidiary of Advanced Holdings Ltd. (Advanced Holdings Ltd., 200 cited by Mohee, 2015). In Seychelles, the Chinese government and the Ministry of Agriculture of Seychelles are financing the construction of pilot biogas plants in four animal farms on the island (REEEP Policy Database, 2012). In Mauritius, there is currently a large-scale biogas plant on the island at the St. Martin wastewater treatment plant, where preliminary, primary and secondary treatment sludge is digested for the production of biogas that is subsequently used for generation of electricity (Joysury and Abeeluck, 2013 cited by Mohee 2015). In addition, there is a small-scale biogas plant in animal farms, such as one in the Vedic Farm ISKCON (ISKCON, 2004). It is also expected that the creation of the Kievnov Science and Environmental Technologies Co. Ltd company will contribute to the development and application of anaerobic digestion in Mauritius (KSET, 2012, Business Mega, 2011). Although substantial research has been conducted on Aujeszky's disease within the Mauritian context, the implementation of large-scale biogas plants has not yet been considered a priority by the government or private sectors. In contrast, thermochemical processes such as gasification are being proposed as potential large-scale WTE plants in Mauritius (GIS, 2014) at the expense of more sustainable AD.

Summary of Chapter 3

Anaerobic digestion is a biological process through which organic matter in the absence of oxygen and by means of a specific group of bacteria is degraded in a set of gaseous compounds, known as biogas, mainly made up by methane (CH_4) and carbon dioxide (CO_2), and a byproduct rich in nutrients.

Generating Biogas from anaerobic digestion is one of the most common processes used by nature to degrade organic matter. The research process is as old as scientific research can be and includes the names of most of the world's most famous researchers. The first scientific notation on biogas is attributed to Jan Baptista Van Helmont, in 1630, who found that in the decomposition of the organic matter some flammable gases were obtained (Abbasi et al, 2012). Over the years there has been progress in understanding the process, but it has been since the mid twentieth century when more progress has been made, existing today a great knowledge of the reactions taking place.

Microbiological and biochemical studies indicate that the anaerobic degradation process is performed in four main steps (hydrolysis, acidogenesis, acetogenesis and methanogenesis) and involves numerous families of microorganisms, being specifically the methanogenic bacteria those that produce biogas. Thus, anaerobic digestion, as waste treatment method, enables to obtain a high energy gas, which can be readily usable, and a stabilized end product (digestate) with lower organic content that can be used as fertilizer.

The basic objective of the technology is to maintain the possible highest bacterial activity in the digester, as these microorganisms are the most responsible for the transformation. For this reason, it is essential to monitor the operating parameters and process control in order that they stay within the appropriate ranges.

Anaerobic digestion is therefore a good alternative for treating wastes with high biodegradable organic matter (Nallathambi, 1997, Mata-Alvarez et al., 2000; Baraza et al., 2003) as seen in the previous chapter. Thus, this treatment is suitable for high load wastewater with biodegradable organic matter (discharges from sugar industries, distilleries, breweries, canneries, paper mills, etc..) (Del Toro, 2001), agricultural and livestock waste (manure, waste slaughterhouse, etc.) (Gannon, et al. 1994; Mahony et al., 2002), residual biomass, which comprises both the organic fraction of municipal solid waste (Tchobanoglous et al., 1994) as sludge of urban waste water treatment (Choi, 1997), as seen in Chapter 2, and mixture of wastes in what is known as co-digestion (Sosnowski et al., 2003).

Moreover, its use implies a number of benefits not only environmental and energetic, but also others that are inherent to the nature of the technology itself that makes its application in rural areas very attractive.

Anaerobic digestion has been widely researched both for its energy production and for its waste management potential and, as will be seen in the next sections, it has been implemented in many countries. Currently there are millions of digesters in operation in the world, which shows that it is a mature technology, although the process is still being investigated in order to make the best possible design in each case and thus obtain maximum energy, environmental and economic returns.

Experiences have been carried out in some SIDS, as will be seen below, and not always with good results. This could be due to the lack of knowledge, capacity and experience of the people who managed the digesters (UNEP, 1998). A major problem in SIDS is the lack of properly trained personnel. For these biogas plants to be successful, one of the basic limiting factors is the correct management of the technology by the communities where they are implemented (Gómez et al., 2010), which is a challenge for the near future in the case of the adoption of waste management technologies such as anaerobic digestion. The training is therefore of the utmost importance and experts must be recruited to help in the training of the locals to deal with possible waste management technologies such as anaerobic digestion.

4. Anaerobic technologies. Digesters in rural areas of developing countries.

The energy transformation of organic waste by anaerobic fermentation is a process that has been practiced for over a hundred years and served a very important energetic function. Over the years the technology has been evolving through advances in research reaching a deeper knowledge of the process, both microbiological and the parameters that regulate this fermentation, which notably led to progress in technological aspects and greatly improve its efficiency. A classification of the digesters is based on the charging frequency. Moreover, there are currently a large number of technologies adapted to waste treatment by anaerobic digestion, the selection of one or another depends mainly on the characteristics of the landfill to be treated. The technologies can be divided according to their degree of complexity, thus we have technologies of small size and low cost, and advanced technologies more often applied in larger digesters. This chapter discusses the technology aspects of small size and low cost which are the most widely used in rural areas and provides information for the construction and design of a digester with these features.

4.1. Brief History: Evolution of technology

Asia is a pioneer in the treatment by anaerobic digestion. China is one of the first countries in the world to discover and use biogas. Already in the years 1890-1920, digesters developed in some Chinese provinces. In 1921, Luo Guorui built a biogas tank of eight cubic meters and founded the company ‘Guorui Biogas Lamp’.

On the other hand, some authors attribute to India the building of the first anaerobic digester in 1897 by Matunga Leper Matunga in Bombay (Mumbai) using human waste to generate gas in order to satisfy their lighting needs (Khanal 2008). Already in 1900, the first digesters for the production of biogas from organic waste were built in India.

In Europe, French Mouras, in 1881, applied the first anaerobic digestion for waste water treatment in a crude version of a septic tank of his invention, which he called "automatic treasure" (McCarty et al. 1982). Later, in 1895, an Englishman, Cameron, built like a tank but improving the effectiveness of treatment, and called it "septic tank". In 1897, due to the good results obtained from the use of this tank, the local government of Exeter (UK) approved wastewater treatment throughout the city by this system. Cameron recognized the value of methane gas generated during the decomposition of sludge in septic tanks and some of the gas was used for lighting and heating purposes (Chawla 1986).

In the twentieth century the first progress in research and technology was made, being in 1911 when operating digesters on farms in Great Britain began.

In 1920, German engineer Karl Imhoff developed a kind of tank of dual function, reception and processing for waste water (Imhoff, 1956). Provided an upper chamber by passing the wastewater with sedimentation period and another lower chamber, in which the material falls by gravity, where anaerobic digestion occurred. This digester tank was called ’Imhoff tank’.

Around 1921, in Birmingham (England) settled the first engine to use sludge gas of 25 HP and was so successful that in 1927 they installed a 150 HP engine, other one in 1928 and two 400 HP engines in 1930, in the same town (Greeley and Velzy, 1936).

In 1939 at Kampur (India) the Indian Agricultural Research Institute developed the first biogas from manure.

During much of twentieth century, the development of anaerobic digestion technology remained exclusively linked to the stabilization of the biodegradable solid urban waste water. This led to the design of complete mixing type reactor in mesophilic range, widely used even today for the digestion of waste water sludge and animal manure. Between 1927 and 1950 he performed various experimental studies of gas production from livestock waste. In the 1950s, were developed in India simple digesters models that were suitable for rural households. These early models established clearly that biogas plants could: provide light and heat in the rural villages, eliminating the need to import fuel to burn cow dung, or to deforest the land, provide a rich fertilizer digested waste; and improve health conditions, providing airtight containers digesters which reduces diseases for manure exposed (Fry, 1973).

It is from the 40s, when a greater interest in anaerobic digestion in Europe when, following World War II, scarce energy sources (Fry, 1973). For this reason, are developed in Germany a large number of anaerobic digestion facilities in order to develop new renewable energy sources. In 1951, he built a digester that generated more than 16 million m^3 of biogas from sewage sludge, which were used for different uses such as energy production for internal consumption of the plant (3.4%), heating digester (16.7%), in the local gas supply system (28.5%) and turn it into fuel for motor vehicles (51.4%). Although the technology spread to other countries in Western Europe, this interest was waning by the increasing consumption of fossil fuels. When stopped the shortage conditions were only some digesters operating in Germany and France.

It is from the petroleum crisis of 1973 when renewed interest in this technology in European countries. It boosted research and development programs and industrial plants were built. Until the petroleum crisis occurred, the anaerobic process was considered in industrialized countries like USA, Canada and parts of Europe as a treatment to reduce high organic burdens of some waste without taking advantage of sludge as fertilizer or methane as fuel (Valles, 1980).

Between 1950 and 1970 anaerobic digestion was developed largely in China and India. In both countries the raw materials were animal excreta (800 million tons per year of cattle dung in India) and humans, domestic waste and some agricultural residues (Fry, 1973). In the 70s the construction of digesters in rural China grew enormously reaching in 1977 about 5 million digesters in operation due, apparently, to the use of cheaper materials which reduced the investment costs (Pfeffer, 1974, Smill, 1977), even some authors attribute the cipher of 7 million in 1978. In the 80, Chinese leader Deng Xiaoping continued to support the project and currently China is by far the country with largest number of digesters installed worldwide.

The maturity that over the years was acquiring this technology is reflected in the following points:

- Recognition of methanogenic microbial consortium set
- Design development of various digesters.
- Execution of digesters on farms and industries.
- Start of landfill biogas exploitation.

The application of anaerobic digestion systems for decontamination of industrial waste water was stimulated not only by the sharp rise in fossil fuel prices in the 1970s but also for the rules of pollution control increasingly stringent. For many rulers became a viable domestic energy resource with the potential to reduce the dependence on petroleum (Klass, 1998).

Furthermore, lack of suitability digestion of complete mixing type for treating industrial waste water low load and mainly soluble organic composition, led to the concept of recycling biosolids and retaining active biomass in the digester. This evolution of digester designs significantly improved using the process of anaerobic digestion such as waste water treatment. In the last decade, China established administrative systems to carry out projects on biogas (e.g. on farms run by the state), research, etc.

In the field of basic research are at the forefront the United States, China, India and several European countries with researchers who study many aspects of the complex anaerobic fermentation in acidic and methanogenic stages, in order to optimize biogas production processes. These countries, in turn, develop applied research digesters and large landfills l, equipped with automatic control systems, biogas purification and storage, and energy production, allowing them to obtain high efficiencies in them.

In recent years the initial energy objective that drove the development of anaerobic digestion, had been transformed into a target debugging, however now become again important the energy aspect of the process.

Currently, United States is driving the landfill biogas through bioreactor landfill construction.

Regarding developing countries, China still has the largest number of digesters, estimated at several million. In general, are simple technology digesters implanted in rural areas, its average capacity is 10 m^3 and supply the energy that is used for domestic and the effluent have agricultural used.

The rising price of fossil fuels has made biogas one of the most attractive applications. These, which were previously limited to waste energy recovery, have been extended with the use of co-digestion with other waste and/or energy crops.

From the perspective of developed and developing countries, anaerobic biotechnology contributes to fulfill three basic requirements: a) To improve the health by controlling pollution, b) renewable energy generation for domestic activities and c) provide stabilized materials (digestate or biol) as a bio-fertilizer for crops. Therefore, anaerobic biotechnology plays an important role in the control of contamination and to obtain valuable resources such as energy and added value products.

More recently, the growing concern about the possible consequences of climate change and the evidence of the relationship between them and the use of fossil fuels, have reinforced the interest in expanding the participation of renewable energy sources.

In developing countries, the use of commercial-scale biogas increased considerably with the possibility of obtaining Certified Emissions Reduction (CER's), so-called "carbon credits" through the Clean Development Mechanism (CDM). This is an established mechanism under the Kyoto Protocol, which aims to help developing countries to achieve sustainable development by promoting investment, environmentally friendly, by governments or companies from industrialized countries. Carbon credits - CERs are treated by the markets in Latin America as a "product", which means that its value has greater relationship with the owner's right to trade them than with the right to use them. Being a relatively new market, operators learn "on the fly", rescuing and taking note of the situation of those external factors that may influence their quotes.

4.2. Digesters types depending on the load frequency

According to the charging frequency, the digesters are classified as:

4.2.1. Batch Digester

The digester must be loaded once totally and then downloaded once it has completed the digestion process. That is, the digester is loaded and the organic matter is digested, and later its respective TRH is discharged and fed back. The biogas production rate in this type of digester is high at first, reaching a peak, but then drops sharply because the bacteria have no chance to develop.

This system is recommended when the material to be processed is produced intermittently. The advantage of this type of digester is that it serves for digestion of cellulosic materials or lignin content that cannot be treated in continuous type digesters due to possible clogging of the supply and return ducts. Moreover, it can work with substrates with high solids content, thereby reducing the need to use water to mix the biomass.

They are more used with less developed low-cost technologies.

To exploit the production a line of digesters is used so that they are loaded at different times and biogas production, in general terms, remain constant. These digesters are used in Guatemala (De la Torre, N., 2008).

4.2.2. Continuous digester

This type of digester works this way: once fed to first load, one must keep feeding regularly. The biomass must be mixed with water, this mixture must be produced outside the digester before feeding and a digester output element that collects digested sludge is required.

Once the digestion process has stabilized, the production rate is fairly constant, when the feed rate and temperature is always kept. You must check that inlet and outlet pipes are not blocked as a result of digestion.

Such digesters are mainly developed for waste water treatment, i.e. is industrially applicable. Plants are generally very large, for which commercial kits are used to feed, to provide heating and agitation, as well as for control. They are more used in advanced technologies.

4.2.3. Semi-continuous digester

These digesters are a combination of batch digester type and batch or continuous type. In this type of digester, volume entering displaces an equal amount of effluent which is evacuated through the exit. As a result, the volume of substrate that feed the digester remains constant. The load is usually done daily, but the total discharge rate in contrast to Batch is only made once or twice a year, usually coinciding with the period of planting to take advantage of the power fertilizer residues and fermented sludge digestion, part of them are reused as food for the digester. This type of digester is the most widely used worldwide in the countryside, in the case of small digesters or for home use. The most representative designs are Hindu model, Chinese model and Taiwanese model that will be seen in this chapter.

4.3. Anaerobic digestion in rural areas of developing countries.

The use of anaerobic digestion in rural areas of developing countries takes place through two types of technologies according to their degree of development:

- Basic technologies:

The intended purpose is to provide energy, health and organic fertilizers for farmers in marginal areas or producers in countries with rural areas of very low income and difficult access to conventional energy sources. Technology developed seeks to obtain digesters with minimum cost and easy maintenance, but with poor efficiency and low levels of energy production.

- Advanced technologies:

They are oriented to agriculture and agro-industrial sector upper middle income. The goal here is to provide energy and to solve serious pollution problems. The high-efficiency digesters developed for this application have higher initial cost and have systems which make its management and maintenance more complex. The impact they have in rural environment is:

- They increase environmental sustainability of agricultural and livestock production.
- They strengthen of the regional economy.
- They reduce energy expenses.
- Increased production / national supply of fertilizers for agriculture.
- Environmental Preservation reducing greenhouse gas emissions.
- They create new sources of billing, with the sale of biofertilizer and carbon credits.
- Assessment of by-products of agricultural production.

Moreover, in terms of their capacity, there is a general classification for biogas production plants: high capacity plants or industrial facilities and small capacity or sometimes also called "mini digesters". This chapter will deal with basic technologies usually with small capacity and low cost.

Advanced technologies, which are usually associated with high-capacity facilities, do not occur only in rural areas, and they will be discussed in the next chapter.

4.3.1. Technology Integration

Activities which in many cases are assumed to be routine and easy as cooking, lighting or electricity, they can become a daily challenge for many people on the planet. Systems based on the production and use of biogas from biodegradable waste can solve many of these problems and help improve the quality and standards of life of the inhabitants of many areas.

The rising costs and limited availability of renewable energy sources, combined with the difficulty of distribution in rural areas and high cost of chemical fertilizers, makes necessary further develop and adapting more efficient and cheaper technologies for the optimal use of animal waste and the production of fuel and fertilizer in agricultural systems. One of them consists in the use of digesters to degrade the waste generated in rural communities, generating biogas to satisfy certain energy demands and an improved fertilizer.

To be successful these plants should at least satisfy three limiting basic factors: the availability of water for mixing with manure that will be introduced in the digester, the amount of raw materials and the proper management of the technology by the communities where they are deployed. In fact, one of the requirements that demand the design of digesters is simplicity, both in the execution of the work and in its operation and maintenance.

The successful operation of these digesters will improve, in a short-medium term, both the quality and the standards of life of many people on the planet while long-term will contribute to develop a sector of economic activity associated with these systems. For this to be possible, many factors must integrate both environmental and sociological factors, and technical and economic. Only if it works taking into account all of them it will achieve the objectives pursued with such facilities.

4.3.2. Advantages and disadvantages of the application of basic digesters in rural

Among the advantages of the use of low-cost basic biodigestores in rural areas are:

1. It decreases the felling of forests because it is not necessary to use wood for cooking.
2. It humanizes the work of the farmers, who previously had to search for firewood in increasingly remote locations.
3. Diversity of uses (lighting, cooking, electricity generation, motor transport and others).
4. It produces biofertilizer rich in nitrogen, phosphorus and potassium, able to compete with chemical fertilizers, which are more expensive and environmentally damaging.
5. It removes organic wastes, such as animal excreta, polluting of the environment and source of disease to humans and animals.
6. Family economy improves.

As to the drawbacks and disadvantages, they may be summarized in two:

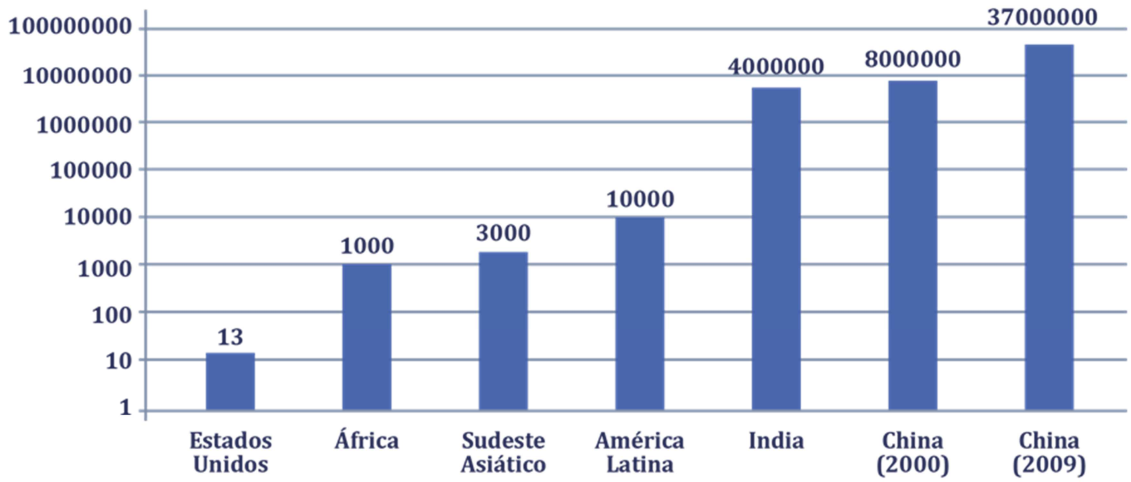
1. Need to accumulate organic debris near the biodigester.
2. Explosion risk in case of not meeting the safety standards for combustible gases.

4.4. Small-scale digesters and low cost

As already mentioned, anaerobic digestion or biodigestion is a technology that improves the traditional energetic use of biomass, in environment, social and economic terms. At the same time, it allows sustainable management of organic waste, making them a resource to generate biogas (renewable energy) and digested (natural fertilizer). The results of the digestion process produce benefits: 1. The captured methane is converted into a renewable energy source, 2. Emissions of greenhouse gases, waste water pollution and noxious odors are dramatically reduced, and 3. It creates an organic fertilizer such as microorganisms that transform organic contaminants in dissolved nutrients (Archer and Kirsop, 1990, Powers et al., 1999 and USEPA, 2004). In addition, small-scale agricultural digesters are cheap and easy to build, making them an appropriate technology to improve the environment and livelihoods of farmers (Botero and Preston, 1987, Chara et al., 1999, Xiaohua and 2005 Jingfei Lansing et al., 2008).

The family scale biodigestion has been widespread in countries like China and India since the last quarter of the century and more recently in Nepal (Biogas Support Program). The development of "home" biogas technology is more than 70 years old in India (Myles, 2001) and is widely used in regions and countries such as China, Thailand, Latin America and South Africa (Gómez et al., 2010).

Figure 9 shows small-scale digesters installed worldwide (Burns, 2010). Latin America, after China and India, is the region that more digesters with these features have.



Source: Bunrs, 2009.

Figure 9: Small-scale digesters installed worldwide

The number of biodigesters across both Asia and Africa is increasing, mostly due to national domestic biogas programmes, such the ABPP. **Table 30** also provides an overview of the cumulative production numbers of biogas units installed through the support of SNS and/or Hivos by the end of 2013.

Table 30: Number of biodigesters that have been built in Asia and Africa where Hivos and/or SVN operate up to 2013 (SNV, 2014)

	Starting date	Cumulative number of digesters built under the programmes by the end of 2013
Nepal	1992	292927
Viet Nam	2003	173905
Cambodia	2006	20288
Lao PRD	2007	2888
Indonesia	2009	11331
Pakistan	2009	334
Bangladesh	2006	31886
Burkina Faso	2010	4014
Ethiopia	2009	8161
Kenya	2009	11579
Rwanda	2007	3517
Tanzania	2009	8799
Uganda	2009	5168
Bhutan	2011	839
Cameroon	2009	198
Benin	2010	72
Senegal	2010	334

Source: SNV, 2014.

In addition, this table reveals that thousands of biogas units have been built in the participating countries. In some countries one sees the accomplishment of tens of thousands or even hundreds of thousands biogas units. For example, since 2009, Kenya has constructed 11,579 biodigesters through this initiative. The rate of installation in Asia compared to the installation rate in Africa is even higher. Vietnam constructed 173,905 units since 2003 and Nepal achieved the highest number of biodigesters: 292,979 biogas plants since 1992. The Indonesia Domestic Biogas Programme supported by Hivos achieved a milestone of 11,331 biogas plants installations by the end of 2013 (Hivos, 2013).

In LAC, in Costa Rica specifically, there are approximately 1,000 low-cost digesters that treat human and agricultural waste. Although low cost digestion systems have been extended, a shortage in the investigation of the digester performance has occurred. Research and development on technology of anaerobic digestion in the United States and Europe has focused on large-scale systems of great capital investment, which are suitable for industrial-scale holdings, but with an average cost of 1.5 million dollars, largely inaccessible to the medium and small-scale farmer (Inglis, 2006 and USEPA, 2006).

Small-scale anaerobic digesters are usually operated as semi-batch processes. A fixed amount of manure is mixed with a fixed amount of water and fed into the digester once a day. Biogas is utilized at meal times throughout the day.

Currently, three types of small scale anaerobic digesters are most often used in the developing world, including fixed-dome digesters, floating-drum digesters, and polyethylene tubular digesters. The family scale biodigestion has been widely spread in countries like China and India and the most used digesters have been, respectively, the fixed dome and floating dome. However, the complexity of their construction and the relatively high cost may be limiting for implementation in other countries. The tubular plastic biodigester, of simple and economical construction, allows further expansion of this technology.

Moreover, the local availability of the digester parts is also a very important issue to consider when choosing the design. When a piece is broken and needs replacement, members of the community should have access to it in order to continue operating the digester. Other important considerations to be taken into account in the selection of the design are: the local climate throughout the year, the amount of waste and water available daily, if required skilled labor for the construction of an anaerobic digester, and mainly the ease of the digester operation.

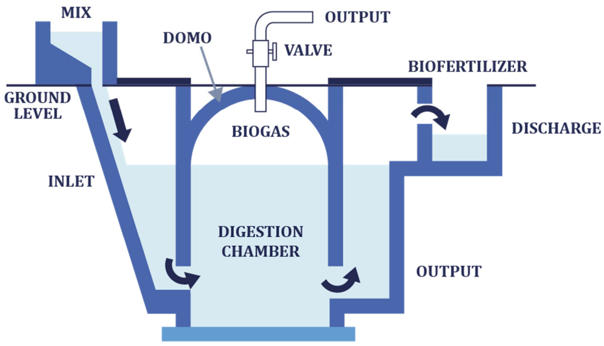
Digesters, once completed, must be airtight as well as all existing joints in order to prevent entry of oxygen. The biogas produced, which has a 60-70% methanol concentration, can be used directly as the heat source, eliminating the need for burning wood or purchase natural gas for cooking or heating. For an additional fee, you can install an electric generator to produce electricity (Rajabapaiah et al., 1993).

The global trend in the development of these low cost and small size digesters is to reduce costs and increase the life of these facilities, with the aim of reaching as many users of this technology as possible.

For these plants to be successful, at least three basic limiting factors must be satisfied: the availability of water to make the mixture with the manure that will be introduced into the digester, the amount of raw material as well as the acceptance and the correct handling of the technology by of the communities where they are implemented. In fact, one of the requisites required for the design of biodigesters is simplicity, both in the execution of the work and in its management and maintenance (Gómez et al, 2010).

4.4.1 Fixed-Dome Anaerobic Digester

The fixed-dome anaerobic digester, also known as "Chinese model" digester due to its origin, it dates back to 1936 (Buxton, D. and Reed, B., 2010). It has underground masonry compartment (which can be brick or precast), also known as fermentation chamber, and a fixed dome biogas storage (**Figure 10** and **Illustration 1**). Single piece structure reduces the complexity of maintenance. Fixed-dome digesters are operated by feeding dung mixed with water as sludge in an inlet tube. This sludge flows by gravity into the bottom of the digester. It contains a layer of biosolids and a layer of liquid above them (Rowse, 2011).



Source: Prepared by the author based on information collected.

Figure 10: Fixed-Dome Anaerobic Digester

Illustration 1: Fixed-Dome Anaerobic Digester

As the anaerobic microbial processes take place, volatile solids are consumed by microorganisms and methane and carbon dioxide are produced. Biogas is stored within the digester, creating a gradual pressure buildup. As the pressure increases beyond the equilibrium point 4, the gas pressure will push digested slurry from the bottom of the digester up the second pipe into the collection tank. The slurry mass will accumulate, although the mass is reduced from that of the slurry fed into the digester. The collection tank must be emptied when it becomes full (Ocwieja, 2010).

Fixed-dome digesters are usually constructed of masonry and must be gas-tight. They are ideally constructed inside a pit dug in the ground, which protects the structure, provides insulation, and provides open space for other uses above ground (GTZ/GIZ, 1999). The masonry is sealed for gas-tightness by a polymer paint (also used to waterproof water storage tanks) on the inside of the digester (GTZ/GIZ, 1999).

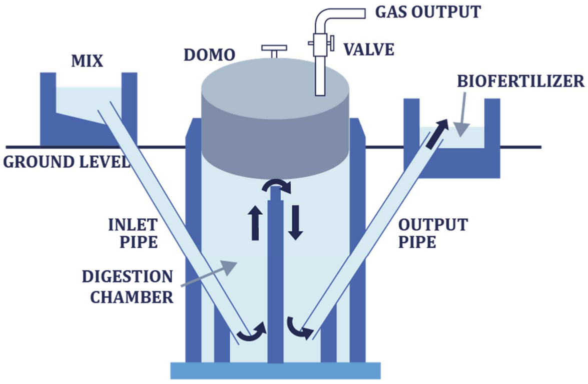
The main advantages of fixed-dome digesters are: 1. Digesters have no moving parts, 2. The costs are relatively low, and 3. The design lifespan is 20 years (GTZ/GIZ, 1999), although some authors give a 20-50 years lifespan if routine maintenance is performed.

Disadvantages of fixed-dome digesters are: 1. Special sealants are required, 2. High technical skills are required for construction, 3. Gas pressures fluctuate, which causes complication of gas use (GTZ/GIZ, 1999), 4. Despite being economical, they have a high capital cost compared to other technologies. This has prevented its widespread in Latin America and 5. Operation is not easily understood by the household, since the amount of gas present in the digester cannot be seen (Ocwieja, 2010).

4.4.2 Floating Drum Anaerobic Digester

This type of digester, also known as "Indian model" digester due to its origin was developed in 1956 (Buxton, D. and Reed, B., 2010). It distinguishes from the Chinese model because in this case a moving drum is used. When there is no biogas, the drum floats either in a water jacket that surrounds the digester or directly in suspension. When biogas is produced, the drum, which is mounted on a mobile guide frame, goes up with increasing gas pressure on it (GTZ/GIZ, 1999).

The drum can be made out of metal, concrete or plastic (Buxton & Reed, 2010; Munasingha & Wijesuriya, 2007; Lawbuary, 2006; Singh & Sooch, 2003). Also, the digester is composed of a storage tank in a cylindrical shape, which can be constructed out of stone, brick or concrete. To allow the entry of organic matter and the output of the biofertilizer, two tubes are used (plastic, cement, ceramics or other) which connect the storage tank with the charge and discharge (**Figure 11** and **Illustration 2**). It also has pipes, shut-off valves and safety to ensure the smooth operation of the digester. Floating drum digesters are operated by feeding dung mixed with water through the inlet pipe to the digester.



Source: Prepared by the author based on information collected.

Figure 11: Floating Drum Anaerobic Digester

Illustration 2: Floating Drum Anaerobic Digester

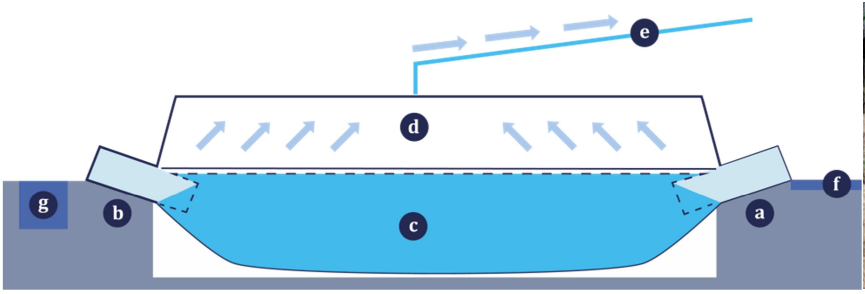
Similar to the fixed-dome digester, the slurry flows down the inlet pipe and enters the bottom of the digester. There is a layer of biosolids on the bottom and a layer of liquid effluent above that (Rowse, 2011).

One of the advantages of the Chinese model floating-drum digester is that the operator can visually see and better understand how the digester works because the dome rises and falls with higher and lower gas pressure, respectively (Ocwieja, 2010). Floating-drum digesters are easy to operate (GTZ/GIZ, 1999). Gas tightness is easier to maintain in the floating-drum design by removing rust and re-painting regularly (GTZ/GIZ, 1999).

Disadvantages of the floating-drum digester are: 1.- The steel drum is relatively expensive and requires frequent maintenance, 2.- The design life of a floating-drum digester is 5-15 years, 3.- Additionally, the drum can become stuck on the guide frame, requiring maintenance (GTZ/GIZ, 1999) and 4.- According to Ocwieja (2010), floating drums are harder to obtain, leading to increased cost.

4.4.3 Tubular Polyethylene Anaerobic Digester

Currently, new designs that have greatly lowered the initial costs of the digesters have been tested. The limited economy motivated Taiwanese engineers to investigate digesters with flexible materials (FAO, 1992), which involved a lower cost. Initially materials were used like nylon and neoprene, but the results were negative and they proved to be very expensive. Through the years the materials have been developing and today the communities that use this type of digester make it with plastics. Possible construction materials are polyethylene and PVC (geomembrane), being the last one more resistant but also more expensive (Pedraza, 2002), so they are usually made out of polyethylene. In the tubular polyethylene anaerobic digester, also known as "Taiwanese model" digester, construction and workmanship are easy and low cost because the materials are very simple. The key components of this digester are: a polyethylene thin film bag, usually two-layered, able to withstand normal working pressure of biogas and which stores the mixed residue with water, you should always leave the volume required to store biogas (**Figure 12** and **Illustration 3**).



Source: Prepared by the author based on information collected.

Figure 12: Tubular polyethylene digester **Illustration 3: Tubular digester**

Tubular digester is placed into a trench with a slope of 2-5% to facilitate gravity flow. The waste water flows through the polyethylene tube with a semi-continuous flow as the previous (C). Slurry is fed into the digester through inlet pipe (A) of the loading container (F). When the digester is in balance, an equal mass of concentrated liquid leaves the digester through the outlet pipe (B) and is collected in a digestate collection container (G). When many biosolids are accumulated in the digester, they must be emptied periodically (GTZ/EnDev, 2010). The gas is stored above the digestion sludge (D) and no additional external gas storage (GTZ/EnDev, 2010). The outlet pipe (E) leads to biogas utilization.

When the digester is in equilibrium, an equal mass of liquid concentrate exits the digester through the exit pipe. According to TZ/EnDev (2010), an equal mass of liquid effluent exits the digester as manure and water are fed into the digester. However, this does not follow because biosolids accumulate in the digester and must be emptied periodically (GTZ/EnDev, 2010). Gas is stored above the digesting sludge and there is additional external gas storage (GTZ/EnDev, 2010).

In order for the facility to start operating, other accessories are needed such as shut-off valves, safety valves, pipes and adapters. Usually, as a protection, a trench coated with concrete or other material is constructed, adequately sized to fit on the digester. A 8-m long (25 m^3) digester can treat waste from 55 pigs (50 kg) and produce up to 6 m^3 of biogas per day, with a methane content above 60% (Lansing et al., 2008). According to Lansing (Lansing, et al. 2010), the addition of small amounts of cooking fat resulted in an increase of 124% in the production of methane with no heat in plug flow reactors.

As stated, the tubular digester is the least expensive and easiest to construct, however, lifetime is only 2-10 years (GTZ/EnDev, 2010), although some authors consider necessary to mount a new facility every three years. It is also very vulnerable to breakage due to adverse weather conditions, by the actions of man and animals.

4.5. Construction and design of a tubular polyethylene digester

The tubular polyethylene model is selected for the design of low cost anaerobic digesters due to the simplicity of the technology, economic side and especially for being the most used in the LAC region.

When designing and building a digester, a number of considerations must be taken into account depending on various criteria described below (CEDECAP, 2007).

4.5.1. Dimensioning and design

A. Calculation of the amount of manure: There is no consensus on the bibliography on livestock waste production. To determine the availability of raw materials, the information provided in Table 2 or **Table 31** references may be estimated.

Table 31: Daily fresh manure production by animal type

Animal	Manure (kg/100 kg live weight)
Cow	8
Pig	4
Horse	7
Goat	4
Rabbit	3

Source: Martí, J., 2008.

Depending on the number of available animals, you can make an estimate of the daily amount of waste to digest. For example, 400 kg cow daily produce 32 kg of manure.

Moreover, the amount of available manure depends on livestock management in the area. In the case of tabulated cattle, all manure produced is exploited and in the case of tabulated cattle only at night, what would only take a 25% advantage.

B. Matter to digest: As already referred, in order to obtain biogas from animal waste, the most suitable mixture is the relationship manure: water of 1:4. This mixture is called daily load.

C. Retention time: As already seen, the degradation rate depends largely on the ambient temperature, because at higher temperatures the retention time required is less. **Table 32** shows an estimation of HRT according to room temperature.

Table 32: HRT according environment temperature

Characteristic region	Temperature (ºC)	HRT (days)
High Plateau	10	55
Valley	20	25
Tropics	30	10

Source: CEDECAP, 2007.

D. Digester dimensions: The total volume of the digester has to accommodate a gas and a liquid part. Normally there is a 75% space for the liquid phase and the remaining 25% for the gas phase.

The total volume is the sum of the gas and the liquid volume: $V_T = V_G + V_L$

And therefore the liquid volume is three quarters of the total: $V_L = V_T \times 3/4$

The gas volume is a quarter of the total: $V_G = V_T \times ¼ = V_L / 3$

The tubular polyethylene is sold in 50 m rolls, with a roll width that usually ranges from 1, 1.25, 1.50, 1.75 and 2 m. In the case of polyethylene digesters, the base formula is the volume of a cylinder, i.e.:

$$V_T = \pi \times r^2 \times L; \text{ where: } \pi = 3.1415, r = \text{radius}, L = \text{Length}$$

Knowing the total volume of the digester and the effective sections of available plastics (by roll width), it is easy to determine the required length. If the volume of the digester is $V_T = π \times r^2 \times L$, and we know all parameters except the length, clearing of the above formula is obtained: $L = V_T / (π \times r^2)$.

Thereby a table is generated in which the results of each roll length and width are placed. **Table 33** relates the roll width to the length of the digester.

Table 33: Relationship between the diameter and length

Roll width (m)	Radius (m)	Diameter (m)	Section $Π x r^2$ (m^2)	Length (m)
1	0,32	0,64	0,32	V/0,32
1,25	0,40	0,80	0,50	V/0,50
1,50	0,48	0,96	0,72	V/0,72
1,75	0,56	1,12	0,97	V/0,97
2	0,64	1,28	1,27	V/1,27

To determine digester dimensions, it is desirable that the relationship between diameter and length keeps a ratio of between 1:5 and 1:10, being most desirable that this ratio be between 1:7 and 1:8 (Marti, J., 2002; CEDECAP, 2007). For digesters with lengths greater than 10 m, it should be considered the placement of straps that help to stir the mixture and prevent crusting on the surface.

4.5.2. Building Materials

The digester that has been considered is fairly simple and inexpensive. However, its construction requires heavy manpower and skills at the time of making the wall and putting the insulation. The materials needed are shown in **Table 34.**

Table 34: Materials for construction of tubular polyethylene anaerobic digester

Material	Description
Black film UV (2x50) 300 micr.	UV Polyethylene used to make the biodigester
Translucent film (2x50) 300 micr.	UV Polyethylene used to make the greenhouse
HDPE hosepipe	Pipe for gas connection
Elbows	To splice connections
One "T"	Connection for biogas distribution
Ball key tool	Connection to control gas output
Flange	For connecting tubes
Adapters	For connecting tubes
Tube 16 cm	Connection for biogas output in the kitchen
Tools	5 m Tape Measure. Adhesive tape. Wire/cord. Pliers. Gums (3 tires /biodigester). Manual sealer. Steel scourer. Teflon. Scissors. Cloves. Die wrench½"

Source: CEDECAP, 2007.

4.5.3. Working area

Depending on where the digester is built, we should note a number of considerations:

- It is recommended that installation of the digester is made as close as possible to the place where the pickup area of animal or human excrement is located.

- The dimensions of the digester are adjusted according to the availability of space.
- Installing a solar greenhouse in areas with temperatures equal to or below 10°C can be considered.
- To maintain stability of temperature is convenient to partially bury the digester or fence it with a wall and use insulators.
- It is convenient to have into account the sun's path when placing the biodigester.

4.5.4. Construction of the structure of the digester.

Dimensions of the biodigester trench
The final design requires knowing the dimensions of the trench which will accommodate the tubular plastic. The length of the trench is determined by the length of the digester, and its depth and width will depend on the roll width used in the construction of the digester. In general terms, one can employ the dimensions shown in **Table 35**, depending on the width of the roll.

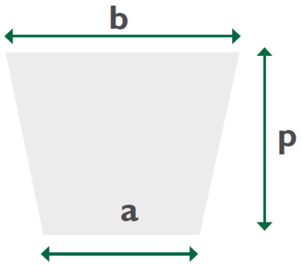


Table 35: Dimensions for the ditch

Roll width (m)	a (m)	b (m)	P (m)
1	0,3	0,5	0,6
1,25	0,4	0,6	0,7
1,50	0,5	0,7	0,8
1,75	0,6	0,8	0,9
2	0,7	0,9	1,0

Source: Martí, J., 2008.

It must be considered that, when hosting the digester in the trench, its walls will support all the pressure of the digester liquid volume. The dome biogas will be on the top and occupy 25% of the total volume.

If a trench is constructed without considering the width, it can happen that the biogas dome is too small or even too large. In case the dome occupies more than 25% of the volume, you can subtract the liquid phase volume and therefore reduce the retention time.

Construction of the trench

To build the structure that will house the digester you must follow these steps:

- Dig a hole of the same dimensions as the digester with the base with a "U" or "V" form .
- If placed in cold areas, below 10ºC, a fence around the biodigester shall be built (brick or adobe) to preserve temperature. In the case of adobe buildings and lengths greater than 7 m, it shall be considered that the structure has safety standards at certain stage.
- You should dig two trenches, one for the inlet and another for the outlet. The input trench will have a 45° angle approximately, and shall enter close to the bottom, leaving no more than 30 cm between the entry point and the bottom of the tank. The inlet pipe should be above the tank at least 40 cm. The outlet pipe should have a 30° angle.

4.5.5. Installing the digester and first load

Once the structure is ready, we will proceed to install the digester and the placement of the containers that facilitate material loading and digest unloading. The steps are the following (CEDECAP, 2007):

- Cut the polyethylene according to the established dimensions. Install the gas outlet valve.
- Install the hose and the valve in the gas outlet.
- Proceed to install the inlet and outlet pipes. The tube length is between 1 and 1.20 m long. It is necessary to cover them externally with a rubber strip about 3 or 4 cm. thick in order to protect the digester of chips produced by cutting the pipe.
- In the case of being necessary to install a greenhouse, you must prepare the structure for supporting the cover before putting the digester.
- Move the biodigester to adobe or brick structure. Before replacing it, the surface of the structure shall be covered with insulating material layers and crevices protection (raffia bags, straw, ...).
- Installed the digester, measure the pitch of each pipe, it is recommended that the tilt angle range between 30° and 45°. Once achieved the location, hold the tubes to wooden poles, passing through the center of the tube a string or wire, in order to maintain this position.
- Place the input mix vessels and the output of digestate.
- Install the connecting pipe of the digester to the gas collection vessel, and thence to the point of consumption. Is suggested to envisage a distance no greater than 20 m. The number of valves and elbows depend on the distribution of use: number of burners for cooking, lighting, etc.
- After installing the digester, you can proceed with the load. The initial charge should be made with water to a quarter of the system. Subsequently introduce appropriate manure load. The second charge was carried out on a 1/4 equivalence, one of water for 4 of manure. Will be filled until the inner mouths of inlet and outlet tubes are covered up with mud to keep out air to the digester, and under anaerobic conditions.

4.5.6. Greenhouse construction

The construction of the greenhouse structure is important to help maintain a constant high temperature inside the digester. The greenhouse structure will be stuck with plastic tubes in the walls of the fence of 40 cm high. The biodigester will be completely sealed by the front and rear with adobe walls.

4.5.7. Construction of gas line

Regarding the construction of the gas lines, in most installations a ½ inch diameter is used. The best solution for safety and lifetime is to use galvanized iron pipes, but if the cost is too high, they can be replaced by plastic. PVC pipes for water can be used, or for irrigation, but of high quality ones to prevent cracks, which must be protected from the sun. For connections quality PVC cement is used, or via threads and Teflon.º

For the design of the pipes, it must be taken into account: 1. Do not utilize used pipes and bends; 2. Place at least one safety valve, and 3. Never install tubes in horizontal, always sloping (at each low point install a water trap) to prevent condensation problems in the pipes.

At the outlet of the biogas conduction, after the first ball valve, place a "T" so that biogas can continue to flow into the kitchen, but the third out of the "T" is joined by a pipe part, which is inserted into the water-filled bottle. The pipe should be immersed in water 8-13 cm, depending on the height above sea level of the place, the distance to the kitchen, and type of cuisine. The greater the height, the lesser the pressure needed, and lesser must be the tube submerged in the water. The greater the distance, the greater the pressure for cooking needed and the deeper the tube should be submerged. To determine ideal pressure is necessary to test the biogas combustion in the kitchen until the users are satisfied.

The safety valve allows gas to escape into the air when the pressure of the digester reaches a threshold value, equivalent to the water column that submerge the tube (10 cm water column = 10 mbar = 0.98 kPa).

4.5.8. Biogas production

The manure mixture with water inside the digester, in absence of air, will produce biogas. This production is not constant and is a process that lasts more or less the retention time estimated by the work temperature. In this way one kilo of manure will produce biogas gradually along the retention time to which it is exposed.

There are different methods to estimate the production of biogas of a biodigester according to daily load of manure. The easiest way is to apply bibliographic data, such as average values in Table 11.

You can also apply the concepts of "total solids" and "volatile solids", which is more accurate if you know the data.

Daily production of biogas depends on the amount of volatile solids that is in the load of manure and slurry as volatile solids represent the portion of total solids that can be biodegraded and converted into biogas. Thus, for theoretical biogas production is necessary to know the amount of manure and slurry to be entered daily in the biodigester and from these values determine the content of total solids and volatile solids. Therefore, based on the amount of manure already determined to calculate the digester design are determined the total solids and volatile solids.

Determination of total and volatile solids: There is extensive literature where you can consult the total solids content of manure and slurry. According to the data of Table 11, corresponding to production of biogas per kg of VS, we can know how much biogas can be produced daily.

In the case of having two types of animals, we should determine the production of each type and summing them.

To determine biogas production per unit of volume of the digester, the amount obtained should be divided into the volume of liquid in the digester and the biogas m^3 per unit of volume of digester per day be determined.

In this way one can estimate the volume of biogas per day that can be obtained whenever appropriate retention times for each working temperature are met.

4.6. Factors influencing the operation and control of this type of digesters

As referred, a number of factors are important in the operation of an anaerobic digester. At this point, we will only make some considerations of some of these factors in relation to this type of digesters.

In relation to HRT, Garfi studied psychrophilic anaerobic digestion at temperatures as low as 10°C, and recommend a 70 days SRT for a polyethylene tubular anaerobic digester with no mixing. At temperatures close to 30°C, 20 to 30 days SRTs are recommended (Garfi et al., 2011). It is important to design reactors for sufficient retention times so that volatile solids destruction can take place (Vesilind, 1998).

The recommended organic loading rate for low-rate anaerobic digestion (digestion with no heat and no mixing) is 0.5- 1.6 kg VSS/(m^3.d). Sharma & Pellizzi (1991) recommended that the organic loading rate for standard–rate anaerobic digesters discussed in this work should be 1.0 – 3.5 kg VS/(m^3.d).

If the loading rate in anaerobic digestion is too high for the system conditions, it can result in the accumulation of volatile fatty acids (VFA) in the reactor and can lead to reactor souring, or failure. Therefore, it is very important that the designed organic loading rate is conservative.

Specifically, in rural areas of developing countries, there will be fluctuations in ambient temperature, fluctuations in the substrate manure feed over time, limited operator oversight, and no process control. Lastly, if the anaerobic digester fails, it will likely result in failure of the anaerobic digestion development project, and the community will lose faith in the technology. Loss of faith in a technology can be significant, and can impede other anaerobic digestion projects for the future. A Safety Factor of 10 (Rittmann & McCarty, 2001; Speece, 1996) was used in the semi-empirical kinetic model piece of the Excel spreadsheet (Subsection 3.2.6).

Moreover, with respect to mixing, in the fixed dome and floating drum anaerobic digester designs, no mixing takes place, other than the mixing that occurs as a result of gas formation in the digesting sludge layer, which then rises to the top of the digester (Tchobanoglous et al., 2003). In the tubular PFR, as with PFRs in general, "plugs" within the digester have uniform concentrations of substrate and microorganisms, and in the ideal case, no mixing occurs in a forward direction.

Recommended parameters are listed in **Table 36.**

Table 36: Suggested operation parameters for rural developing world applications

Operation Parameters	Value	Source(s)
SRT $^{min}_{lim}$ (d)	4	Tchobanoglous et al., 2003
Safety factor	10-30	Rittmann and McCarty, 2001
SRT (d)	20-70	Garfi et al., 2011
pH	6,6-7,6	Tchobanoglous et al., 2003
OLR (kg VS/m^3.d)	1,0-3,5	Sharma and Pellizzi, 1991

4.7. Programs for development. Experiences with low cost digesters

In developing countries, where energy is scarce and expensive, anaerobic digestion has focused mainly on the production of energy through biogas plants.

In recent years various digesters implementation programs have been conducted, mostly in China and India but also in other areas such as Nepal, Tanzania and the Andean Zone (Peru-Bolivia).

In the eighties ITINTEC (Industrial Technology Research Institute of Technical Standards) developed together with the CIPENC (Center for Research and Promotion of Non-Conventional Energy) the first Biogas Research Program in Peru installing a total of 51 digesters, most Chinese type, in rural areas. According to the impact evaluation study conducted by ITDG (Diversified Technical Institute Grajales-Colombia) and EWB (Engineers without borders), the failure of this project were the type of biodigester and the incorrect sizing choice according to livestock resources, but especially the lack of training and monitoring provided to beneficiaries of the facilities (Spagnoletta, 2008).

In Bolivia, through the German Technical Cooperation, implementation projects of biomethanisation technology as an energetic alternative were developed, which aimed to directly benefit approximately 1,000 families in late 2010. Under the concept of democratization of technology and through multiple training workshops, dozens of technicians, Non-governmental Development Organizations (NGDOs) and families have been trained.

Another example of transfer technology is that developed in the northern Peruvian Andes, where through a low cost pilot implementation family digesters has managed to demonstrate the adaptability of this technology in the hands of Engineers Without Borders and ITDG Practice Solutions.

With the results of these experiences the type of technology to develop has been defined, a tubular digester model adapted to the conditions in the Andean region according to the altitude, temperature, livestock resources and socio-economic factors of the various areas of implementation. It is a digester between 8 and 10 m^3 fed daily with 20 kg of fresh manure and 60 litters of water to produce 80 litters of a fertilizer (digested) daily. Given the local climate, it is been installed under cover as a greenhouse in order to keep the temperature as constant as possible. Basic facilities additionally come with a storage tank (reservoir or gasometer) between 1 and 2 m^3, a safety valve and two stoves.

INIA (National Institute of Agricultural Innovation Cajamarca - Peru) together with ITDG and its partners (ISF, UPC, Green Empowerment) have opted for the construction of a small pilot plant with 4 systems which develop research activities in order to study and parameterize the process with which to create better models adapted to different weather conditions and characterize the different types of fertilizers. The results, together with appropriate management models to the socioeconomic characteristics of the region, will allow a technological appropriation by the families of the most disadvantaged areas.

It has also been able to create a South American network technology building in which different international agents are involved, specialized in research and cooperation for development from more than 10 countries whose mission is to promote applied research in anaerobic digestion as a tool to improve the welfare of the population of Latin America and the Caribbean.

4.7.1. Experiences in SIDS. Bringing Biogas to Samoa (SIDS Action Platform).

In Samoa, an innovative project idea has turned an environmental challenge into an energy asset. Samoa has turned the invasive Merremia vine, other invasive weeds and green agricultural waste into renewable energy in the form of biogas.

Like many states on the Pacific islands, Samoa is heavily dependent on fossil fuels for power generation; approximately 69 percent of national energy production comes from diesel-fueled generators. This is an expensive solution for island countries that pay high prices to ship fuel to local shores. In addition, fossil fuel-based energy is highly polluting, and CO_2 emissions contributes to climate change that islands states such as Samoa are vulnerable to; increased extreme weather and rising sea levels. This is why Samoa is looking for sustainable energy solutions that are affordable to its population and with low environmental footprint and greenhouse gas emissions.

Samoa was currently facing the rapid spread of invasive Merrimia vine, a vine that has killed more than 60 percent of Samoa's forests. But the vine, as biomass, can potentially also be fuel for bioenergy. Samoa has developed biogas energy systems fuelled by the vine and other green waste. Such waste is currently disposed of by burning. The goal is to demonstrate the viability of biogas solutions on the island, while at the same time stopping the spread of the invasive vine.

Sala Sagato, assistant chief executive officer of the Renewable Energy Division for the Ministry of Natural Resource and Environment in Samoa has high expectations of the Merremia biogas project.

"*Being able to offer biogas solutions for households and private sector here in Samoa is a way to provide people with clean and affordable energy solutions that at the same time takes care of the problem of the invasive Merremia vine. The project will also offer alternative waste management, reduce burning of green waste and provide organic fertilizer for the agricultural sector*" (UNDP, 2014).

The biogas project has emerged from the regional project called PIGGAREP – Pacific Island Greenhouse Gas Abatement through Renewable Energy Project. The project is funded by the Global Environment Facility (GEF), with United Nations Development Programme (UNDP) as implementing agency and the Secretariat of the Pacific Regional Environment Programme (SPREP) as implementing partner. The project has covered eleven Pacific island countries and has provided feasibility studies, training, awareness and renewable energy projects across the Pacific since 2008.

The biogas project has emerged from the regional project called PIGGAREP - Reduction of greenhouse gases in the Pacific Islands through the Renewable Energy Project. The project has been financed by the Global Environment Facility (GEF), with the United Nations Development Program (UNDP) as the executing agency and the Secretariat of the Pacific Regional Environment Program (SPREP) as an associate in the execution. The project has covered eleven Pacific island countries and has provided feasibility studies, training, awareness and renewable energy projects throughout the Pacific since 2008.

In 2012, funds were provided for a demonstration project in Piu Village to demonstrate that an invasive vine (merremia) could be a resource to produce biogas that could be used in cooking and lighting for village homes. This demonstration system was installed in early 2013 by BioEnceptionz Ltd of Wellington, New Zealand. (BioEnceptionz is a social non-profit company specialized in showing the potential of bioenergy systems in the Pacific Islands.). This demonstration project successfully fulfilled its objectives and has since grown with increased investment from other government partners.

In 2013, the construction of the Resource Testing and Community Engagement Center began in order to carry out research on biodigesters. The centre provides Samoa with the capability of methodically testing and cataloguing the biogas potential of a wide range of possible feedstocks that can be used in biodigesters to produce biogas, including for commercial scale operations. These feedstocks, include ˜green waste" such as grasses, vines, foliage drop and foodwaste and, as well, crop residues (such as taro leaves), crop processing wastes, and over abundant crop products with low market value. The "community engagement" aspect of this centre is in both seeing the biodigester technologies in operation, and in the use of biogas. The biogas can be used as a free cooking fuel resource to the host site and charitable community groups. To maintain a constant supply of biogas, in addition to the biogas test cells, the centre will include a biodigester that can be ˜fed" with foodwaste from the host site as well as some local area restaurants.The tourism sector is crucial to Samoa's economy and ongoing economic development. However this is impeded by the very high cost of energy in Samoa. Supporting the showcasing of viable approaches for the tourism sector to have affordable renewable energy is of key interest to the Samoa Tourism Authority. This project is about sustainable Development, renewable energies, and improving livelihoods. The aim is to achieve a commercially viable project to attract more partners and be able to do so in the PIEDs. The strategic objective is to support sustainable development, provide growth to businesses, improve people's livelihoods and ensure that the environment is not damaged. The Biodigester project fulfills it.

The next stage in the project was extended from April 2014 to 2015 and its objective has been double. On the one hand, to provide a greenwaste biodigester in a 5000 litre plastic tank that produces biogas that can be used for some on-site purpose, for example, cooking and heating water in Women in Business (WIB) nursery. WIB is an organisation that helps sustainable farmers to export organic products and contribute to Samoa's GDP. On the other hand, that could be a step towards a a larger project, build a biodigester that stores at least 60 cubic meters of biogas. A key question has been to know how many cubic meters per day of gas can be produced from a given digester size for the raw materials that are the likely mix in this application. For this, a good knowledge has been obtained from the results of the largest digester of the Resource Testing Center. The desire is to attract partners for other SIDS in the second phase of the project.

The Ministry of Natural Resources and Environment of Samoa is very interested in the potential application of biodigester technologies. They have conducted two feasibility studies supported by the EU-funded water and sanitation programme, and the UN FAO office in Samoa. The "biogas potential" data that will come from the resource analysis programme will provide much needed information on Samoa's circumstances for a wide range of possible applications of biodigesters. Samoa Biogas Systems which was called BioEnceptionz, is an entity based in New Zealand that operates under the principles of a non-profit social enterprise. They conceive, plan with host governments and donors, and implement feasibility studies involving advanced biomass and waste-based energy systems suitable for Pacific Island and other developing countries. They provide proof of the technical and economic applicability of the technologies. They are involved in the development of financeable business models that can be used by local companies when these new systems are rolled out.

Summary of Chapter 4

Since Guoui Luo (1921), Matunga Leper (1987) and Jean-Louis Mouras (1881) built the first digesters in China, India and France, respectively, over the years the technology has evolved greatly through the advances of research and deeper understanding of the process, both microbiological and the parameters governing this fermentation, which notably led to progress in technological aspects and greatly improve their efficiency.

An initial classification of the digesters is the frequency response of the load, thus digesters can be discontinuous, semicontinuous and continuous. Being these last the most commonly been developed.

Considering the level of technological development, we can establish two groups, small-scale and low-cost digesters, which are mainly used in rural areas in developing countries, and the group consisting of digesters of advanced technologies which will be discussed in the later chapter.

The group of small-scale and low-cost digesters comprises three models of digester: fixed-dome digesters (Chinese model), floating drum digesters (Indian model) and tubular polyethylene digester (Taiwanese model). For these plants to be successful, at least three basic limiting factors must be satisfied: the availability of water to make the mixture with the manure that will be introduced into the digester, the amount of raw material as well as the acceptance and the correct handling of the technology by of the communities where they are implemented. In fact, one of the requisites required for the design of biodigesters is simplicity, both in the execution of the work and in its management and maintenance (Gómez et al, 2010). From a practical standpoint, it has provided information on the design and construction of a polyethylene tubular digester. This model has been selected for being a simple and inexpensive construction (Preston, 2002), and for being the most used in LAC.

The family scale biodigestion has been widespread in countries like China and India since the last quarter century and more recently in Nepal, Thailand, Latin America and South Africa. In recent years there have been experiences in some countries, notably China and India, but also in other areas such as Nepal, Tanzania and the Andean Zone (Peru-Bolivia), where they have carried out biodigesters implementation programs. Specifically, many programs and projects, through international cooperation organizations have been developing appropriate technological alternatives that allow access to clean and safe energy in the Andean region (Peru-Bolivia).

Regarding SIDS, in Samoa, an innovative project idea has turned an environmental challenge into an energy asset. Samoa has turned the invasive Merremia vine, other invasive weeds and green agricultural waste into renewable energy in the form of biogas.

Samoa faced the rapid spread of the invasive vine Merrimia, a vine that has killed more than 60 percent of Samoa's forests. But the vine, as biomass that it is, can also be potentially fuel for bioenergy. Samoa has developed biogas energy systems powered by the vine and other green waste that were eliminated by burning. The objective has been to demonstrate the feasibility of energy solutions on the island, through the production of biogas, and, at the same time, stop the spread of invasive vine.

In 2012, funds were provided for a demonstration project in Piu Village to demonstrate that an invasive vine (merremia) could be a resource to produce biogas that could be used in cooking and lighting for village homes. In 2013, the construction of the Resource Testing and Community Engagement Center began in order to carry out research on biodigesters. The centre provides Samoa with the capability of methodically testing and cataloguing the biogas potential of a wide range of possible feedstocks that can be used in biodigesters to produce biogas, including for commercial scale operations

The next stage of the project was extended from April 2014 to 2015 and its objective has been double. On the one hand, to provide a green waste biodigester that produces biogas that can be used for some purposes on the site itself, for example, cooking and heating water in Women in Business (WIB) nursery. WIB is an organization that helps sustainable farmers export organic products and contribute to Samoa's GDP. On the other hand, what could be a step towards a larger project, build a biodigester that stores at least 60 cubic meters of biogas. A key question has been to know how many cubic meters per day of gas can be produced from a given digester size for the raw materials that are the likely mix in this application. For this, a good knowledge has been obtained from the results of the largest digester of the Resource Testing Center. The desire is to attract partners for other SIDS in the second phase of the project.

5. Advanced Anaerobic Technologies

As discussed, according to the loading system, anaerobic digester technology is classified into batch, semi-continuous and continuous. In these latter, the loading and unloading are carried out continuously. As there are no stops, they have a much higher yield. These systems have been the most studied and new technologies have been developed.

In recent years there has been considerable progress in understanding the process, both about microbiology as of the parameters that regulate degradation, which has produced considerable advances in improving its efficiency. The main objective of these high-rate digesters is to treat biodegradable wastewaters efficiently and economically. There are currently a large number of technologies adapted to the treatment of waste by anaerobic digestion. The selection of one or another depends mainly on the characteristics of waste to try.

In this chapter, the main available advanced anaerobic technologies, known as *High-Rate Digesters*, are shown. These digesters are classified according to how the microorganisms are inside the digester. Designs and features are shown as well as their uses in function of the waste.

5.1. Interaction between substrate, nutrients and microorganisms

Because of the complexity of many wastewaters due to its chemical composition and the presence of various organisms in the most of cases, it is convenient for studying the treatment to consider several fundamental aspects among which can highlight the microbial interactions. The primary objective of the wastewater treatment plant is to remove organic matter and that is achieved by facilitating the development, in natural conditions, of microbial populations and not of especially a microorganism.

Although the possibility of a selected sowing, in certain cases of treatment it must be considered that there are almost always heterogeneous microbial populations. These are usually a very complex mixture of different genera and species of bacteria. The concentration of the biological components of these populations is not constant, since there are fluctuations over time that can be very drastic. Although biological treatment processes can tolerate certain variations, there are limits which produce failures in the process when are exceeded. Moreover, regarding the relationship between substrates, the codigestion of organic waste is been developing largely, which allows the treatment of mixed wastes in order to optimize the energy production, as well as facilitating management of organic waste in the application area. The main advantage of the codigestion is to exploit the synergy of the mixtures and offset the deficiencies of each substrate separately.

The anaerobic digesters technology varies greatly in relation to the complexity and design. It has shown that a single design is not suitable for different effluents. The maximum organic loading rate of an anaerobic process is limited by the retention time and the activity of the microorganisms involved in the biochemical degradation of organic matter. Since methane forming bacteria have a low growth rate, the retention of the microorganisms is the key to the operation of advanced anaerobic digesters, which permit operate with low hydraulic retention time (HRT) and high solids retention time (SRT). The techniques currently used are based on how are the microorganisms inside the digester. There are two groups, suspended-growth systems and attached-growth systems. Each of these groups comprises, in turn, different types of digesters. Moreover, since the anaerobic digestion process takes place in several stages at which different microorganisms act at different speeds, it has also emerged the two-phase technology in order to facilitate each step separately.

Figure 13 shows the main existing technologies.

- Depending on how biomass (microorganisms) grows
  - Suspended-growth
    - CSTR (Continuously Stirred Tank Reactor)
    - Plug Flow
    - Anaerobic Contact
    - UASB (Upflow Anaerobic Sludge Blanket)
  - Attached-growth
    - Anaerobic Filter
    - Fixed Film
    - Expanded Bed
    - Fluidized Bed
  - Mixed Technologies
    - EGSB
    - IC

If phase separation is performed in the process: Two-Phase (two digesters)

Source: Prepared by the author based on information collected.

Figure 13: Classification of anaerobic digesters technologies

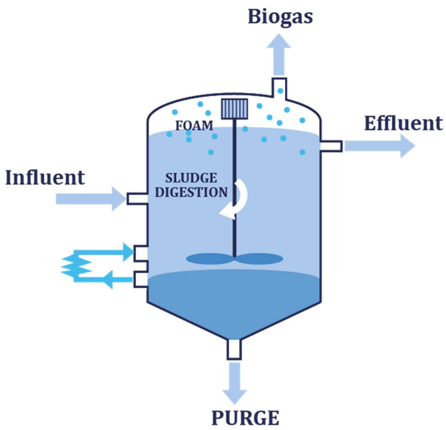
Some authors classify these technologies as: First Generation of High-Rate Digesters (CSTR, Plug Flow, Anaerobic Contact), Second-Generation of High-Rate (UASB, Anaerobic Filter, Fixed Film, Expanded Bed and Fluidized Bed) and Third Generation of High-Rate (hybrids of the second generation of high-rate anaerobic digesters - some with added features) (Abbasi et Tauseef, 2012).

5.2. Suspended-growth Digesters

Suspended-growth biomass digesters have been the first developed. In these digesters, microorganisms (microbial biomass) are suspended in the digester, as "floating"; they are not fixed to any support. In turn, this group consists of different types of digesters that are classified, from lowest to highest degree of technical complexity, in: CSTR, Plug Flow, Anaerobic Contact and UASB. The following describes each of them.

5.2.1. Continuously Stirred Tank Reactor (CSTR) or Complete Mix Digester

Completely mixed digesters, or also called CSTR (continuously stirred up tank reactor), are technically simple. These digesters are characterized by having a system for mixing the content of the digester either continuously or periodically (**Figure 14**). Mixing can be mechanical, hydraulic or pneumatic, in this last case is produced by compression and bubbling biogas. Agitation by biogas is preferred in large digesters. The treatment efficiency of a CSTR is further enhanced by heating the digester content with a proper temperature control system (Abbasi et al., 2012). Usually have heating to maintain the temperature of the sludge digestion in the mesophilic range (35-37°C). The CSTRs are operated in semi-continuously or continuously; that is, the wastewater is fed either periodically (semi-continuously) or continuously to the digester. In some cases, depending on the waste to be treated, the digester is purged periodically. By insulating the digester and mixing the contents, it is possible to install digesters of very large capacities, for example, up to 5,000 m^3 (Walfer, 2008).



Source: Prepared by the author based on information collected.

Figure 14: Continuously Stirred Tank Reactor

There is not retention of biomass or sludge recirculation, which implies that their solids retention time (TRS), or time they stay solids within the digester, are equal to their hydraulic residence time (HRT), and therefore, these have to be high (15-30 days). According Rittmann and McCarty (2001), the minimum HRT for anaerobic digester completely mixed at 35 ° C is 10 days. The starting time is between 30 and 90 days.

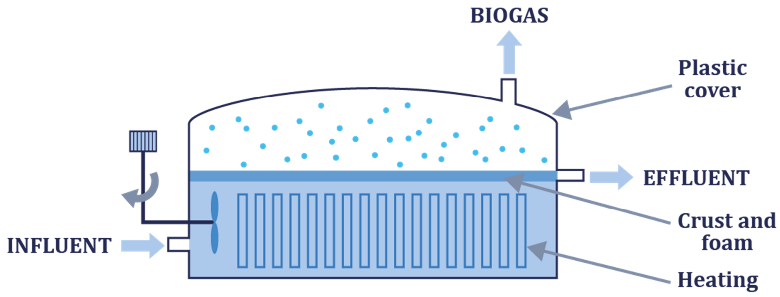
The active biomass concentrations (anaerobic) that can be achieved are limited, which means that the volumetric loads and the gas production in these digesters are low. In the process are achieved volumetric loads of 1-6 kg DQO/m^3.d. In terms of solid concentration, this ranges from 2 to 5 g VSS/l in the interior and 25-100 SS g/l in the effluent. They are mainly used for waste with high concentrations of suspended solids (2-8%) as for example, livestock waste and sewage sludge.

5.2.2. Plug Flow Digester

Plug flow digesters are made up by channels dug in the ground and usually coated with plastic, which serves both as deposit of biogas and as thermal insulation (**Figure 15**).

Technically they are similar to the complete mixture digesters and also its operating parameters are similar to these. Digesters are simple and do not have retention suspended biomass or sludge recirculation, which implies that HRT are high (20-30 days) and equal to SRT.

In these digesters exists a horizontal flow of substances into the digester by lateral mechanical agitation or injection, due to the entrance of the influent, either pulsed or continuous. They are heated, indoor coil to maintain the biomass at 35-37 °C. One typical problem of these digesters is the formation of foams and crusts which hinder detachment of the biogas and the degradation of the solids. This type of digester is used for the treatment of livestock waste, namely waste that already containing an inoculum of anaerobic microorganisms (Carreras, 2010).



Source: Prepared by the author based on information collected.

Figure 15: Plug flow digester

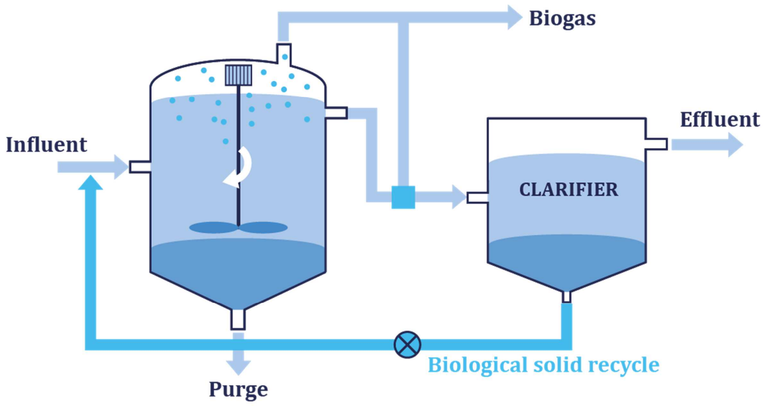
5.2.3. Anaerobic Contact Digester

In CSTRs (as in the low-rate digesters described in Chapter 5) the microbial population gets washed away from the reactor along with the effluent. It was felt that if the microbial wash out can be prevented, in other words the retention time of the solid (SRT) is enhanced even as the hydraulic retention time (HRT) is lowered, it will lead to the presence of greater concentration of micro-organisms in the reactor, thereby making the digestion much more efficient.

To achieve this, microbial population from the effluent stream is separated and is recycled back into the digester (**Figure 16**) and is mixed thoroughly with the feed, thus increasing the biomass concentration (solids) in the digester and reducing therefore the HRT. Accordingly, as SRT is greater than HRT, increases the efficiency of the process. The digester's performance depends mainly on the efficiency with which the micro-organisms and SS settle. Moreover, periodically, depending on the characteristics of the waste, it may be necessary to purge the digester to prevent accumulation of non-biodegradable solids.

The hydraulic retention time of these digesters ranges from 2 to 6 days. The biomass concentration in the digester ranges from 4-6 g/L with maximum concentration as high as 25-30 g/L depending on settle-ability of sludge. The loading rate ranges from 0.5-10 kg COD/m^3.day (Abbasi et al., 2012). The required SRT could be maintained by controlling the recycle rate similar to activated sludge process. The starting time is between 20 and 60 days and regarding the solids concentration is between 5 and 10 g VSS/L inside and between 0.5 and 20 g SS/L in the effluent (Carreras, 2010).

The process is suitable for dairy wastes, sugar-beet wastes, etc. Difficulty is encountered in obtaining good settling (Steffen 1961; van den Berg and Lentz 1979).



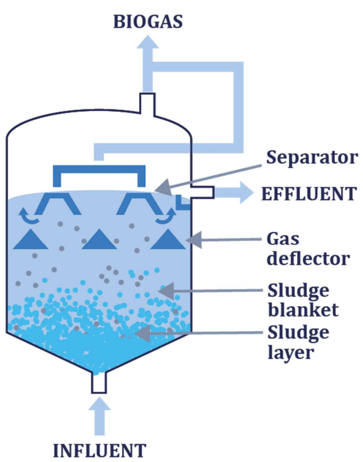
Source: Prepared by the author based on information collected.

Figure 16: Anaerobic contact digester.

5.2.4. Upflow Anaerobic Sludge Blanket (UASB) Digester

Subsequent developments in the anaerobic digester design have concentrated on the retention of the active microflora within the digester, independent of the hydraulic flow, and without the use of recycling procedures (Colleran et al. 1983). These "retained biomass" reactors include the UASB digester, anaerobic filter (AF), fixed film (FF), fluidized bed (FB) and expanded bed (EB) reactors. The AF, FF, FB and EB digesters rely on the propensity of bacteria, especially the methanogens, to attach themselves to the surface of inert support materials which ensure their retention within the reactor (Evans et al. 2009) and will be in the next section. The UASB design depends on the aggregation of the active flora into dense granules which are retained in the digester for extremely long periods by the operation of an efficient gas–liquid separator-device (Lettinga et al. 1980).

The main problem associated with AFs, which is the plugging of the filters by the suspended bacterial growth, was sought to be overcome in the development of UASB (*Upflow Anaerobic Sludge Blanket)*. The discoverer of UASB, Gaetze Lettinga, replaced the solid packing media of the AF by a simple gas collection device (**Figure 17**) to avoid the kind of plugging of the packing by the suspended growth of bacteria, which occurs in AFs (Lettinga et al. 1983). In UASB digesters, the active microbial biomass forms dense granules, which are highly settle-able (Abbasi and Abbasi 2010). As a result, very high concentration of active biomass is achievable per unit of volume of the digester.



Source: Prepared by the author based on information collected.

Figure 17: UASB digester.

UASBs are operable at high COD loading rates and provide adequate treatment at lesser HRTs than is possible with the AFs. Important components of UASB are: influent flow distributor, sludge blanket, solid-liquid-gas separator and effluent collector. The feed enters through the bottom of the reactor and flows upward. After passing through the active granular sludge the treated wastewater passes through a gas–liquid–solid separation device. This device separates solids (granules) from the liquid effluent and also separates gas bubbles from the effluent. Only the liquid effluent flows out of the reactor while the solid sludge settles back in the reactor and the gas is collected in the gas collector.

The key to UASBs performance is the quality of granules of its sludge (Hulshoff Pol et al. 2004; Aiyuk et al. 2006; Durai and Rajasimman 2011). While certain wastes result in a granular sludge quite readily (sugar-processing waste and wastes containing mainly volatile acids), other wastes develop this granular sludge very slowly and some not at all. Hence this constitutes the major challenge in the success of UASB technology. Inoculation with a large amount of granular sludge from a well-functioning UASB often helps. The sludge retains its characteristics most of the time with a given type of waste, but not always when changing from one waste to another (O'Flaherty et al. 2006; Ward et al. 2008).

Formation mechanisms of high density granules that are in UASB digesters may be biological or physico-chemical. In the first case granulated bacteria are selected and in the second precipitating compounds are used (sulphides, carbonates). In the lower zone is developed concentrated sludge layer (4-10%) with good settle-ability characteristics. On this, other more dispersed bacterial growth layer (sludge blanket) is developed in which the solids have lower settling rates. The sludge concentration in this area is 1.5 to 3 %. The stirring system is self-mixing, by the upward movement of gas bubbles and the flow of influent through the digester. The influent climb rate is 0.05 to 3 m/h.

UASB's are essentially a suspended growth system in which proper hydraulic and organic loading rate is maintained in order to facilitate the dense biomass aggregation known as granulation. The size of granules is about 1-3 mm diameter. Since granules are bigger in size and heavier, they will settle down and retain within the reactor. The concentration of biomass in the reactor may become as high as 50 g/L. Thus, a very high SRT can be achieved even at very low HRT of 4 hours.

The hydraulic retention time for these digesters is usually 1 to 2 days. Loading volumetric can get higher than the contact process (about 10 to 25 kg COD/m^{3}d). Startup time is between 30 and 60 days and solid concentration 20 to 40 g VSS/L within the digester and from 0 to 5 g SS/L in the effluent (Carreras, 2010).

They are used for the treatment of different agroindustrial wastewater such as: alcohol, yeast factory, breweries, coffee makers, feculeras, canneries, sugar processing, canneries, distilleries, dairy, paper, etc.

5.3. Attached-growth Digesters

As referred above, there are different digesters that rely on the propensity of bacteria, especially the methanogens, to attach themselves to the surface of inert supports which ensure their retention within the reactor (Evans et al. 2009). Therefore, these digesters are characterized by having within a blanket of inert material which serves as support for microorganisms that are forming a layer of adhered biomass, a part of the microorganisms are retained in the interstices of the blanket. The influent flow through these interstices generates mixing and contact between influent and the biomass, in this manner occurs the wastewater decontamination.

The requirements which must have the support are:

- Structurally robust: to support its own weight plus the weight of the solids.
- Biologically and chemically inert: to avoid reactions between bed and microorganisms.
- High surface area: to provide greater adherence of biological solids allowing accumulation of large amounts of biomass, to improve contact between the influent and biological solids and, therefore, increasing the SRT.
- High porosity: thus, reducing the possibility of clogging.
- Form not flattened or smooth: to ensure high porosity and to act as physical barrier preventing the solids outlet with the effluent.
- Low cost: because from the economic point of view it provides more viability to the process.

Depending on whether the holder is fixed or not inside digester, these digesters can be classified into: fixed or moving surfaces. **Illustration 4** shows different types of fixed supports used.

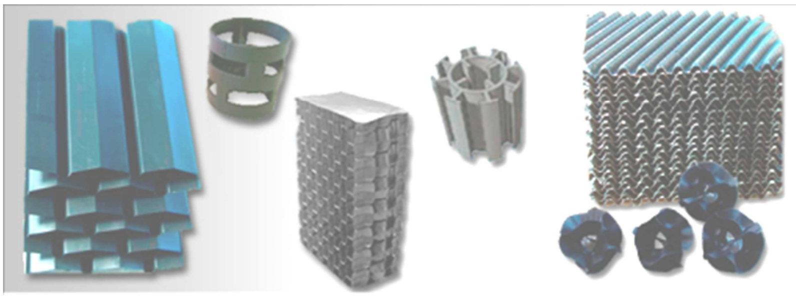


Illustration 4: Some fixed supports used.

5.3.1. Biomass attached to fixed surfaces

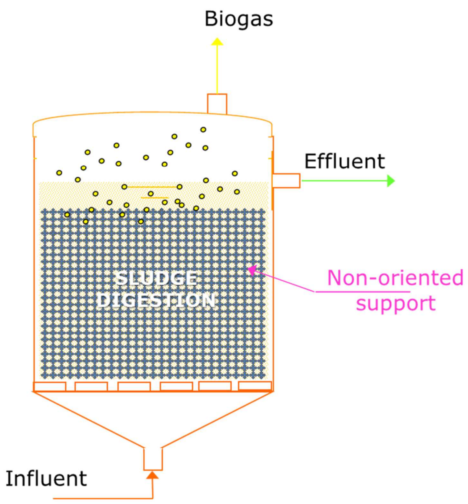
The materials used as support are varied. The most commonly used is PVC (polyvinyl chloride) but sometimes ceramics is also used, polyethylene spheres, granite, etc. They must have high porosity and specific surface area between 100 and 200 m^2/m^3. Once wastewater is introduced into the digester, an active microbial flora gradually develops and becomes attached as a biofilm to the surface of the support material. Although they do not get very high loads (5-15 kg $DQO/m^3.d$) they are very stable digesters. Hydraulic residence times are similar to UASB technology, ranging from 0.5 to 3 days. The starting time is 20 to 70 days and the concentration of solids is 10 to 20 g VSS / l within the digester and SS 0 to 10 g/l in the effluent. In turn, they can be differentiated into two types: Anaerobic Filters and Downflow Fixed Film.

Anaerobic Filter Digester

These digesters consist of a vertical column packed in random fashion, with an inert support material. The particle size should be uniform, with diameters ranging from 4 to 7 cm. **Illustration 5** shows a fixed support type used in Spanish digesters.

Illustration 5: Fixed support type.

The distribution header for feeding introduction to the matrix-bed is located at the bottom of the column, thereby creating an upward flow through the submerged support material (**Figure 18**).



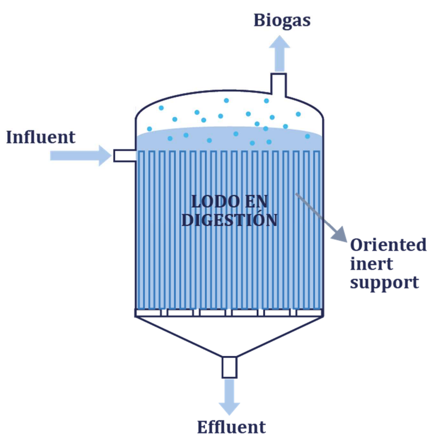
Source: Prepared by the author based on information collected.

Figure 18: Anaerobic filter digester.

The process is particularly suitable for dilute soluble wastes, or wastes with easily degradable suspended materials. The main limitation of this process is the accumulation of solids in the packing material, which may plug the reactor (Young, J.C., and Dahab, M.F., 1983).

Fixed Film Digester

This digester was developed to avoid the problems faced with the AF due to the accumulation of solids in the packing material and consequent plugging. The digester contains solid packing similar to AFs but, in this case, the inert support is forming blocks and placed in an oriented position, not random, within the digester (**Figure 19**). They are operated in the downflow mode the waste enters from the top and flows downwards.



Source: Prepared by the author based on information collected.

Figure 19: Fixed Film Digester

The formation and stability of an active biomass film on the surface of the support material of the reactor is important (Murray, W.D. and Van Den Berg, L., 1981). The FF digesters are capable of treating a wide variety of wastes from reasonably diluted to concentrated ones (Kennedy, K.J and Vander Berg, I., 1982; Sharma, K., et al., 2009).

5.3.2. Biomass attached to moving surfaces

These digesters contain a blanket of inert material of small size (0.3 to 3 mm) which remains expanded because of the upward velocity of the influent (Van Haandel, A. et al. 2006). The inert material can be made out of various materials, such as sand or PVC, and must have a very high specific surface area between 1,000 and 4,000 m^2/m^3. The bacteria colonize these small particles and form a bed through which the liquid flows to debug. **Illustration 6** shows a type of mobile support used in Spanish digesters. Sepiolite is one of the most commonly used materials. There is a sedimenter in the top of the digester to avoid the exit of sludge particles with the effluent.

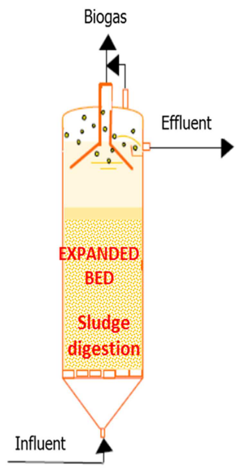
Illustration 6: Mobile support type

This technology can withstand high loads (10-40 kg DQO/m^3.d) and employ hydraulic residence times of 5 to 20 hours. These digesters have a starting time of 30 to 70 days, and a solids concentration in the effluent from 0 to 5 g SS / L. The bed expansion improves contact between influent and bacteria and the clogging problems are prevented. The unexpanded fill occupies about 10% of the volume of the digester. As for the design, these digesters are longer than previous ones to get better expansion, thus being the diameter / height ratio smaller.

Depending on the degree of expansion that the particles have inside the digester, under the upflow velocity applied to the influent, there are two types of digesters: Expanded bed and Fluidized bed.

Expanded Bed Digester

The small inert material is expanded by the upflow velocity of influent wastewater. In the expanded bed digester a sufficient upflow velocity is maintained to expand the bed by 15-30% (**Figure 20**). This digester has less clogging problem and better substrate diffusion within the biofilm. These digesters have an upflow velocity of the influent from 2 to 10 m / h and the solids concentration in the digester is 10 to 30 g VSS / L (Carreras, 2010).

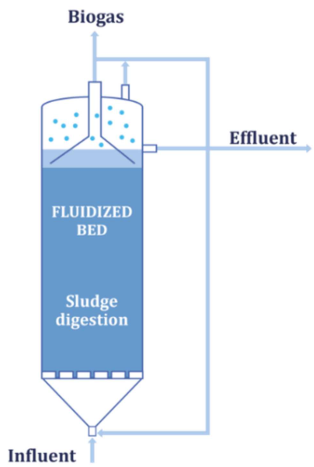


Source: Prepared by the author based on information collected.

Figure 20: Expanded bed digester

Fluidized Bed Digester

In this digester the bed is expanded by the upflow velocity of influent wastewater and by recirculate effluent. The bed expansion is higher than 30%, being able to be as high as 100% and even more. The upflow velocity of influent is of 6-20 m/h (Carreras, 2010). The concentration of solids into the digester ranges from 10 to 40 g VSS / l. **Figure 21** shows a scheme of this digester type.



Source: Prepared by the author based on information collected.

Figure 21: Fluidized bed digester

5.4. Mixed technologies

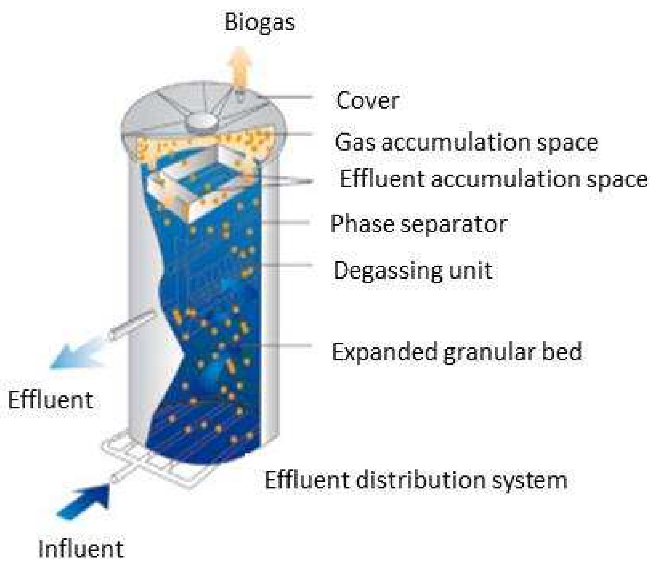
The difficulties for the control of the fluidized bed reactors as well as their energy requirements have led to the development of the concept of bed reactors of expanded granular sludge or EGSB (expanded granular sludge bed) and internal circulation (IC), in which of the inert support for the biofilm. That is, new generations of the UASB have emerged. There are authors who consider them to be third generation.

The distinctive feature is an increase in the flow velocity of the wastewater passing through the mud bed. The increase of the flow allows the partial expansion (fluidification) of the granular mud bed, improving the contact of the mud with the wastewater, as well as the improvement of the segregation of the small inactive particles in suspension from the mud bed.

The increase of the flow velocity is carried out through the use of high reactors or through the incorporation of the effluent recycling (or both).

5.4.1. EGSB Digester

The phase separation system is somewhat more sophisticated than in the UASB. The EGSB reactor (**Figure 22** is an example of commercial EGSB digester) has an organic loading rate (OLR) of up to 20 kg COD / m^3.d and the recirculation allows to work without problems with a wide range of concentrations. (Tshilumba, 2004).



Fonte: Pountal, 2015.

Figure 22: EGSB digester.

They take maximum advantage of the high sedimentation of the anaerobic granules and operate with ascending speeds of more than 8 m / h (up to 30 m / h), by means of an increase in the height / diameter ratio with respect to the traditional UASBs (height between 12 and 20 m) and an external recirculation.

The elimination of the resistance to the transfer of mass towards the biofilm produced by the turbulence allows to work in psychrophilic conditions with good success, as well as with effluents of low concentrations of organic matter (less than 1g COD / L). Its use has also been indicated for effluents that tend to generate foam problems in UASB systems.

The EGSB design is suitable for low-load soluble wastewater (less than 1 to 2 g soluble COD / l) or for wastewater containing poorly biodegradable or inert suspended particles, which should not accumulate in the mud bed.

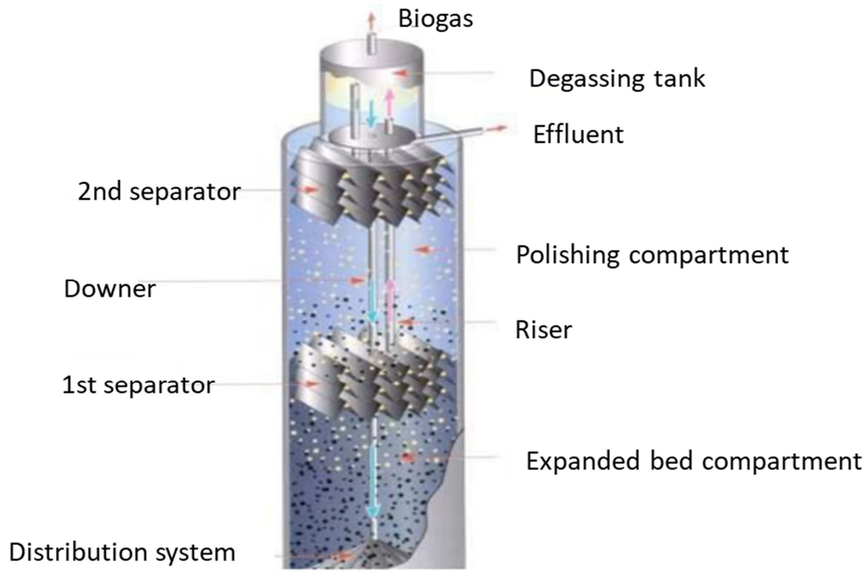
5.4.2. IC Digester

The Internal Circulation or IC digester (**Figure 23**) has an OLR of up to 35 kg COD / m^3.d, greater than EGSB digesters (Tshilumba, 2004). This high rate of organic load is due, mainly, to its internal recirculation that allows a better contact between the biomass and the influent of the residual water, which results in a greater activity of the biomass.

In addition, the IC digester has 2 separation modules, one of them at half height and the other at the upper end, that separate 3 phases, gas, liquid and biomass. The gas-liquid mixture collected in the middle zone is transported to the top where it is degassed. Then the liquid returns to the lower end where it mixes with the incoming stream. This improves the retention of the biomass and, consequently, allows a greater activity of the biomass and a better final quality of the effluent.

This type of digester has been applied in the following industries: Pulp and paper industry in the brewing and beverages industry, distillation and fermentation industry, chemical and petrochemical industries

More than 161 IC reactors had been built around the world in the last 10 years prior to 2004, making the IC reactor one of the most demanded anaerobic technologies in the world (Tshilumba, 2004).



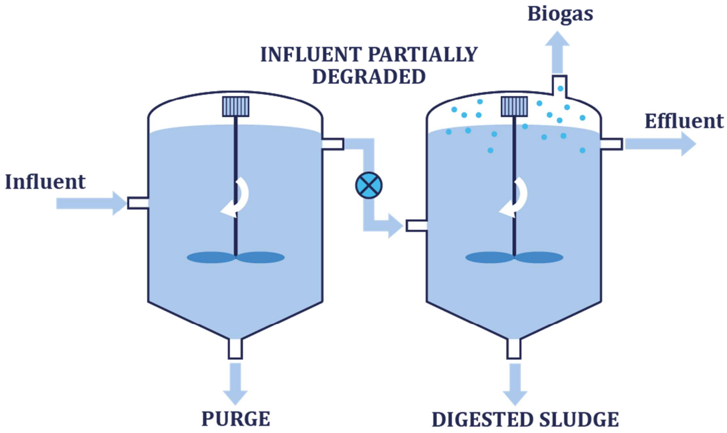
Fonte: Pountal, 2015.

Figure 23: IC digester

5.5. Two-Phase Digester

The anaerobic digestion process takes place in several stages. In each one, different kinds of microorganisms are involved with different metabolic characteristics. The latest advanced anaerobic digestion technologies seek to separate the phases and optimize them separately.

This technology consists of two digesters. In each one a part of the fermentation process is performed (**Figure 24**). This separation of phases is very interesting when the bacteria optimal conditions involved in the process are not the same. In this way both can be separately encouraged (Abbasi and Abbasi, 2010).



Source: Prepared by the author based on information collected.

Figure 24: Two-phase anaerobic digester

Experiments have been carried separating the hydrolysis and acidogenic phases of methanogenic phase. Also, in some cases, performing hydrolysis phase in the first digester and acidogenic and methanogenic phases in the second one. Variants of these two-phase systems have the disadvantage of greater complication of the plant and possible adverse situations avoiding interrelationships between microorganisms of acidogenic and methanogenic phases.

Among the advantages of this system are included:

- The first digester serves as damper when some load excess arrives in the influent, providing high safety and stability to the system. This digester also removes dissolved oxygen from the influent, so that efficiency in the second digester is high.
- Allows a biogas richer in methane, which affects the economic balance.
- Allows greater flexibility in load variations, pH and temperature, while offering greater ease in acting, monitoring and control.

This technology has been developed due to the good yields that it is achieving.

5.6. Comparison between different technologies

Table 37 shows each technology characteristic parameters.

Table 37: Parameters characteristic of anaerobic digestion technologies

Parameter	CSTR	Anaerobic Contact	UASB	Anaerobic Filter	Expanded Bed	Fluidized Bed
HRT (d)	15-30	2-6	1-3	1-4	0,3-1	0,3-1
Loading rate (kgDQO/m^{3}d)	1-6	2-7	10-30	5-15	10-40	10-40
Effluents SS (g SS/l)	25-100	0,5-20	0-5	0-10	0-5	0-5
Upflow velocity (m/h)	-	-	0.05-3	0.01-0.1	2-10	6-10
Sludge recirculation ratio	-	0.5-2	-	-	2-100	5-500

Also, the behavior and response of each of the technologies in the development process or unexpected events that may occur are shown in **Table 38**.

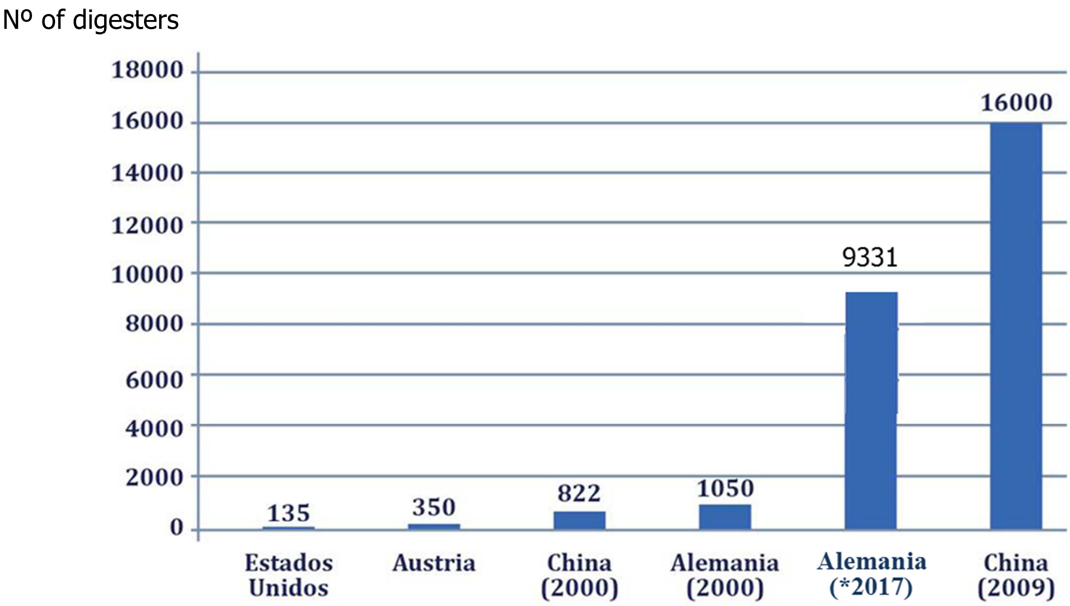
Table 38: Behavior of anaerobic digestion technologies

Parameter	CSTR	Anaerobic Contact	UASB	Anaerobic Filter	Fluidized Bed
Startup	-	++++	+	+++	++
Operation	+	+	++	++++	++
Controllability	-	++++	++	++	++
Shock resistance:					
Temperature	-	++	++++	++++	++++
Toxics	-	++	+++	++++	++++
Organic loading	-	+++	++++	++++	++++
Suspended solids	+++	++	+	-	+
Sludge processing	++++	+++	-	-	-

- = bad; += acceptable; ++= good; +++= very good; ++++ = excellent

5.7. Evolution of industrial digesters (large size)

Both China and Germany have experienced spectacular growth in larger scale anaerobic digestion plants than previously seen, as shown in **Figure 25**.



Source: Burns, 2009, FvB, 2018.

Figure 25: Countries with the highest number of digesters.

Germany is the European country that has most supported biogas. The official data provided by the Fachverband Biogas (FvB), the original name of the German Biogas Association, confirm the considerable increase in the number of biogas plants, mainly on farms, over the last few years.

In this country they improved the process by co-digestion of cattle droppings with important quantities of corn silage, thus improving the C/N ratio, since the slurry is low due to its high nitrogen content. This has greatly influenced the planting decisions of German farmers. According to surveys on the sowing carried out during the spring, in 2010 the area destined for this purpose increased by 12%, amounting to 1.86 million hectares.

The FvB pointed out that in 2011 more than 1,310 new plants came into operation, equivalent to 650 MW. The German association also notes that in 2009 the average production of the plants fell, probably because the agricultural sector used significant amounts of animal manure in the digesters. The explanation is that the German farmers benefited from the collection of an additional bonus, which amounted to about 4 cents/kWh, with the use of this type of substrate. This bonus was introduced in the German Renewable Energy Act to encourage the use of waste and waste products.

Figure 26 shows the evolution of biogas plants in Germany. At the end of this year, 2017, they estimate that a total of 9346 installations could be counted and reach 4,497 MW of installed capacity.

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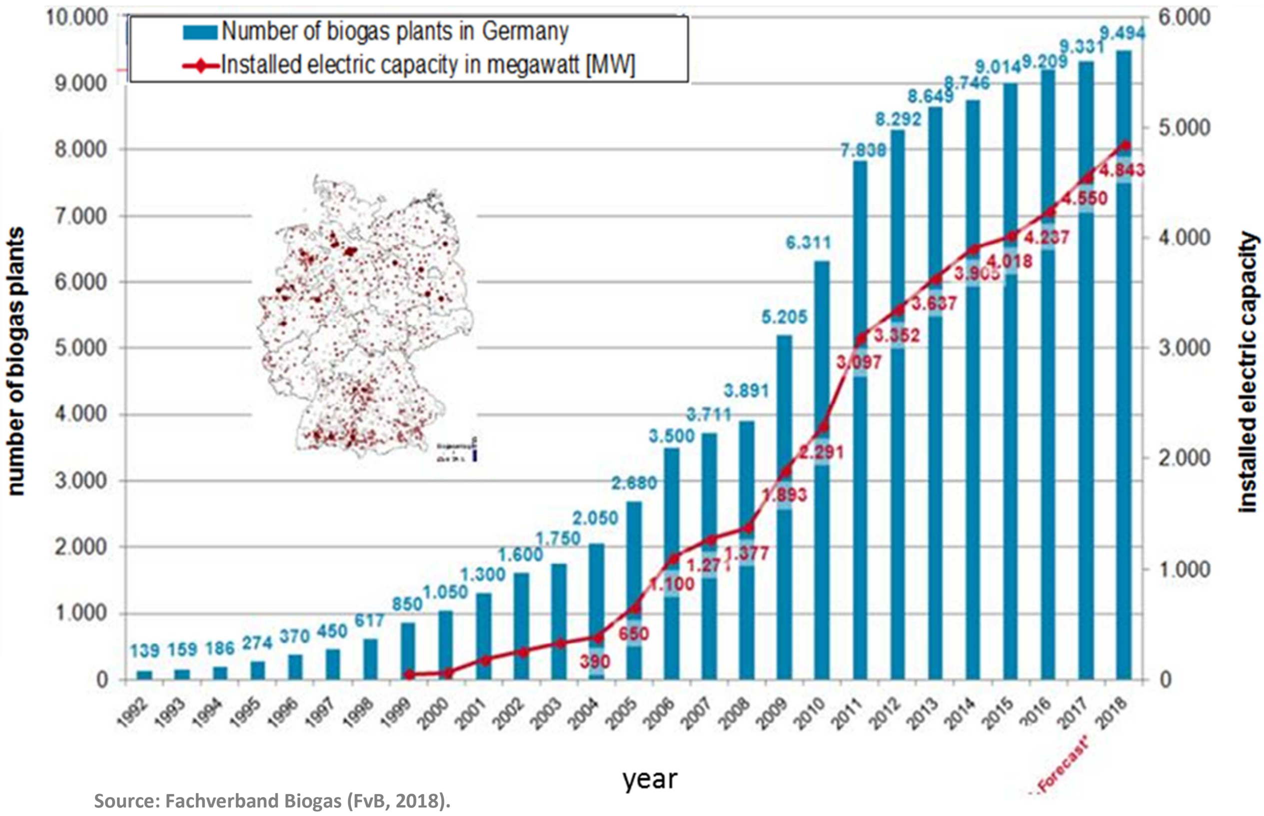


Source: Fachverband Biogas (FvB, 2018).

Figure 26: Evolution of biogas plants in Germany

5.8. Practical experience in a SIDS of the Caribbean Region: Anaerobic Digestion Brugal Plant in Dominican Republic

Below is information on the anaerobic digestion plant, located in a Caribbean SIDS, specifically in the Dominican Republic, which treats the vinasse of the Ron Brugal distillery, producing at the same time a significant amount of biogas that is used in the own plant.

5.8.1. Introduction

The consortium Brugal in the Dominican Republic is the largest producer of alcohol and rum on the island. The distillery is located in San Pedro de Macoris, 70 kilometers east from the city of Santo Domingo and Rum Brugal Factory is located in Puerto Plata at 215 km north from the capital city.

The distillery capacity is 55,000 L / d with two set of columns, burner-concentrator and rectifier, respectively. The two burner-concentrator columns work in vacuum. Among the two rectifier columns, one has reboiler and the other one not.

The production of vinasse, that is 12 to 13 times the alcohol production, goes to a treatment plant of anaerobic digestion with anaerobic filter digesters, "Down-Flow". The biogas is burned into a boiler installed to provide heat to the process.

5.8.2. Process

In the sugar plantations along the island the juice that will be transformed into molasses is extracted. Then, it is taken to the Brugal distilleries where it is stored in huge tanks and diluted with water. During the fermentation process, the sugar turns into alcohol and the resultant product is available for distillation.

When fermented must is distilled from molasses into alcohol, you get a dark liquid residue called vinasse. This vinasse contains 90% water and 10% solids. Among these solids, 95% are soluble solids and 5% are in suspension. It is a highly polluting wastewater and must be properly treated because it can constitute an important environmental problem because, in addition, his generation is high, as it has been said, 12 to 13 times the amount of alcohol produced. If a company produces 55,000 L of alcohol / day, it will produce 660,000 to 715,000 L of vinasse per day.

The average composition of vinasse generated in the Brugal rum distillery in San Pedro de Macoris is shown in **Table 39**. A variation on the composition will depend on the characteristics of the different molasses which are used in the fermentation and in the fermentation process itself.

Table 39: Average composition of the vinasse

Parameter	Value	Unit
BOD	36.000-42.000	mg/L
COD	80.000-105.000	mg/L
TSS	4.000-10.000	mg/L
pH	4,0-5,0	-
Alkalinity ($CaCO_3$)	600-1.700	mg/L
Volatile acids (acetic acid)	4.000-7.000	mg/L
Specific gravity	1,02-1,05	-
Sulfates	4.000-10000	mg/L
Temperature	80-90	ºC

Source: Del Toro, 2001.

5.8.3. Treatment plant vinasse generated in Ron Brugal

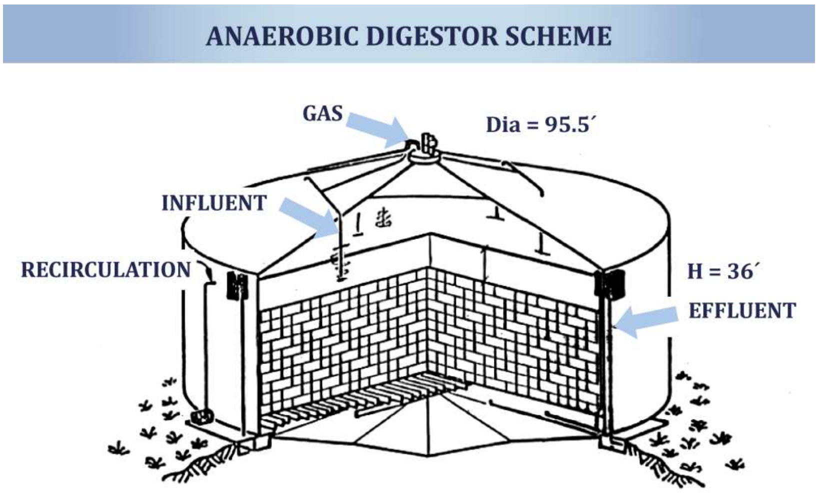
Since 1974, the company Bacardi and, Dr. Michael Szendrey, biotechnology expert, started doing experiments in a pilot plant with a digester of downflow which contained inside PVC plastic filler in form of "honeycomb". This filler served as support for bacteria. Cow manure previously prepared was used as inoculum.

After several years of experiments, and once analyzed all available types of digesters, it was decided to install the digester developed by the company Bacardi and Dr. Szendrey in Puerto Rico. In December 1981, the company launched the Bacardi treatment plant of 1,93 million gallons of capacity. The project was completed with the installation of a boiler to burn the biogas. Currently there are three digesters in operationwith thw same capacity (**Illustration 7**).

Illustration 7: Digesters of the vinasse treatment plant of Brugal

5.8.4. Characteristics of anaerobic digestion of Brugal

The chosen technology was digesters Type Filter "downflow". **Figure 27** shows a scheme of the digester. The tank has a 1.93-million-gallon capacity, where 75% of its volume is occupied by a PVC plastic support so that the bacteria are retained.



Source: Del Toro,, 2001.

Figure 27: Outline of anaerobic digester of Brugal in Dominican Republic

Starting the digester: All biological process need time to adjust, an initial phase of bacterial adaptation is necessary. To start the digester, it has been initially loaded with 100,000 pounds of digested sludge from Bacardi digester in Puerto Rico. This sludge had 20% solids, equivalent to 20,000 lb. of dry matter. Like all biological processes, time was needed to adjust it. After 3-5 months, the digester began to be stabilized, i.e. had enough retained bacteria in the PVC plastic support (Del Toro, A.G., 2001).

Digester Operation and Parameters: The digester is fed from the top and, constantly, several pumps are recirculating the waste water. The level is automatically controlled and any excess gas is burned in a flare. The optimum operating parameters of the process are shown in **Table 40**.

Table 40: Optimum operating parameters of the process

Parameter	Value
Feed temperature of the vinasse	Maximum 37 °C
Temperature in the digester	Maximum 39 °C
pH	7.0 – 7.2
Volatile acids	Maximum 3,500 mg/l
Alkalinity	Maximum 3,000 mg/l
% methane in biogas	50 – 57
% reduction	70 – 80

Source: Del Toro, 2001.

The percentage reduction depends on the difference between the COD of influent and effluent. COD is taken as reference, because it is a fast analysis (2 hours), as opposed to the BOD, which lasts five days. Any variation in these parameters can cause low production of gas and / or gas of poor quality.

5.8.5. Characteristic of biogas obtained in the plant

The digester is designed to produce 24,000 ft^3 / h of biogas with average feeding of 28 m^3 / h. The composition of biogas produced is shown in **Table 41**.

Table 41: Biogas composition in Brugal anaerobic digesters

Compound	Concentration (%)
Methane (CH_4)	50 - 55% (V/V)
Hydrogen sulphide (H_2S)	1 - 3%
Carbon dioxide (CO_2)	35 - 49%
Calorific power	500 Btu / ft^3
Biogas production	9 ft^3 / $lb.COD_{removed}$
Energy available	4.500 $Btu/lb.COD_{removed}$
Removal efficiency	70 - 80%

Source: Del Toro, 2001.

5.9. Singular and strategic project PROBIOGAS

The singular and strategic project PROBIOGAS included a collection of inter-related scientific and technological activities with the common aim of developing sustainable systems for producing and using biogas in agro-industrial environments, demonstrating its viability and promoting it in Spain. In PROBIOGAS, 31 partners participated, 15 R&D centers and 16 Spanish companies and organizations linked to different areas of knowledge of biogas. The project lasted seven years and it was funded by the Spanish Government, through its aid program Singular and Strategic Projects with European Funds. Project activities started in late 2007.

Agroindustrial residues are particularly important in Spain since it is the first European country in cultivation-used area, fourth in livestock production and fifth in food production on the industrial level.

5.9.1. Objective

The main objective of the project was the development of sustainable systems of biogas production and use in agro-industrial environments, as well as demonstrating its feasibility and promotion in Spain.

Moreover, a number of specific objectives raised among which are the following:

1. Facilitate the development and consolidation of "Agro-industrial Biogas" as Renewable Energy in Spain from a scientific-technical contribution.
2. Demonstrate the ability of biogas plants to contribute to the reduction of CO_2 emissions and other greenhouse gases, as well as to the Global Sustainability of Agroindustrial Environments (agriculture, livestock and food industries).
3. Quantify the amount and availability of raw materials mainly organic waste, its potential for biogas production and sustainable use.
4. Development of new anaerobic co-digestion techniques from the most common agro-industrial waste and with greater possibilities in Spain.
5. Characterize and improve the digestates produced in anaerobic co-digestion systems for application in native crops.
6. Evaluate alternatives of agro-industrial Biogas use, including its use as fuel in cogeneration engines, vehicles, mixture into natural gas networks and fuel cells, among others.
7. Demonstrate the viability and sustainability of industrial-scale anaerobic co-digestion plants of agro-industrial waste through several demonstration projects.
8. Disseminate the results of the project through brochures, guides, web pages (www.probiogas.es), presence at conferences, seminars, conferences, media, etc., both in related professional sectors and society in general.

5.9.2. Scope

The activities of PROBIOGAS were focused on agro-industrial biogas source, not from landfills, sewage treatment plants or organic fraction of municipal solid wastes. "Agroindustrial" defined in PROBIOGAS encompasses mainly agricultural activities, livestock and food industries, as well as other activities that could share this scenario in the future (energy crops and bioenergy industries) (Carreras, 2011b).

Another important aspect to note about the PROBIOGAS project scope was the study of the co-digestion.

The project was made up of 13 sub-projects and included feasibility studies, research and development, demonstration projects on an industrial scale, and complementary actions for the coordination and dissemination of the project.
In the subproject 1 a software tool was developed, METANIZA, designed to evaluate the sustainability of agro-industrial biogas plants in Spain from three points of view: economic, energetic and environmental (Peña et al., 2012).

Also, within the demonstration subprojects, the project Co-digestion of citrus waste and manure (SP8) is included. Its objective was to assess the codigestion of livestock waste (manure from 2000 cows) with citrus waste. The used technology was Two-Phase, a plug flow digester (900 m^3) and other completely mixed digester (2,200 m^3) (**Illustration 8**). The biogas is converted into electricity through cogeneration. The biogas is burnt in an engine to produce 499 kW of electrical energy and thermal energy. The values were: generation of 4000000 kWhe / year (green electricity), electric and thermal energy equivalent to 307 homes and 2,808 t of CO_2 emission avoided.

There is available information about PROBIOGAS project on its website: www.probiogas.es

Illustration 8: Biogas Plant performed under PROBIOGAS

Summary of Chapter 5

The primary goal of waste treatment is to reduce the content of organic matter as much as possible, which is achieved by facilitating the development of microbial populations involved. As mentioned above, the deeper knowledge of the microorganisms involved in the anaerobic degradation and of the parameters that control the process have allowed to progress considerably in the technological aspects, significantly performance improving.

There is currently a large number of anaerobic digestion technologies, more advanced than those seen in the previous chapter, applied to the treatment of waste. The digesters design has been evolving in order to achieve high microorganisms concentrations (biomass) into the digesters and greater retention of them (high solids retention time), even when working with high loading rates (low hydraulic residence time).

Advanced anaerobic technologies can be divided into two groups: suspended-growth systems and attached-growth systems. Each of these groups is made up by different types of digesters. In the first group, microorganisms (microbial biomass) are suspended into the digester; they are not fixed to any support. This group consists of different types of digesters that are classified, from lowest to highest degree of technical complexity, in: CSTR, Plug Flow, Anaerobic Contact and UASB. In the second group, microorganisms are attached to inert support into the digester. Depending on whether the supports are fixed or not inside digester, these digesters can be classified into: biomass attached to fixed surfaces, as: Anaerobic Filter and Fixed Film, or biomass attached to moving surfaces, as: Expanded Bed and Fluidized Bed. However, relatively recently, a new generation of digesters that have characteristics of the UASB and the fluidized bed have emerged. These are the EGSB and IC digesters. There are authors who consider them to be third generation. The distinguishing feature is an increase in the flow velocity of the wastewater passing through the mud bed. The increase of the flow allows the partial expansion (fluidification) of the mud bed, improving the contact of the mud with the wastewater, as well as the improvement of the segregation of the small inactive particles in suspension from the mud bed. Moreover, since the anaerobic digestion process takes place in several stages in which different microorganisms act at different rates, the technology has also emerged anaerobic digestion technology in Two-Phase in order to facilitate each step separately. Choosing the type of digester mainly depends on the characteristics of the waste being treated.

It should be noted the spectacular growth that China and Germany have had on the number of digesters installed. Countries have developed as they developed the technological capacity, i.e. the ability to identify and evaluate the range of transferable technology components, to evaluate and select a technology, exploit it, adapt it, improve it and develop, finally, its own technology. In this regard, both private and state enterprises play an important role.

From the private point of view, it should be noted the anaerobic industrial plant to treat vinasse that Brugal Company has in San Pedro de Macoris (Dominican Republic). After the necessary characterization and investigation process, the distillery constructed two digesters with a useful capacity of three million gallons. The technology chosen was Anaerobic Filter. The plant has a removal efficiency of 70-80% and biogas production is 9 ft^3/COD removed. The energy available is 4,500 Btu/lb. COD removed and biogas methane content is 50-55%, representing a calorific value of 500 Btu/ft^3. Biogas is used in one of the two boilers available in the plant to produce heat in the process. The plant data show that anaerobic digestion is a technology that can yield consolidated environmental and economic benefits through biogas production.

In order to boost development anaerobic digestion to treat agro-industrial waste in Spain, PROBIOGAS was carried out, a singular strategic project funded by the Ministry of Science and Innovation and which involved 31 partners (15 centers R & D and 16 companies / institutions) from 9 Spanish autonomous regions. PROBIOGAS was incorporated as a set of inter-related scientific and technological activities with the common aim of developing sustainable systems for producing and using biogas in agro-industrial environments, demonstrating its viability and promoting it in Spain. One of the results was the construction of a Two-Phase digester, plug flow digester (900 m^3) and complete mixed (2,200 m^3) for treating cattle manure with agro-industrial waste in co-digestion. The production of biogas is converted into electricity through a cogeneration engine.

6. Landfill gas. Biogas from MSW landfill

Among the existing methods for the treatment of waste, the landfill is still the most popular option due to low economic costs, social rejection to incineration and existing limitations for recycling or waste behave. According to a World Bank publication on a global review of solid waste management, 59% of the MSW generated in the world are deposited in landfills (Hoornweg and Bhada-Tata, 2012).

The concept of landfill appeared describing an operation of "cut and cover" used for waste deposited in California in the 30s. In Europe this technique was introduced in Bradford (England) in 1935, shortly after France, and in Spain after 1945. Over time this system has been refined and in recent years there have been considerable scientific and technical advances in the understanding of the deposited waste decomposition process, as in the embodiment of appropriate engineering and machinery employed.

In a landfill, the municipal waste is discharged on the ground and stretched forming thin layers. The waste then is compacted to reduce its volume and covered with suitable materials to minimize the risk of environmental pollution and to promote biological transformations of fermentable materials. These layers are confined by slopes, in order to avoid the drag by rainfall, being operated on a limited front in order to limit the slope uncovered.

Whenever waste is deposited, the organic matter biological degradation they contain takes place. The process which occurs usually is called anaerobic digestion. In general, we can admit that a controlled landfill acts as an anaerobic digester which, through a series of physicochemical processes, mainly microbiological (anaerobic fermentation) that occur inside the discharge platforms, results in the appearance of a gas mixture or "biogas" and a liquid with a high organic load and therefore with highly malodorous pollutant known as "leachate". Biogas is a readily usable energy.

When a landfill completes its capacity for waste, it should proceed to its closing and sealing that must be specified in the initial project. Control and environmental monitoring systems should be envisaged (gas control, leachate control and treatment...) and condition the space it takes to give the final use provided for it in the planning phase.

Despite its simplicity, which is one of its advantages, the landfill (sanitary landfill) does not support improvised acts. It should be seen as an engineering work, and as such, it requires a specific project based on appropriate studies that allow appropriate selection of the most suitable solution. A landfill is controlled when taken all reasonable steps to avoid anything that is harmful or annoying to the environment.

The Inter-American Development Bank (IDB) is developing a set of guidelines for specific sectors and subsectors of recognized impact on climate change. These guidelines are intended to provide minimum performance criteria, clear and quantitative, on climate change to be met for the IDB to support projects, as well as guidance on the evaluation and reduction of greenhouse gases emissions of the projects. The purpose of the guidelines on landfills is to establish, for the financing of new landfills and biogas plants, an approach that is in keeping with the IDB's commitment to protect the environment and to reduce the adverse effects of climate change. Under these guidelines, which currently apply only to new biogas plants, the IDB provides innovative rules for financing landfill construction projects by requiring the reduction of greenhouse gases emissions through the capture and destruction of biogas (Boulet, et al., 2010).

6.1. Treatment of MSW in SIDS

Landfilling is the act of final disposal of waste materials and is the least desired option according to the hierarchy of waste management (WARR Act No 58, 2001). However, it is highly practiced in most countries, included SIDS, mainly due to the fact that dumping is relatively cheap compared to other waste management options (Renou et al., 2008), especially if it is not made under the right conditions, that is to say as sanitary landfill. For this reason, often, the most frequent solution to deposit the waste is the uncontrolled landfill. As a result of the relatively high cost of landfills, cities tend to make little progress towards landfill implementation unless the regulatory framework and environmental agencies apply the pressure (The World Bank, 2011). Meanwhile, the availability of landfill capacity in many developed nations has been constant or decreasing due to regulatory restrictions, location and environmental permits in new landfills and landfill expansions. According to the Landfill Directive of the European Union (EU), all member countries of the EU must reduce the amount of biodegradable waste sent to landfills (Directive 1999/31 / EC). For example, Spain (Royal Decree 1481) is obliged to reduce the amount of biodegradable waste sent to landfills according to the amount of this material discharged in 1995 to 75 percent in 2010, 50 percent in 2013 and 35 percent in 2016. As a result, new approaches to waste management have been incorporated into public and institutional policies at the local and national levels.

The objective of sanitary landfill design is to provide for safe disposal of waste while protecting human health and the environment. Sanitary landfills should be designed and managed to protect soil, ground water, surface water and air. Other important objectives of sanitary landfill design are to maximize the waste disposal quantity in the available space given site conditions, geometry, consideration of slope stability and future potential uses.

Although landfills exist in many SIDS, most of them are poorly located and poorly managed and, in addition, are not sanitary (UNEP, 1998). However, this is not the case in all cases. SIDS, which has an economy based on tourism, such as Cuba, prohibits both landfilling and dumping into the sea (Binder and Mosler, 2007). In the Pacific Cook Islands, the RSU is packed before being deposited in the landfill in order to extend the useful life of landfills (ADB, 2014, cited by Moheer et al, 2015). On the other hand, many SIDS such as Fiji, the Cook Islands and Tonga are already moving towards the sanitary landfill due to the negative environmental and health impacts of uncontrolled waste dumping (UNEP, 1999, ADB, 2014a). An example of a landfill or sanitary landfill that is well managed is the Mare Chicose sanitary landfill, in Mauritius, with a capacity of 224,990 m^2, where the waste is disposed in cells with double high density polyethylene lining, leachate management, cover final and surface and groundwater monitoring in place, along with the generation of 3.3 MW of landfill gas electricity (Kowlesser, 2012; Beerachee, 2012 cited by Mohee et al, 2015).

However, even though sanitary landfill represents the cheapest way to dispose of waste, it remains the least desirable option due to the loss of potentially useful materials that waste has, such as recyclable materials that can be reused.

As it has been shown in the UN draft (UN, 2017), one of the most important problems that SIDS have is related to waste. The implementation of the WPA (World Program of Action for the Protection of the Marine Environment from Land-based Activities) is necessary to prevent, reduce and control waste and pollution, as well as the need to provide support for the creation of capacity to reduce and manage waste and pollution.

Food security generates concern in SIDS, because climate variability affects agriculture. Solid waste is a source of greenhouse gases (GHG), not only because of its relation to production and consumption, but also because of methane (CH_4) emissions when disposed of in landfills that do not comply with the appropriate safety measures. CH_4 emissions produce about 16% of the total greenhouse effect (IPCC, 2016). Globally, landfills are the third largest anthropogenic source of methane, accounting for approximately 11 percent of estimated global methane emissions or nearly 799 million metric tons of carbon dioxide equivalent emissions in 2010 (USEPA, 2011). Thus, landfill methane emissions represent the largest source of GHG emissions in the waste sector.

The sanitary landfill remains the predominant method of waste disposal in most parts of the world. However, as referred to, sometimes open dumps or those that do not meet the minimum requirements are also called sanitary landfills. The capture of biogas significantly reduces methane emissions and, when captured gas is used to generate energy, it can lead to a saving in greenhouse gases. It should be noted that this gas has significant energetic value which can be readily usable, as it will be seen en the next chapter. Therefore, a good landfills management has undoubtedly environmental and also economic benefits that may become very important.

Incorporating integrated solid waste management and Landfill gas energy (LFGE) best practices can help to protect human health and the environment from the dangers of improperly managed and disposed waste. Finding the proper mix of practices to meet a local community's means and needs will help ensure a healthier population and environment.

The amount of methane created depends primarily on the composition, quantity and moisture content of the waste and the design and management practices of the landfill. Sanitary landfills, designed to maximize the anaerobic decomposition of waste, produce more methane than open dumps and other solid waste disposal options that allow for aerobic decomposition. As developing countries transition to control or sanitary landfills, methane emissions will rise as more waste is managed in a manner that is conducive to its generation. As a result, LFG collection and control measures are of increasing importance for managing these emissions. For example, in the 1990s, several major cities in South Africa experienced problems with increased demand for landfill capacity, which presented opportunities for both the collection of LFG from existing closed waste dump sites and the design of new sanitary landfill facilities that optimized LFG output for commercial purposes (USAID, 2004). Several municipalities then implemented LFG recovery at better managed landfills and constructed sanitary landfills.

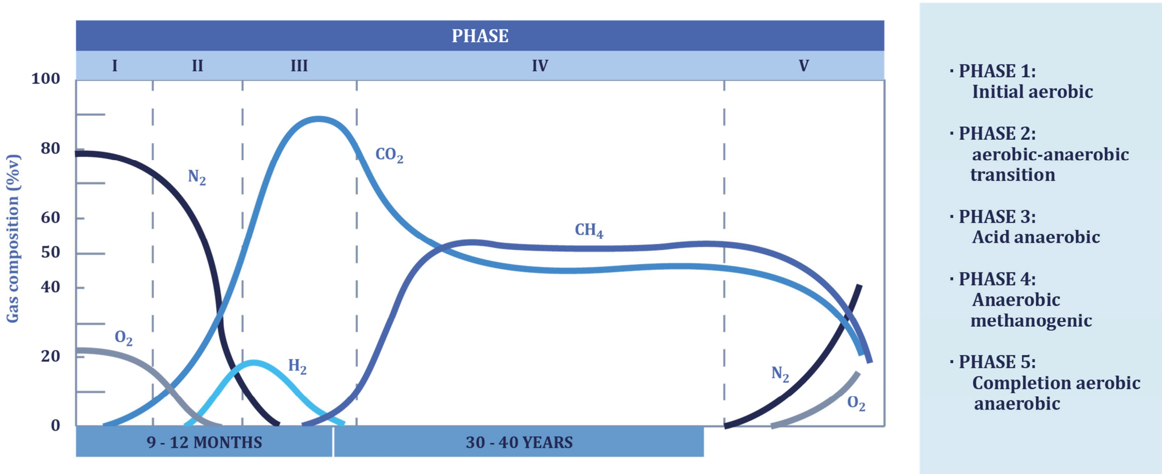
The recovery of methane in landfills; waste incineration with energy recovery; composting; Waste recycling and minimization can reduce GHG emissions. Changes in lifestyle and behavior patterns can contribute to the mitigation of climate change.

There is general agreement in the entire waste sector that the greatest benefit for the climate is achieved through better management of the most important materials for the prevention of waste (USEPA, 2012). The recycling of most materials results in improved greenhouse gas savings. In general, without waste and recovered materials represent the main activities for which the waste sector can contribute significantly to the mitigation of climate change.

Solid waste management is a powerful tool to reduce greenhouse gas (GHG) emissions in the world where shared responsibility is fundamental to the necessary changes in the way we do things now.

6.2. Stages of formation of biogas in a sanitary landfill

Biogas production process in a sanitary landfill occurs through five stages or phases which are collected in **Figure 28**.



Source: Tchobanoglous, 1993.

Figure 28: Landfill gas formation process

The characteristics of these stages are:

1. Aerobic phase: The immediate phase of the landfill. Degradation process begins, it dominates the N_2. Aerobic microorganisms consume the available oxygen and produce a growing CO_2 formation. It has a short duration, estimated approximately in 15 days.

2. First anaerobic phase (absence of methane), also known as transition phase: Predominantly aerobic shift to anaerobic bacteria. This stage is characterized by the absence of oxygen and the formation of fermentation acids. At the end of this stage higher concentration of CO_2 is achieved, the emergence of H_2 and the decline in the proportion of N_2. It lasts about 2 months.

3. Second anaerobic phase (formation and increase of methane): An anaerobic phase which produces the beginning of the emergence of methane and the decline of the other products. The pH begins to drop while the waste becomes acidic. It is estimated to last 2 years.

4. Third anaerobic phase or stabilization phase: The acids produced in the previous phases are converted into methane and carbon dioxide. The pH reverts to neutral levels. Biogas production is highest at this stage. It started about a year from waste deposition. It lasts between 10 and 20 years, depending on landfill conditions. It is characterized by maintaining the concentrations of CH_4 and CO_2 at about 60 and 40% respectively.

5. Anaerobic-aerobic phase of completion. There is a progressive decrease in the generation of biogas. The availability of organic matter and nutrients becomes limited. It stabilizes the composition of the leachate. Continued slow degradation of the more recalcitrant organic matter.

6.3. Conveniences of landfill gas extraction

The extraction of biogas is considered necessary from the environmental viewpoint and in many cases also from the energy viewpoint. These produced gases move around the discharge mass, reach the surface and flow to the outside, therefore from the environmental point of view it is important to extract, because:

- The compounds that significantly contribute to the greenhouse effect are removed. The fact that biogas is composed mainly of methane (CH_4), a powerful greenhouse gas, makes its capture prevent the release of these compounds into the atmosphere and therefore significantly decrease its contribution to the environmental problem.
- Elimination of possible risks of explosion (as occurred in some landfills) when the critical concentrations of some gas components were achieved (CH_4 in this case) being reactive with air oxygen in certain proportions.
- It avoids potential risk of fire, particularly in days where high temperatures are reached.
- Vegetation damage of the area is eliminated, since the biogas displaces the soil air and prevents the proper development of plants (should not be planted on the surface of a landfill if it has not previously been degassed).
- Odors are avoided due to the presence of compounds in biogas that, although are present in small amounts, have the disadvantage of being extremely malodorous, as is the case of the hydrogen sulphide and mercaptans mainly.
- Possible risk of reducing the concentration of ozone is avoided. The possible content of chlorinated and fluorinated hydrocarbons (freons) of biogas poses a specific problem. These compounds are contained in spray cans and can escape outside when metal containers are corroded. Due to their chemical stability, especially fluorinated hydrocarbons, reach the stratosphere where chlorine atom is separated and the radical causes the breakdown of the ozone molecule.

From the point of view of energy it is also important its recovery because it can constitute a potential energy as discussed later.

6.4. Extraction infrastructure and use of landfill gas

Improving the conditions of an SWD site to the standard of a properly designed and operated sanitary landfill will likely improve the collection of LFG. It is important that stakeholders understand how the various components of an SWD site affect the generation of LFG, the methane content, and the collection efficiency of the LFG collection system, including how common flaws in design and overall operation can affect LFG generation. Implementing training opportunities can help to reduce these design and operational flaws. Well-designed and operated sanitary landfills will generate LFG that can be feasibly collected and used and provide cost savings over the life of the project.

A way to reduce the nuisances and risks associated with gas emissions and, at the same time take advantage of it to generate energy is to extract it and to use it. This is achieved by making a system of wells in the pouring platform to which they are joined by a pipeline system to transport the gas to a site where it can be processed.

An installation of landfill biogas extraction consists mainly of collection wells, associated piping, set of valves, control and monitoring equipment, extraction pump, biogas cleaning systems and equipment for utilization and disposal of waste gases, and also the energy suppliers that make it all work.

Below there is a briefly description about the basic elements of an extraction system with leveraging biogas in a sanitary landfill.

6.4.1. Collection wells and Conduction lines

Through the collection wells regularly distributed over the landfill surface extraction of the biogas generated in the inside of the landfill is carried out. In wells, perforated pipes are inserted, in approximately 20% of its surface area, to allow the uptake of biogas (**Illustration 9**); but the top (in the last section of 2-3 m approximately) is not perforated to prevent leakages. Generally, high density polyethylene ones are used, although they may also be made out of synthetic polymeric materials. Between the well and the pipes, which have a smaller diameter, gravel is inserted in order to obtain biogas drainage.

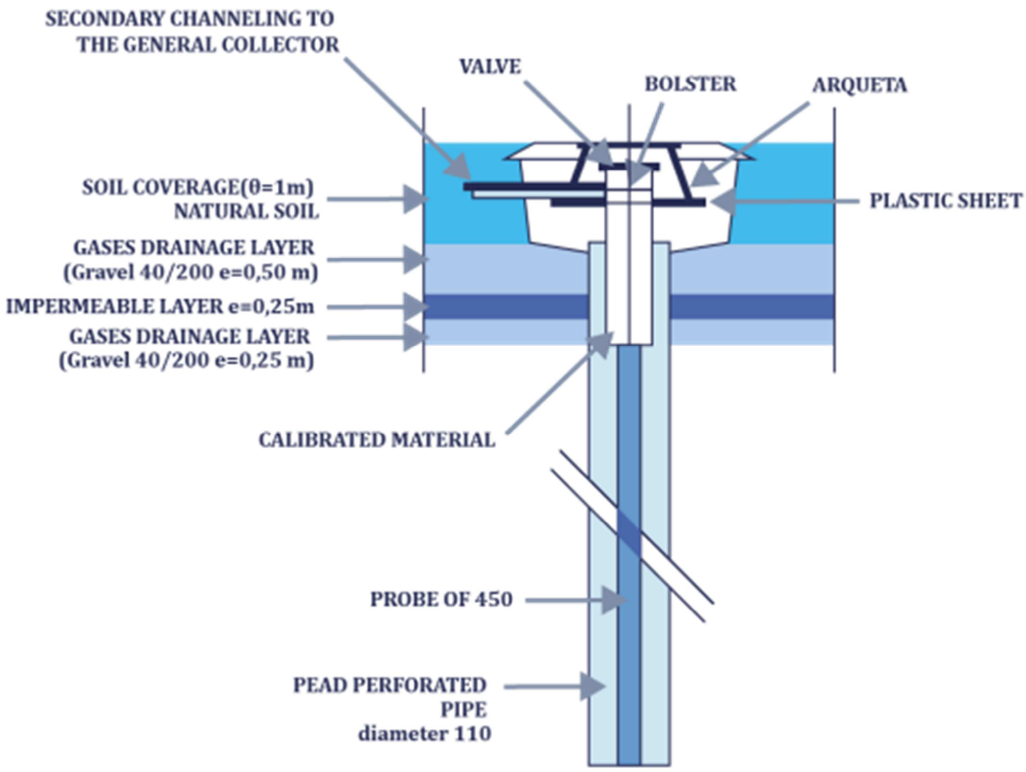
The wells are formed by a special locking head to prevent the entry of oxygen to the gas flow or the outputs of it to the atmosphere. It can get outdoors (**Illustration 10**) or be buried (**Figure 29**). The depth of the wells will be according to the deposited layers in the landfill. The required wells are placed to cover the entire surface of the landfill considering that the radius of action is approximately 25 m for sanitary landfills with depths of at least 20 m.

Illustration 9: Perforated pipes

Illustration 10: Wellhead outdoors

The driving of biogas to the center of suction and measurement is made through lines or pipes (**Illustration 11**), of high density polyethylene from the top of the wells to the extraction plant or collectors according to the system used.

The wells, although less frequent, can also be horizontal. Horizontal extraction wells can be installed while an SWD site is still receiving waste and may be used if LFG collection is desired in an area before closure. Horizontal extraction wells are placed in a trench within the refuse. The trench is backfilled with gravel (or other aggregate such as tire chips or broken glass), and the perforated pipe is installed in the center of the trench. A geotextile fabric is recommended on the top of the trench to reduce clogging of the aggregate by the backfill or trash above.



Source: Prepared by the author based on information collected.

Figure 29: Well-head in chest.

Illustration 11: Biogas lines

6.4.2. Torch

All the extraction and utilization installations of biogas must be equipped with a torch as security measure to eliminate the biogas that is not used (**Illustration 12**). The burning is done for environmental reasons (reduction of methane emissions), but above all, to reduce the risks of fire and explosion.

Illustration 12: Torch installed in landfill

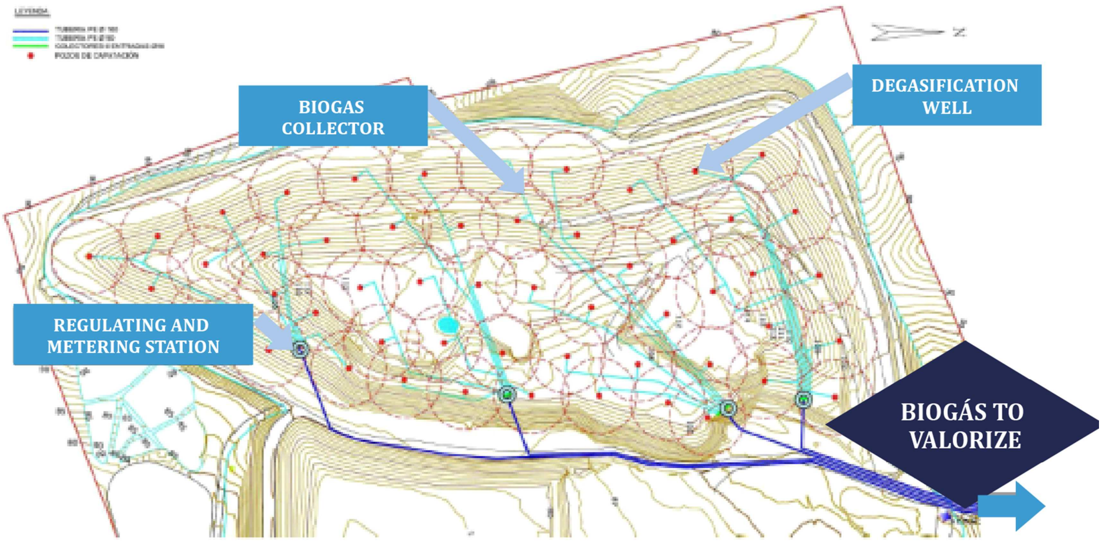
6.4.3. Regulating and metering station

The regulating and metering station (**Illustration 13**) controls the quantity and quality (methane and oxygen) of extracted biogas in each line. The site of the installation will be available within an area that does not affect the normal operation of the landfill and close, as possible, to the collection wells.

Illustration 13: Regulating and metering station

6.4.4. Landfill gas collection system

Figure 30 shows a diagram with all the necessary elements to carry out the global collection of landfill gas.



Source: No permission to provide the name of the landfill.

Figure 30: Global extraction system of biogas in a sanitary landfill

6.4.5. Cleaning and Conditioning of landfill gas.

Landfill gas (LFG) must be previously refined in any of its energy applications. In addition, LFG tends to have a greater number of minority compounds than biogas from biodigesters. The purification systems vary depending on the use that is going to be given. The most commonly used is cogeneration. In that case, and due to its high moisture content, and usually the presence of corrosive compounds, it is necessary to condition it before it is used.

Below are the components that should be reduced / deleted and the reason.

- Water vapor. Water vapor drastically decreases the biogas ICP, as well as, facilitates the formation of corrosive acids.

- Halogenated hydrocarbons. Particularly those that have chlorine and fluorine favor the corrosion of the internal parts of the machines.

- Hydrogen sulfide (H_2S). Prevent corrosion and avoid toxic concentrations for the human being, as well as, prevent the formation of sulfur oxides (SO_2) that enables the formation of sulphurous acid (H_2SO_3) that is highly corrosive. It is necessary to eliminate it below certain limits so that the biogas can be used.

- Siloxanes. Avoid the deposition of silica in the different internal parts of the machines, thereby eliminating the possibility of wear of parts and pieces and the loss of stability of parts that rotate at high speed.

There are specific methods for the reduction for the reduction of H_2S, such as biofilters and iron filters, and for the reduction of humidity, such as water traps and condensation. As general methods for the reduction of H_2S, siloxanes, water vapor, halogenated hydrocarbons, etc., active carbon or a combination of methods is used.

This topic is developed more in depth in the next chapter.

6.4.6. Associated investment costs

The economic viability for LFGE projects relies heavily on identifying suitable financing mechanisms, evaluating the economic feasibility of various options, and selecting the most viable option to meet the goals of stakeholders (for example, financial objectives, public health benefits, environmental protection and climate change mitigation).

Table 42 summarizes the investment costs associated with the most appropriate biogas technology for Latin America and the Caribbean. Overall, the construction and operation of such biogas plants is economically viable in countries of the region (Terraza and Willumsen, 2010).

Table 42: Investment costs of a sanitary landfill biogas plant

Components	Cost	Cost/t ($U.S.) *
Project preparation	10% - 15% of total investment	0,08 - 0,18 US$/t
Capturing system	30.000 - 50.000 US$/ha	0,15 - 0,40 US$/t
Gas pumping system**	75 - 200 US$/m^3 biogas/hour	0,05 - 0,30 US$/t
Burning system	40 - 80 US$/m^3 biogas/hour	0,02 - 0,04 US$/t
Gas engine units/ generator	1.100 - 1.700 US$/kWe installed	0,60 - 1,10 US$/t
Boiler room	40 - 80 US$/wheat installed	0,17 - 0,34 US$/t

* Tons of waste in landfill. ** Includes blower or compressor, control and regulation and treatment.
Source: Terraza and Willumsen, 2010.

Table 43 summarizes the operating and maintenance costs associated with the most appropriate biogas landfill technology for Latin America and the Caribbean.

Table 43: Annual costs for operation and maintenance of various landfill gas systems

Type biogas plant	Annual cost of operation and maintenance*
Plant with torch system	4% - 8% of total investment cost
Plant with boilers system	4% - 8% of total investment cost
Plant with electricity production	10% - 12% of total investment cost

* Tons of waste in landfill.
Source: Terraza and Willumsen, 2010.

6.5. Energy potential of a sanitary landfill

The most interesting property of biogas is its energy value, due to its high content of methane. The biogas composition affects the possibilities for its use, since the concentration of methane determines its inferior calorific value (ICV) and a high concentration of any trace components (hydrogen sulphide, halogenated organic compounds, ...) can make it enough corrosive as to render impractical its energy use, mainly in engines. The ICV of a biogas with a methane content of 60% is 5,500 kcal/m^{3}N.

6.5.1. Biogas production in a sanitary landfill

Biogas production depends on several parameters, namely: 1. Landfill temperature (at higher temperature, faster biogas decomposition and production); 2. Moisture index of the waste mass is determined by the type of waste and the level of precipitation in the area (biogas optimal production requires a 50-60% humidity level or higher; 3. The waste composition (degradable carbon content determines the potential for biogas production); 4. Wastes structure (small particles offer better conditions for methane producing bacteria); 5. The age of waste (in general, maximum production occurs between 3 and 8 years after to be deposited, and gradually decreases during the next 30 - 75 years; 6. The end cover use to prevent ingress of atmospheric air, nevertheless permitting infiltration of rainwater, and 7. Designing, operating plan and practice in filler the facilities, especially compaction and coverage practices (EPA, 2005a). Estimating biogas production of a sanitary landfill is therefore difficult to assess.

Theoretically, it can be considered that 370 m^3 of biogas per ton of waste deposited are produced, with approximately 50% organic matter and 35% humidity. Considering that only part of the residue is biometanizable, that not all the biogas can be extracted (generally 50-70% using efficient extraction technologies) and that a part of it can escape into the atmosphere, it can be considered that, as an indication, 100 m^3 of biogas per ton of waste deposited can be extracted and used in a period of 15 - 20 years.

In a global study by ISWA (ISWA, 2004) the actual rate of biogas extraction (m^3 of biogas per ton of waste per year) was also examined from existing biogas plants. The analysis showed an extraction rate of 3 to 6 m^3 of biogas per ton of solid waste per year for the useful life of each of the landfills studied.

In four of the five projects analyzed in the region of LAC as part of the World Bank study, extraction rates ranged between 2 and 5 m^3 of biogas per ton per year, with the exception of a facility in which the extremely high level of leachate prevented the gas extraction in wells, limiting the extraction only 0.5 m^3 of gas per ton (Boulet, et al, 2010).

The experimental values reported in the literature differ considerably due precisely to the local nature of the factors outlined above, even within the same country these factors may vary from one region to another, which hinders the direct application of bibliographic data obtained from studies. Because of these variations, the realization of a project of degassing and biogas use in a landfill requires pre-feasibility studies to establish the quality and quantity of produced biogas in order to estimate its energy potential.

During the past 30 years there have been several models to estimate biogas production and extraction (EPA, 2005a): (i) the zero-order model takes as a given the production of a constant annual volume of biogas until all degradable carbon decomposes, by failing to include the effect of the waste age , this model only allows an estimation of national and global biogas emissions, (ii) the first-order model assumes that waste degrades exponentially with time, a first-order model often used is the landfill gas emissions model (LandGEM) 3.02 of the Environmental Protection Agency (EPA) of the United States (EPA. LandGEM emissions model), (iii) multiphase model takes into account specific volumes of different types of waste, including carbon content, to estimate the production of biogas from each waste category. This model is used for estimations in CDM projects and is available on the virtual site of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2006).

Of these, the USEPA LandGEM is the most used model in the United States and in many countries (EPA, 2005b). It has been made versions adapted to the characteristics of some countries in LAC (Central America, Ecuador, Colombia, Mexico, see Webgraphy).

<u>Landfill Gas Emissions Model (LandGEM). Version 3.02.</u>

The "Landfill Gas Emissions Model" (LandGEM) is an automated estimation tool, framed in the calculation program "Microsoft Excel", used to estimate the emissions produced by MSW landfills, both biogas and each of its components such as methane, carbon dioxide, organic components other than methane and other types of air pollutants that might be produced due to the heterogeneous nature of MSW landfills.

In website pages links to this model are available, as well as versions that are adapted to different countries and areas in the LAC region (Ecuador, Colombia, Mexico and Central America) and other countries.

The model is based on a first order equation which estimates the amount of methane per year produced in the landfill, and from it, we estimate the remaining quantities emissions of other greenhouse gases.

$$Q_{CH4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} kL_0 \left(\frac{M_i}{10} \right) e^{-kt_{ij}}$$

The equation has emission factors or essential parameters, as they provide the right information to more accurately estimate the amount and type of emissions that form a MSW landfill, these parameters include such important factors in the biogas production such as humidity, temperature, amount of nutrients available to the microorganisms, the pH, the composition of MSW, the presence of hazardous waste... because the biogas formation is based on anaerobic biological reactions, in which the external environmental factors influence in a major way.
The model uses two types of default emission factors for the k (biogas generation constant) and L0 (biogas generation potential). The first one is influenced by temperature, humidity, nutrient availability to microorganisms and pH, and the second one, by the type and composition of MSW.

- k ⇨ influenced by temperature, humidity, availability of nutrients for microorganisms and pH.
- L_0 ⇨ influenced by the type and composition of MSW.

Default factors are those of the CAA (Clean Air Act) based on U.S. legislation and inventory. These last ones are those that EPA recommends for estimating emissions and make an inventory out of them, in a general way, being able to be extrapolated to the normal conditions that occur in any MSW landfill.

There is also the option to enter these emission factors estimated with data from the landfill whose emissions you want to estimate. This option would be most appropriate because it would take into account the characteristics and environmental factors of the landfill that, as discussed above, are so important in order to find, in a more reliable way, the amount of biogas, and its component gases, which are generated in a landfill.

The data required by the LandGEM model to estimate emissions that are going to be produced in a MSW landfill are basically:

- Opening year.
- Closure year (If unknown is calculated, taking into account the annual MSW quantity entered and the total capacity of the landfill).
- MSW annual amount deposited.
- L_0 and k by default or calculating with the characteristic data of each installation.
- Greenhouse gases you want to estimate.

6.5.2. Potential of biogas

In 2003, it was worldwide recorded a total of 1,150 biogas plants in energy conversion (ISWA, 2004); with a power output of 3,920 MW and an extraction rate of 3.1 m^3/t/year (Willumsen, 2003). Subsequently, EPA gathered updated information on 509 operational biogas plants in the United States until 2009. The new information and estimates based on previous data indicate that in 2008 there were about 1,400 biogas plants over the world (Boulet, 2010). Currently, the use of biogas for energy applications (in traditional landfills bioreactors) is only, approximately, 10% of their potential use.

Regarding Spain, the number of landfill biogas plants have raised from none to over 40 in just over 10 years. Biogas is being used to generate electric energy in 42 Spanish landfills through more than 100 cogeneration motors, with an over 100 MW installed capacity (Carreras, 2011a). This rapid growth had an environmental origin because it was motivated by the entry into force of Royal Decree 1481/2001 which regulates the disposal of waste by landfill deposit, which in turn was issued by requirement of the European Directive on the landfill waste (Directive 1999/31/EC).

The sanitary landfills of Brandeirantes (Brazil), Monterrey (Mexico) and Doña Juana (Colombia), among others, are examples of energetic use of biogas extracted from landfills in LAC region, which have emerged as CDM projects.

As for the use of biogas, it can be used to generate power as long as the local energy market conditions ensure viability. The energy produced in this way displaces fossil fuel consumption and reduces greenhouse gases emissions by existing generating plants. There are various types of biogas energy systems for usage which are discussed in Chapter 7.

6.6. CDM Projects in sanitary landfills. Experiences in Latin America and the Caribbean

The Clean Development Mechanism (CDM) is a tool that has helped finance projects to reduce greenhouse gas emissions in non-industrialized countries, always, and this is an indispensable condition, which contribute to the social, economic and environmental development of the country where it is implemented. The projects related to landfill biogas capture are contemplated as CDM projects.

This mechanism has allowed the registration of 7,800 projects and programs in 107 developing countries with hundreds of billions of dollars in investments, which meant 1,500 million fewer tons of greenhouse gases released into the atmosphere (IPS, 2014_a).

In April 2012, Latin America and the Caribbean (LAC) had recorded 584 CDM projects (15% of total), 1,832 in China (47%) and 786 in India (20%). However, in relative terms, the share of LAC in the CDM is far superior to that of other regions such as Europe and Central Asia, Africa and the Middle East, which have only 1%, 3% and 1% of total projects, respectively (CDM Statistics, 2012).

As for the type of CDM projects in LAC, those concerning the capture of methane in landfills, with 12%, are in third place after renewable energy projects (56%) and avoided methane projects (21%). Behind, at a certain distance, are energy efficiency projects on both, supply and demand (3% each), afforestation and reforestation projects (2%), the HFC and N_2O reduction (2%) and fuel switching (1%).

However, currently the the instrument of the United Nations to support carbon emissions projects in developing countries, the CDM (in charge of certified emission reductions (CERs)) is in crisis due to the collapse of prices they pay for carbon credits. The price of CERs fell to 0.30 dollars in 2014, compared to more than 30 dollars in 2009.

The CDM has collapsed because in recent years the demand of the main buyers fell, countries forced to reduce their polluting emissions under the Kyoto Protocol, because the reduction targets did not increase significantly as there was more economic growth slow. According to the president of the CDM executive board, the source of the problem was the directive of the European Union (EU) of 2009 (to restrict the possibility of international credits and prohibit them altogether from 2020), which came into force on January 1, 2013 (ISP, 2014_a).

For the Alliance of Small Island States (AOSIS), created in 1990, with the main objective of consolidating the voices of SIDS to face global warming, given that financing is a central pillar of the 2015 climate agreement, The current state of the CDM is another worrying issue. From the perspective of the AOSIS, they maintain that the price of CERs can be increased with "green technologies and with incentives for countries to have projects that are more favorable to the environment" through the MDL (ISP, 2014_b). In 2012, the SIDS had 31 projects in the pipeline and 10 registered projects, totaling 8215k CERs. In 2015, 28 SIDS had no CDM projects in preparation (Williams, 2015).

6.6.1. Practical case. New plant in the sanitary landfill of Bordo Poniente (Mexico)

A few months ago, specifically on 1 November 2012, the awarding of the biogas plant contract exploitation of Bordo Poniente (Mexico) landfill to the consortium BMLMX SAPI Power Company for a 25 years period was announced) was announced. The consortium, consisting of three Spanish companies (Southern Energy Europe, CLP Organogas and Tegner) and three Mexican companies (RAM Carbon of Mexico, JCH Inversion Redituable and Iberaltec), will manage the biogas production in Bordo Poniente sanitary landfill, in Mexico Federal District of, Mexico's largest landfill which has accumulated waste over two decades.

The contract involves sanitation and the final closure of the landfill, which accumulated 72 million tons of waste and generated 26% of the greenhouse gases emitted in Mexico City. The project includes the construction of a plant that will use biogas to generate 58 megawatts per hour. The new biogas plant will entail investment of 125 million euros. The contract will allow the consortium to manage a 25-year concession to produce biogas at Bordo Poniente. The project has been considered to be the fifth most important of its kind in LAC. When the concession expires, the Mexican-Spanish consortium will leave the management of the landfill in the hands of National Water Commission. The energy project and the definitive closure of Bordo Poniente will to stop the emissions to the atmosphere of 1.2 million tons of CO_2 each year.

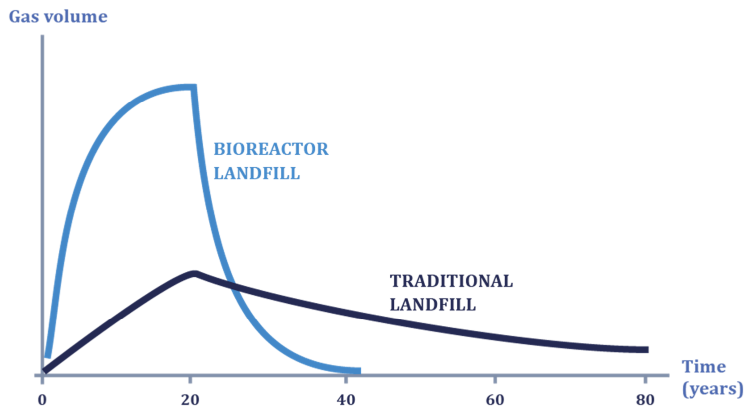
6.7. Anaerobic Bioreactor Landfill

The Regulations of the Clean Air Law of the USEPA (40 CFR 63.1990, National Emission Rules for Hazardous Air Pollutants) defines an anaerobic bioreactor landfill as:

"MSW landfill or a portion of a landfill MSW where any liquid, apart from the leachate or gas condensate, is added in a controlled manner to the waste mass (often in combination with recirculation of leachate) to reach a minimum average of 40% humidity in weight in order to accelerate or improve the anaerobic biodegradation of the waste."

Therefore, the main function of the bioreactor landfill is to accelerate the degradation and to stabilize the waste while maintaining adequate humidity for microorganisms (Reinhart et al., 2002).

Research indicates that a bioreactor landfill can generate biogas at a higher rate than traditional landfills (Yazdani et al., 2006). The biogas is also generated for a shorter period because the source of waste runs out before (**Figure 31**). The result is that the bioreactor produces more biogas in a shorter period of time than the traditional landfill.



Source: Yazdani, 2007; ITRC, 2018

Figure 31: Production of methane in bioreactor landfill and conventional landfill

6.7.1. Characteristics of anaerobic bioreactor landfills.

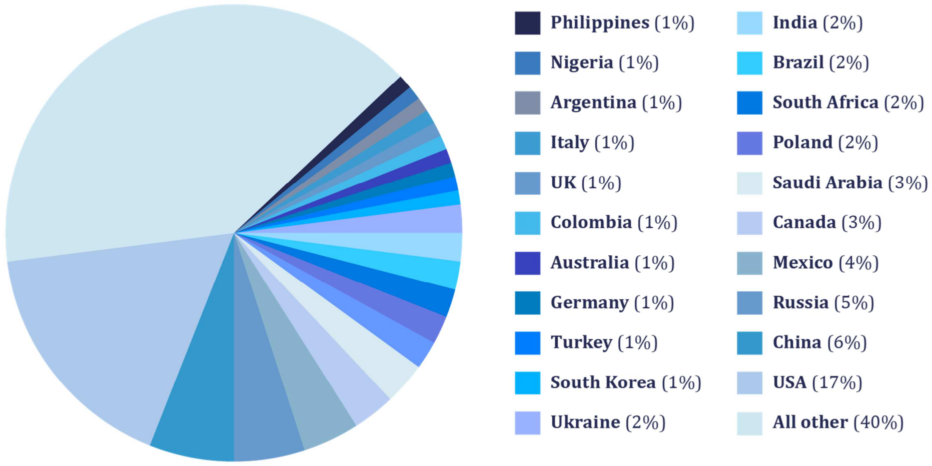
The leachate is injected into the bioreactor to stimulate the natural biodegradation process. Bioreactors often require the support of other liquids such as rain water, wastewater, and sludge treatment of wastewater plants to complement the leached and thereby improve microbiological process by controlling the humidity (Reinhart and Townsend, 1998). The bioreactor landfill differs from a conventional in that the leachate recirculates in a controlled manner; the landfills that recirculate the leachate not necessarily function as optimized bioreactors.

Thus, the humidity content is the most important factor which promotes rapid degradation. Bioreactor technology is based on maintaining optimum humidity content near to field capacity (approximately between 35 and 65%) and to add liquids, as needed, to maintain that level. Humidity content combined with biological microorganisms' action present in wastes is what causes degradation thereof. One consequence is, as stated above, that it produces more biogas in a shorter period of time than the conventional landfill.

6.7.2. Potential advantages of anaerobic bioreactor landfills

The fact that decomposition and biological stabilization of the waste in a landfill bioreactor is produced in a shorter period of time than the time a conventional landfill (dry), takes provides a number of advantages (Valencia, R. 2008), which are described below (EPA, 2003):

- Decomposition and biological stabilization of wastes take years while unconventional landfills it takes decades.
- Low toxicity and mobility of wastes due to anaerobic conditions.
- Reduced costs of leachate treatment.
- Between 15-30% of landfill space gained because the density of the waste increases.
- There is a significant increase in the biogas generation that can be used to produce energy.
- It reduces the post-closure maintenance.
- As the biogas is generated before and in a short period of time, more quantity can be recovered reducing atmosphere emissions, preventing, therefore, the greenhouse effect and reducing to the minimum the environmental risks associated with the decomposition of the residue (**Figure 32**).



Source: EPA, 2004.

Figure 32: Global emissions of methane from landfills (2005)

In turn, this circumstance favors their application in energy recovery projects. Some studies indicate that the bioreactor increases the possibility of making the biogas recovery profitable and in turn, reducing fugitive emissions (Yazdani et al., 2006). This is supposed to be a good opportunity for using them in energy recovery projects. As mentioned, the use of biogas for energy applications (in traditional and bioreactor landfills) is currently only 10% of its potential use approximately. The U.S. Department of Energy estimates that if bioreactor technology was applied currently to 50% of the waste dumped in landfills, it could provide more than 270 billion cubic feet of methane per year, equivalent to one percent of electrical needs of the U.S.

6.7.3. Considerations to take into account in anaerobic bioreactor landfills

The United States Environmental Protection Agency (USEPA) is collecting information on the advantages and disadvantages of bioreactor landfills through case studies on existing landfills and additional data in order to identify specific rules for bioreactor, or recommend operating parameters. The EPA, before identifying rules or recommending parameters, should take into account some considerations.

The bioreactor landfills are generally engineering systems which have high initial investment costs and require additional monitoring and control over its useful life, while it is expected to mean less control during the post-closure period than that required for conventional landfills. The issues to be addressed during the design and operation of a sanitary landfill bioreactor are: Increased gas emissions; Odors increase; Physical instability of the waste mass due to an increased in humidity and density; Instability of coating systems; possible seepage surface and Sanitary landfill fires.

6.7.4. EPA's research about bioreactor landfill. Practical case: Yolo County Landfill

The EPA is studying and conducting research and demonstrations in bioreactor landfills in order to evaluate different aspects such as design, monitoring, behavior, economic viability, etc. One of the major studies is conducted in the Yolo County landfill. First we conducted a pilot-scale bioreactor and, because of the good results obtained, thereafter two more demonstration-scale were developed (3.5 and 6 acres), as part of Project XL USEPA (United States Environmental Protection Agency). The overall project objective is to deal with the spillage for a rapid degradation of solid waste and the maximum generation and control of emissions. Anaerobic degradation of the waste accelerates improving the conditions of biological processes which involves injecting controlled amounts of fluid (leachate, groundwater, gravy water, etc.).

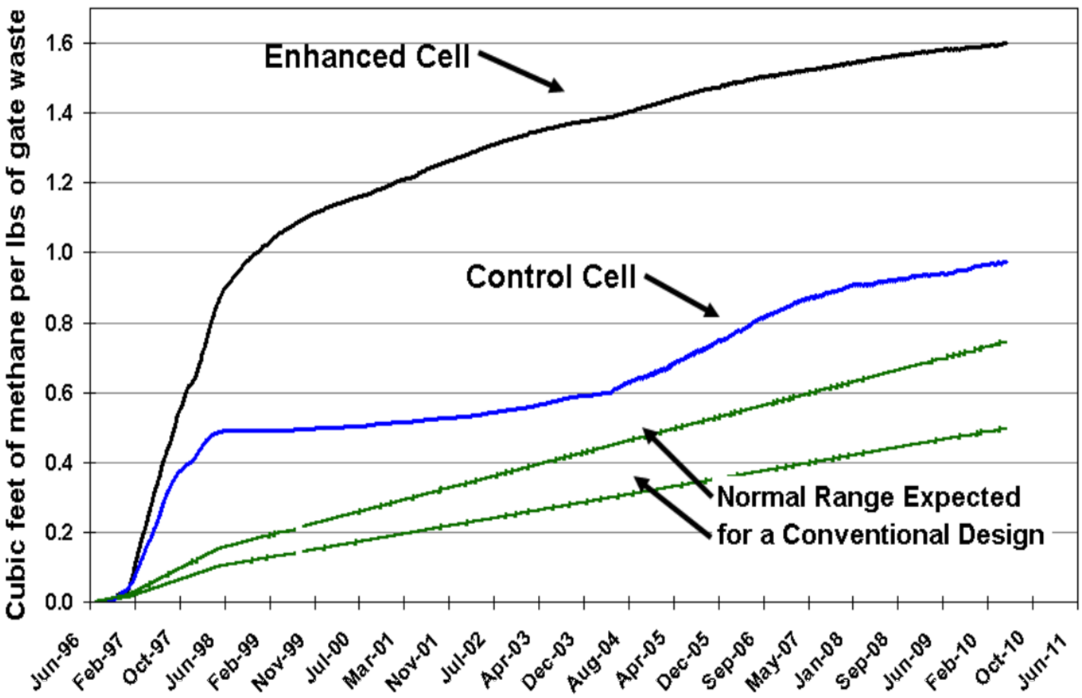
Pilot assay

The pilot demonstration project of Yolo consisted on the construction and operation of two pilot cells, containing each about 9,000 tons of MSW. A cell received additional recirculation liquid, "Improved cell", while the other is operated as a control, that is, as a traditional landfill (Yazdani et al., 2002).

The most important characteristics were:

- A leachate collection system under high permeability waste.
- Multiple humidity and temperature sensors distributed throughout the cells (more than 50) to control the process.
- Using a permeable residue (Green Waste) as daily cover to improve permeability.
- A geomembrane to cover the surface and prevent gases emissions.
- Introduction and recirculation liquids by adding to the surface at multiple points.
- Gas extraction by applying a small vacuum.

The specific characteristics of the test cells were: 100 feet by 100 feet by 40 feet depth. The humidity and temperature sensors were in 3 layers of the improved cell and two in the control cell. Liquid addition was slow and easily manageable, 0.2 to 0.6 gal/ft^2.d. After several years of study, the results obtained are shown in **Figure 33**. As it can be seen, there is a considerable difference in the biogas production from one cell to another.



Source: Seiser and R. Yazdani, 2014.

Figure 33: Methane accumulated in the control cells and bioreactor. Pilot experience.

As evidence the status of the two cells after years of research is shown in **Illustration 14**.

Control Cell

Bioreactor Cell

Source: Yazdani, 2006.

Illustration 14: State of control cells and bioreactor after few years of research.

As evidenced in the illustrations, bioreactor cell has had a greater settlement as a result of the degradative processes have occurred more quickly. The good results achieved in the pilot have prompted to perform a demonstration scale test.

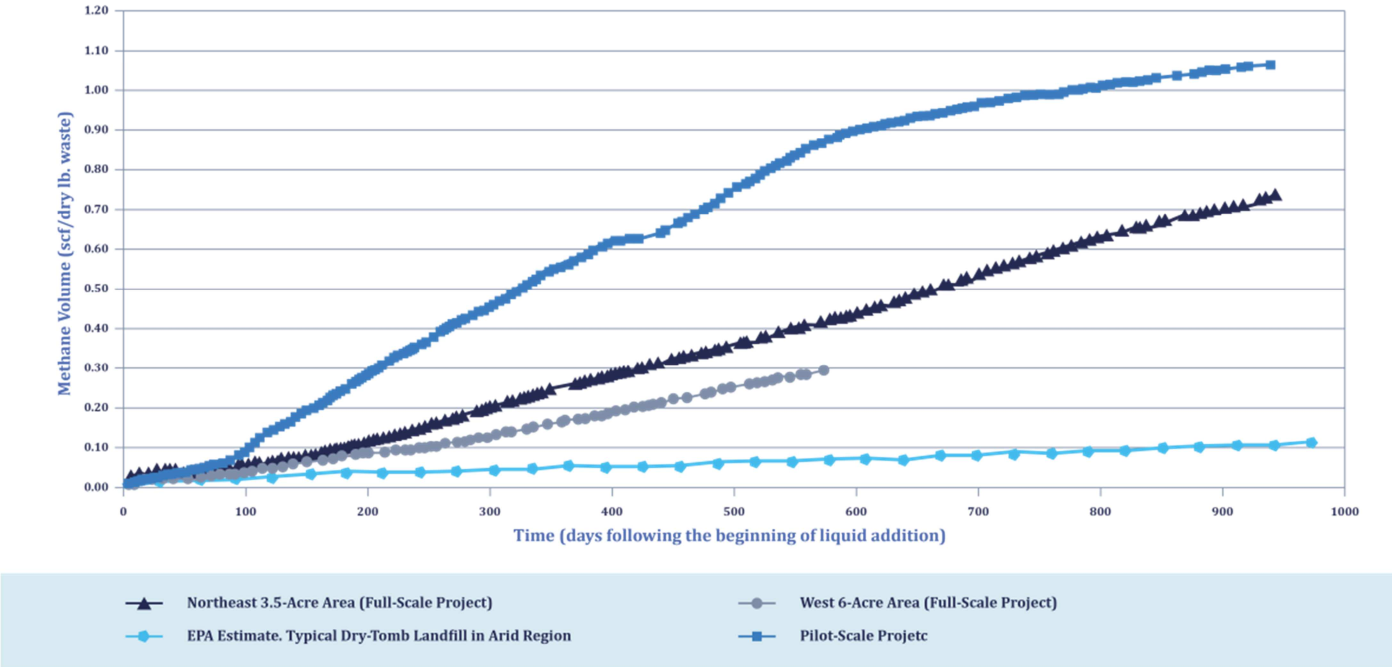
Demonstration Scale

The second phase of the project involved the construction of a 9.5 acre module containing a cell of 6 acres and other of 3.5 acres in the Central Landfill of Yolo County (California). All cells were highly instrumented to control bioreactor performance (humidity sensors, temperature...).

Figure 34 shows the results obtained for the percentage of volume of methane accumulated in all the experiments carried out with cells in anaerobic sensorized Yolo landfill in the framework of the EPA Project XL. In all cases, obtained values were higher than the estimated ones for a cell control (Yazdani, el al. 2005).

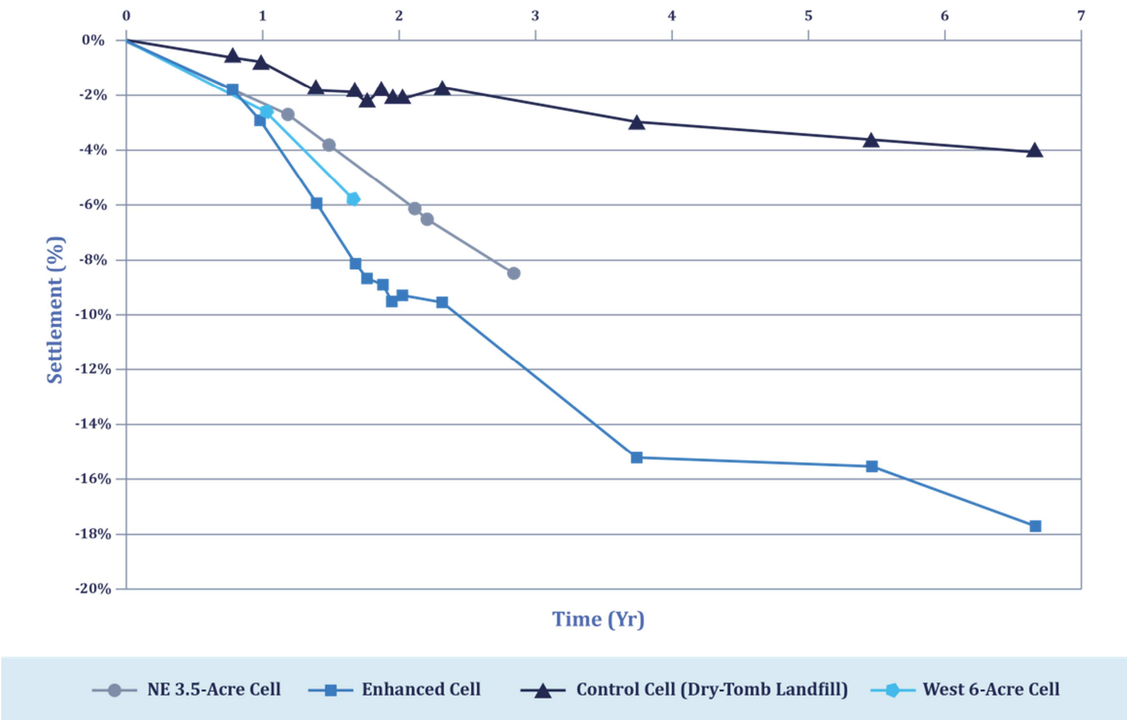
Similarly, **Figure 35** shows the results obtained in relation to the settlements that have occurred in all the experiments carried out in sensorized anaerobic cells in the framework of EPA Project XL. In all cases there is greater settlement in bioreactor cells than in control cell.

As conclusions of the study, we can say that the pilot bioreactor landfill of Yolo County, has behaved as expected in practically all aspects. The main benefits include increased methane capture for energy and preventing methane emissions. This success served as the basis for a large-scale expansion in the landfill itself. The results obtained in larger size cell, confirm again the higher performance achieved in the cells infiltrated with liquid.



Source: Yazdani, 2006. 2007.

Figure 34: Methane accumulated in the control cells and bioreactor. Demonstration Project.



Source: Yazdani, 2006. 2007.

Figure 35: Settlements in the control cells and in bioreactor

Summary of Chapter 6

Among the existing methods for the treatment of waste, dumping is still the most popular option due to low economic costs, social rejection to incineration and existing restrictions for recycle waste. Despite its simplicity compared to other technologies (incineration, gasification), which is one of its advantages, the sanitary landfill does not support improvised acts. It should be regarded as a work of engineering, and as such, it requires a specific project, based on appropriate studies, that allows the appropriate selection of the most suitable solution. A landfill (or filler) is considered healthy when taken all reasonable steps to avoid whatever is harmful or annoying to the environment. According to a World Bank publication on a global review of solid waste management, 59% of the MSW generated in the world are deposited in landfills (Hoornweg and Bhada-Tata, 2012).

When burying waste, the organic fraction contained in them is slowly degraded under anaerobic conditions which make that, over time, biogas is formed inside their pouring platforms in the sanitary landfill. It is convenient to extract this gas not only from an environmental perspective, since it avoids the greenhouse gases emission (GHG), but also because it can be used as an energy source. An installation of biogas extraction landfill consists mainly of catchment wells, associated piping, valves set, control and monitoring equipment, extraction pump, biogas cleaning systems and utilization and using equipment of excess gases and also the energy suppliers that make it all work.

Biogas production depends on several parameters: temperature, humidity index, composition, structure and waste length, use of coverage and design. There are models to estimate the generation of biogas in a sanitary landfill. Of these, the USEPA LandGEM is the most used model in the United States and in a large number of countries (EPA, 2005b). It has been made versions adapted to the characteristics of some countries in LAC (Central America, Ecuador, Colombia, Mexico, see Webgraphy).

The Clean Development Mechanism (CDM) is a tool that has helped finance projects to reduce greenhouse gas emissions in industrialized countries, such as projects related to landfill methane capture. This mechanism has allowed the registration of 7,800 projects and programs in 107 developing countries with hundreds of millions of dollars in investments, which means 1,500 million fewer tons of greenhouse gases released into the atmosphere (IPS, 2014a).

However, currently the instrument of the United Nations to support carbon emissions projects in developing countries; the CDM (in charge of certified emission reductions (CERs)) is in crisis due to the collapse of prices they pay for carbon credits. The price of CERs fell to 0.30 dollars in 2014, compared to more than 30 dollars in 2009. According to the president of the CDM executive board, the source of the problem was the directive of the European Union (EU) of 2009 (to restrict the possibility of international credits and prohibit them altogether from 2020), which came into force on January 1, 2013 (ISP, 2014_a).

For the Alliance of Small Island States (AOSIS), created in 1990, with the main objective of consolidating the voices of SIDS to face global warming, given that financing is a central pillar of the 2015 climate agreement, The current state of the CDM is another worrying issue. From the perspective of the AOSIS, they maintain that the price of CERs can be increased with "green technologies and with incentives for countries to have projects that are more favorable to the environment" through the MDL (ISP, 2014_b). In 2012, the SIDS had 31 projects in the pipeline and 10 registered projects, totaling 8215k CERs. In 2015, 28 SIDS had no CDM projects in preparation (Williams, 2015).

As for bioreactor landfills, the United States have been carrying out in recent years considerable research because of the advantages they have against conventional landfills. An anaerobic bioreactor landfill is an isolated system which favors the microbial degradation of biodegradable waste by adding humidity and controlling the conditions that influence the process. Its operation is based on adding controlled amounts of a liquid to increase the humidity content is the deposited waste in landfills, favoring anaerobic biodegradation by the stimulation of microorganisms. The recirculation of drain effluent (leachate) is the most used. The objective sought is to accelerate the degradation process of biodegradable waste and biogas production achieving stabilization process within shorter time, about 10 years compared to the 30-year duration in conventional landfills. Its main advantages include the reduction of greenhouse gases emissions, to take prior advantage of biogas and to environmentally recover earlier the area. Its main drawback is that it has a higher cost and need better monitoring to control the addition of leachate and landfill stabilization.

Currently in the U.S. there are many research projects related to this technology. EPA is monitoring various landfill bioreactors in order to resolve uncertainties that still exist on the stability of pouring mass, the behavior of the coating and the increased possible emissions since there is greater amount of biogas. One study that has been active for several years is the sanitary landfill of Yolo (California). The good results obtained in pilot cells led to the realization of a demo scale landfill bioreactor in which it was also found that there is a significant difference in the production of biogas and a higher settlement, which confirms that the degradation process has experienced a significant acceleration.

7. Biogas

Biogas is the generic name of the gases produced as a result of anaerobic degradation or organic waste biomethanation, irrespective of the raw material and the technique used. The one produced by the dumping of organic matter of urban waste in landfills is also known in the literature as landfill gas.

Biogas is mainly composed of methane and carbon dioxide. The energetic value of biogas therefore will be determined by the concentration of methane, it is between 20 and 25 MJ/m^3, compared with 33 and 38 MJ/m^3 for natural gas (Werner et al., 1989). Its density is 1.2 kg/m^3, therefore less dense than air and its ignition temperature is 600°C. The biogas composition affects the possibilities for its using, since the methane concentration determines it's PCI and a high concentration of some of its trace components can make it enough corrosive to make unviable its energy using, mainly in engines.

7.1. Characteristics of the main constituents

As discussed, biogas is composed primarily of methane and carbon dioxide. The generated urban waste landfills, due to the variability of the waste organic matter, also contain many other gases that are present in small amounts depending on the composition of the waste, the age of the landfill, site conditions, landfill management and the presence of a biogas collection system (Carreras et al.,, 2005).

The composition and production of biogas and digested substrate depends on the process performance. Considering the heterogeneous composition of the waste (and therefore its energy content), the amount of biogas that can be produced from a particular type of substrate will depend on its chemical composition. As a guide **Table 44** shows the composition of biogas according to the used substrate.

Table 44: Composition of biogas depending on the substrate used

Component	Agricultural waste	Sewage sludge	Industrial waste	Landfill gas
Methane	50-80%	50-80%	50-70%	45-60%
Carbon dioxide	30-50%	20-50%	30-50%	40-60%
Water Hydrogen Hydrogen sulphide Ammonia	Saturated 0-2% 100-700 ppm Traces	Saturated 0-5% 0-1% Traces	Saturated 0-2% 0-8% Traces	Saturated 0-0,2% 0-1% 0,1-1%
Carbon monoxide	0-1%	0-1%	0-1%	0-0,2%
Nitrogen	0-1%	0-3%	0-1%	2-5%
Oxygen	0-1%	0-1%	0-1%	0,1-1%
Organic compounds	Traces	Traces	Traces	0,01-0,6% NMOCs

Source: Modified of Coobs, 1990; Tchobanoglous, Theisen, and Vigil 1993; EPA, 1995 (Landfill Gas).

In general, it can be considered that biogas consists mainly of methane (50-60%) and carbon dioxide (30-40%), with lesser amounts of nitrogen (0-3%), hydrogen (0-1%), oxygen (0-1%), and volatile organic compounds (trace) and hydrogen sulphide (trace). Their average composition is shown in **Figure 36** and is as follows (vol. %):

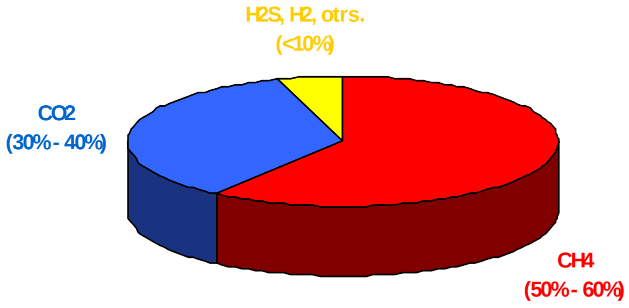


Figure 36: Composition of Biogas

Biogas, because of the methane, has a calorific value of approximately 4500-5600 Kcal/m^3. The calorific value of biogas is determined by the concentration of methane (8,500 Kcal/m^3), and it can be increased by removing all or part of the CO_2 contained in the biogas. The lower calorific value of biogas is about 5,250 Kcal/m^3, for a richness of 60% methane.

The characteristics of the major constituents are listed below.

7.1.1. Methane

Methane is a colorless, odorless and tasteless gas. Its specific mass is less than that of air i.e. 0.717 compared to 1.29 with a PCI of 35.0 MJ/m^3. It is highly explosive, its lower and upper explosion limit in air are, respectively, 5% and 15%. Its solubility in water is about 60 mg/l. Methane gas is not toxic but can cause displacement of oxygen in the soil atmosphere and create a choking hazard. It is a gas that impacts significantly on greenhouse effect, absorbs terrestrial infrared radiation (heat) that would otherwise escape into space, characteristic of greenhouse gases. It is a greenhouse gas 21 times more potent than CO_2. Methane is now more abundant in the atmosphere than in the last 400,000 years and 150% higher than in 1750. The degradation of mismanaged organic matter contributes significantly (at least 5%) to world methane emissions.

7.1.2. Carbon dioxide

From a quantitative point of view, the second most important gas in the composition of biogas is carbon dioxide (CO_2). This gas is odorless, colorless and non-flammable. It is denser than air. Despite its natural "nontoxicity" (some time disputed) carbon dioxide is dangerous to life by displacing oxygen in the respiratory system. It is also a gas with a significant impact on the greenhouse effect.

7.1.3. Minor compounds

Nitrogen (N_2) and Oxygen (O_2): Nitrogen and oxygen, the main constituents of the air, are only present in the landfill gas if atmospheric air has penetrated into the pouring platform.
Hydrogen (H_2): Hydrogen is produced in the early stages of the anaerobic degradation of organic matter. It is a "non-toxic" compound but can act as a simple asphyxiant by displacing oxygen. Hydrogen is the lightest gas and tends to rise quickly to the atmosphere.

Carbon Monoxide (CO): Carbon monoxide is a highly toxic gas. It is colorless, odorless and flammable. It is present in landfill gas in very small concentrations, close to 0.001% vol. and when the waste combustion in absence of oxygen takes place.

Ammonia (NH_3): Ammonia can be produced in trace amounts during the initial stages of the anaerobic degradation. However, it ammonia concentrations of about 30 mg/m^3 can also be found in landfill biogas.

Hydrogen Sulphide (H_2S): Hydrogen sulphide is a very toxic compound and flammable. It also has an unpleasant smell. It is generally emitted in trace amounts; however, if the waste contains large amounts of sulphur compounds, then the production of hydrogen sulphide can be meaningful. Is vital to know its concentration as its presence can affect the chances of energetic using of biogas due to its high corrosive power.

Volatile Organic Compounds (VOCs): These compounds may represent between 1 and 2% of landfill volume, i.e. about 3 mg/m^3. It is important to know these compounds from an environmental viewpoint, since some of these compounds can be hazardous to health in high concentrations. Volatile organic compounds consist of a large number of hydrocarbons, especially alkanes and their oxidation products (aldehydes, ketones, alcohols and esters), as well as aromatic hydrocarbons, halogenated compounds and organ sulfur compounds. The growing interest in air pollution by gaseous products has motivated that extensive research on volatile organic compounds of landfill gas are cited in the literature. It is estimated that up to 350 different trace compounds can be found.

Siloxanes: They are having increasingly presence in the biogas and are cause for concern, not because they are harmful to human health or the environment, but because of technical problems resulting in energy recovery made from biogas, particularly in motors.

7.2. Biogas equivalent to other energy sources

Figure 37 shows value equivalent of BIOGAS with other energy sources

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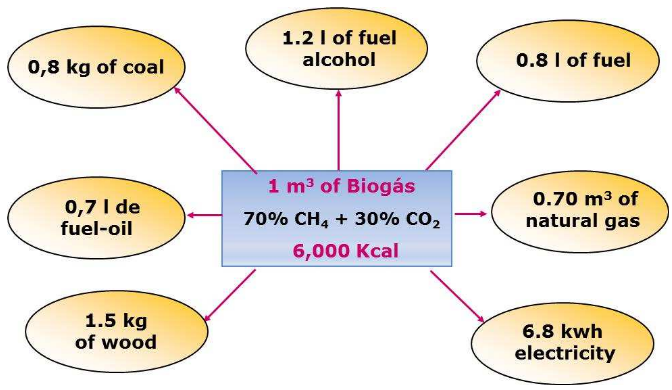


Source: Own elaboration.

Figure 37: Value equivalent of Biogas with other energy sources

7.3. Use of Biogas as Renewable Energy Source

The use of biogas as an energy source is increasing day by day, as renewable energy are gaining more importance as alternatives to traditional sources of non-renewable energy source (oil, gas, coal, etc.). The biogas can use practically the same energy applications developed for natural gas. Its use has evolved over the years. Its first energy applications were in family kitchens and lamps in countries such as China and India.

Table 45 shows the consumption and performance of the major appliances / equipment that use biogas in developing countries.

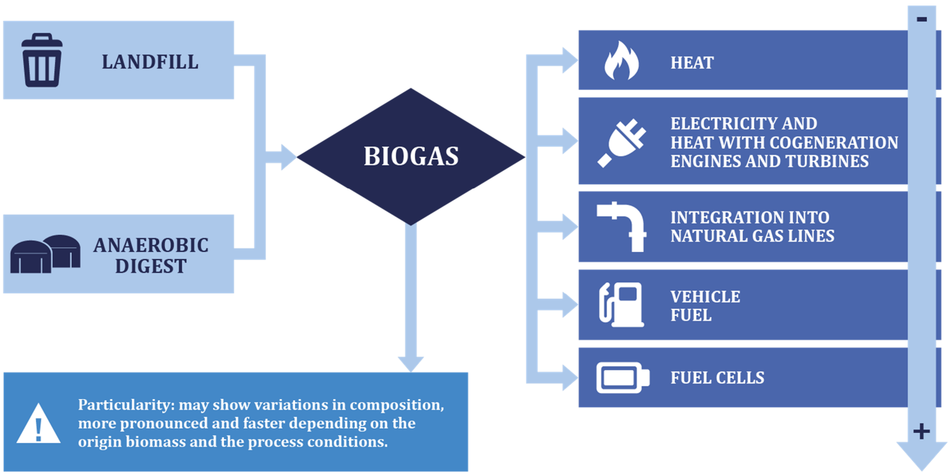
Table 45: Biogas consumption and equipment performance used in developing countries

Appliance	Consumption	Efficiency
Burner cooker	300-600 l/h	50-60%
Gas lamp (60 W)	120-170 l/h	30-50%
Fridge 100 l	30-75 l/h	20-30%
Gas engine	0,5 m^3/kWh	25-30%
10 kW burner	2 m^3/h	80-90%
Infrared 200 W	30 l/h	95-99%
Cogenerator	1 kWe; 0,5 m^3/kWh; 2 kW thermal	Up to 90%

Fuente: Hilbert, 2005.

One cubic meter of biogas in its complete combustion is sufficient to: Generate 1.25 kW/h of electricity; Generate six hours of light equivalent to a 60-watt bulb; Put into operation a refrigerator of 1 m^3 of capacity for 1 hour; Operate an incubator of 1 m^3 of capacity for 30 minutes or Operate a 1-HP motor for 2 hours.

At present time, the applications of greatest interest (**Figure 38**) are: Obtaining direct combustion heat; Engines for power generation with and without heat recovery (cogeneration), cogeneration systems; grid integration of natural gas and Fuel for motorized vehicles. Among these, the most common ones are direct combustion for heat and power generation with cogeneration engines. However, there is a growing interest in other alternatives such as its application as motor fuel and its integration into the natural gas grid.



Source: Prepared by the author based on information collected.

Figure 38: Most important current applications of biogas and degree of refinement

7.3.1. Obtaining heat by direct combustion

The biogas application for obtaining heat by direct combustion is the one that needs fewer requirements in terms of quality, while its application to fuel cells is the one that requires higher level of purity.

Biogas can be used in the generation of heat through combustion. Biogas mixed with air can be burned into a wide spectrum of artifacts mainly decomposed into CO_2 and H_2O.

The complete combustion without excess air and pure oxygen can be represented by the following chemical equations:

$$CH_4 + 2O_2 \Rightarrow CO_2 + 2H_2O$$
$$H_2S + 3/2O_2 \Rightarrow SO_2 + H_2O$$

The minimum requirement of air would be of 21%, but this cipher should be increased to achieve good combustion.

Due to the carbon dioxide content, biogas has a slowly flame propagation velocity, 43 cm/s and therefore the flame tends to escape from burners.

Its applications are: heating and hot water, heating the digesters, incinerating or sterilizing waste from the medical sector, for drying forage and in heaters, gas cookers, lamps or burners-stoves, from both industrial and domestic use.

As referred above, it can also be applied to other devices, such as domestic refrigerators or infrared burners commonly used in the heating of ranching (hatcheries or farrowing crates). Recently, equipment has been developed for milk cooling and/or other agricultural products, which opens an important and profitable field of direct application of biogas.

The main drawback of biogas when used to produce heat is the need to locate the consumer area of this heat as close as possible to the area where it is generated, because due to low calorific value of biogas, it cannot be profitably transported by pipeline. Therefore, it is usual that the heat generated by the combustion of biogas is used in their production facilities.

7.3.2. Electricity generation

This application is certainly the most interesting use that biogas has today. The biogas can be used to generate electricity in three different ways: Combustion engines that are attached to generators of electricity, Turbines or gas microturbines and Stationary fuel cells.

<u>Electricity generation by combustion engines</u>
The biogas can be used as fuel for internal combustion engines, both gasoline (Otto-cycle engines) and diesel (diesel), but first the impurities that can affect the performance and maintenance must be removed. The biogas has an octane rating of between 100 and 110, which makes it very suitable for use in engine of high compression volumetric ratio although, in contrast, it has a low ignition speed.

<u>Electricity generation by gas turbines</u>
The use of gas turbines has increased significantly by being less polluting due to their better performance. This growth has been favored by the increased activity in the gas sector and also for the sustained growth of demand. One advantage of the turbines is that they require less installation time than other equivalent systems, making them highly suitable for rapid development projects. It has higher performance when used in combined cycles.

Despite its good running, it should be noted the strong dependence of these systems on certain parameters such as humidity or pressure, and it determines the power that the turbine can produce and its performance.

Some of its advantages are:

- You can simultaneously produce electricity and heat (cogeneration).
- Practically all heat processes can be recovered (high performance).
- They can operate connected to the electricity grid.
- Low level of pollutants and noise.

- They can work in a combined cycle (gas and steam) to increase its performance.
- They allow the use of low calorific fuels (biogas).

Hydrogen and fuel cells
Continuously declining fossil fuel reserves and the environmental problems associated with their combustion force the search for new energy alternatives. In this context, hydrogen is emerging as a new "energy carrier", i.e. a primary energy carrier to the places of consumption that also offers important advantages. Hydrogen is thus presented as one of the best candidates to be "the fuel of the future". It is possible to obtain hydrogen from renewable energy sources such as wind, solar or hydraulic by the electrolysis of water, forming a completely clean cyclical process. It can also be produced from biomass by thermal or biological decomposition, or by fossil fuels such as gas, oil or coal.

The technologies in hydrogen processes and fuel cells are a promising new field that is aimed towards a new economy called "hydrogen economy" that is expected to be commercial in the coming years and will require a large number of highly specialized technicians in the matter.

7.3.3. Cogeneration systems

These systems look for greater efficiency in the utilization of the energy contained in biogas.

In these cases the mechanical power provided by the motor shaft is used to generate electricity via a generator. Simultaneously, and through a series of heat exchangers located in the motor cooling systems (water and oil) and in the output of the exhaust gas, it recovers heat energy released in the internal combustion. It can be used to heat water for digester heating or for any industrial or agroindustrial use that requires heat energy, thereby better use of energy is achieved than that achieved with conventional electricity generation, where the heat generated in the process is lost.

The main characteristics that must have a biogas engine that generates electric power are:

- A lifetime operating at full load.
- Excellent mechanical degree of efficiency.
- Simple operation and maintenance.
- Ready availability of spare parts.
- Low noise and greenhouse gas emissions.
- Water cooling for it to be utilized for other purposes.
- Capable to operate with biogas with a high content of humidity and traces of other gases besides methane.
- Not containing corrodes metals.

Facilities of electrical energy evacuation

The energy produced by the cogeneration unit has to be transformed and conditioned to its grid feed. The plants that produce electricity for grid feed have a Transformer Center or Substation Lift, when the plant is large and the evacuation power justify the investment.

7.3.4. Integration into the natural gas grid

Biogas should be subject to a process of purification and enrichment to match the characteristics of natural gas, but it is a technology that has proven its viability in other countries, such as Sweden. The biogas produced in these plants (biomethane) has a similar composition to those circulating in the general distribution grid. With this possibility there are new harnessing prospects. Biogas, previously purged to reach the quality requirements of natural gas may be introduced into the distribution grid, because, like natural gas, it is mainly composed of methane and, thereby, its use in large electrical power plants or transport sector.

Among the advantages of this use are:

- Reduced energy dependence.
- Reduced transport costs.
- The grid connects the production area to the areas of higher population density, which allows gas to reach new consumers.
- It is possible to increase production in a remote location and still use 100% of the gas.
- Enhanced local supply security, this is a very important factor because most of the countries consume more natural gas than they produce.

7.3.5. Vehicle Fuel

Along with the generation of electricity, this is the most promising application of biogas. The use of biogas as a transport fuel is similar -technologically speaking- to the use of natural gas.

The biogas can replace the natural gas vehicles powered by this fuel, with prior biogas refining to remove impurities (CO_2, H_2S, NH_3, water and solid particles) and, thus, increase the levels of methane up to nearly 95% (IEA-Bioenergy, 2001). In this regard, two types of technology for refining and cleaning the biogas have been developed for its use as fuel for vehicles:

- Water Absorption (physical absorption).
- Alcanoamin absorption (chemical absorption).

The election of one or another technology depends on the composition of biogas, the capacity of the treatment and the subsequent application of biogas.

Once transformed, the possibilities of use are equal:

- Compressed.
- Liquefied.

It is currently being carried out in Spain AGROBIOMET project, demonstration of a sustainable system of production and use of biomethane in vehicles from livestock waste and biomass alternatives (Rodriguez et al., 2013).

7.4. Energy production from biogas in SIDS

In rural areas of developing countries, the energy applications are generally at a family level, using them mainly for cooking and lighting.

With larger productions, the most obvious applications are the two most commonly used at a general level:

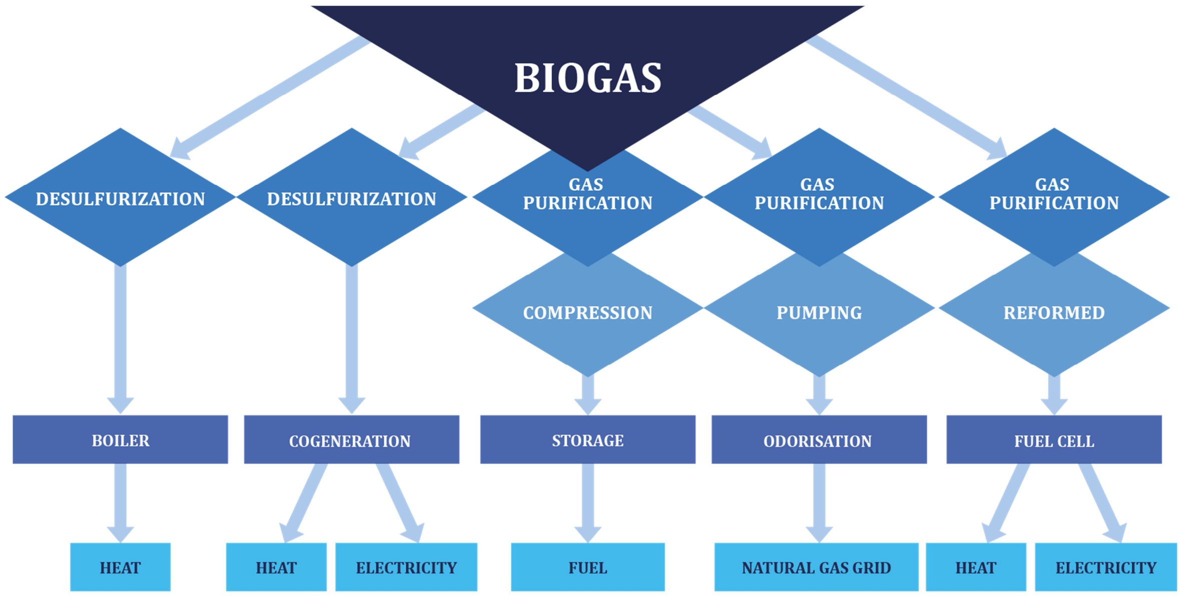
A) Units of gas engine or generator: constitute the most common way to produce electricity from biogas. For small and medium plants, engine-generators groups that can have powers of up to 1 MW are commonly used. In some cases, the heat recovered from the engine cooling and exhaust gases is used for heating. Combined heat systems and electricity (CHP) allow much more efficient using of energy if given proper use to the excess heat recovered. In some larger biogas plants gas or steam turbines are used.

B) The production of heat in a boiler system is another frequently use given to biogas, which can be burned in a furnace or boiler to produce hot water, steam or hot air for heating or drying; the technology to produce energy from units of gas engine or generator and boiler rooms is well known and sufficient knowledge and experience exist in the region in the field as well as spare parts.

7.5. Biogas treatment based on usage

The biogas must be refined previously in any energy applications. In this sense, debug operations vary depending on the use of biogas. **Figure 39** shows the necessary treatment based on the use of biogas.

The quality requirements are higher when used as an automotive fuel, injected into the natural gas distribution lines or used in fuel cells. Biogas purification includes removing CO_2, H_2S, NH_3, water and siloxanes.



Source: Prepared by the author based on information collected.

Figure 39: Necessary treatment to apply to the biogas in terms of its use.

<u>BIOGAS CONDITIONING</u>

Because of its high humidity content and other gases, biogas needs to be treated and conditioned prior to use in cogeneration units. Below are the gas characteristics that need to be upgraded:

- Reduction and/or elimination of H_2S and traces of other gases, purification.
- Reduction of humidity.
- Reduction of CO_2.
- Correction, calibration and pressure control.

7.5.1. Moisture reduction

When biogas goes off 100% saturated with humidity. This problem increases in the summer because of high temperatures. Among the factors influencing the humidity content are: the type of biomass and dissolution percentage. Beside the water vapor, in the stream of biogas solid particles that don't react also travel or which remain inert during biogas production. Both elements are detrimental to the using of biogas, therefore, it becomes necessary to reduce them up to suitable values for the use of biogas as energy material.

Catchment pipes will be installed so that the condensate flows back into the digester or to the condensate discharge point. The minimum slope of installation shall be 5%. A condensing unit will be installed before biogas using at the cogeneration unit. If biogas is cooled at temperatures between 0 and 5°C, the majority of the humidity condenses. These solutions combined with other techniques for reducing H_2S give excellent results and you get a high quality.

The engines using biogas for electricity generation established a maximum humidity content range between 70 and 80% RH depending on the engine manufacturer and the content of foreign particles.

7.5.2. H_2S reduction

Biogas is composed mainly of methane (CH_4) and CO_2 in proportions of approximately 55-65% to 40-45% and traces of other gases such as hydrogen sulphide (H_2S). H_2S content is between 0.1 and 1%. Despite being a small percentage, reducing it is necessary due to the following reasons:

- H_2S toxicity.
- Corrosion of metals by the presence of H_2S and CO_2.
- On the combustion can be formed SO_2, which is highly corrosive.
- Decreased gas calorific power.
- Stimulates the formation of hydrates.

The most common and simple method for the desulfurization of biogas is the injection of small volumes of oxygen inside the digester. It is a process that has been developed effectively in the last 10 years and applied with great success in the purification of biogas in biodigesters all over Europe, but especially in Germany. Sulfobacter oxidizing bacteria convert the H2S into elemental sulphur and hydrogen sulphide and water through the supply of oxygen. During this treatment a sulphur yellow powder yields which is deposited on the surface of the biomass, in the internal walls of the digester, etc. This sulphur powder can be used as fertilizer. The oxygen supply is performed by compressors. If the dosing of oxygen is adequate, a H_2S reduction up to 95% can obtained. The amount of oxygen supplied to the digester is so low that no problems arise in the interior.

7.5.3. CO_2 reduction

When a biogas of higher quality and calorific power is required (for injection to the general distribution grid) the CO_2 content can be reduced. This treatment is especially suitable for large biogas plants where spending on the purification system is justified.

The simpler and more efficient method for the removal of carbon dioxide is its absorption in lime water. This method requires constant vigilance because lime water runs out and is necessary to often replace it. Other chemical solutions can be used but the most economical is the lime water.

Another method is to use another strongly alkaline element as a means of absorption of these gases, such as effluent from micro algae cultivation. Biogas is injected countercurrent in this water so that the water that results from this reaction contains hydrogen carbonate.

7.5.4. Treatment with filters

The biological treatment of polluted gases is established as an alternative to conventional gas treatment, especially when the contaminants compounds are found in a low concentration and the flow to be treated is high. The main component of a biofilter is the medium filter where the biogas unwanted compounds are adsorbed to be further degraded by microorganisms which are formed in the medium.

The biogas is introduced to the filter bed by means of a blower. The filter consists of a tank filled with a filter medium (wood chips, peat moss, volcanic stone, a mixture of several, etc.) conditioner with bulking material (polystyrene particles, stones, etc.) whose role is to give support and, in some cases, as a nutrient source for microorganisms.

Summary of Chapter 7

Biogas derived from a degradative process of organic matter under anaerobic conditions. It consists mainly of methane (CH_4) between 50 and 70% and carbon dioxide (CO_2) between 30 and 50%, plus a number of other compounds present in small amounts as hydrogen (H_2), oxygen (O_2), nitrogen (N_2), hydrogen sulphide (H_2S), volatile organic compounds (VOCs) and siloxanes mainly.

It has many energy applications. In rural areas of developing countries it is used at the family level mainly in kitchens and lamps. In general its main applications are direct combustion for heat production and cogeneration engines producing electricity and heat. Other uses that are becoming increasingly important are its application as a motor fuel and its injection into the natural units of gas grid.

Each application requires some purity requirements, being the least restrictive the use for direct combustion. In cogeneration engines the levels of hydrogen sulphide and siloxanes must be controlled, for corrosion and abrasion problems, respectively. For its use in motor vehicles and to inject it into the grid it must be cleaned to achieve the characteristics of natural gas. Although there are significant differences in cost, there are technologies in the market to apply any of the above uses.

Glossary

Acetogenesis: Stage microbiological where volatile fatty acids (VFA) and alcohols formed in the acidogenesis stage, are degraded to acetate, carbon dioxide and hydrogen by means of fermentative bacteria.

Acid-forming bacteria: Group of bacteria that produce volatile acids in a digester as one of the subproducts of their metabolism.

Acidogenesis: Stage microbiological where amino acids, organic acids and sugars produced in the hydrolysis stage, are converted to alcohols, carbon dioxide, hydrogen and volatile fatty acids (VFA) by fermenting microorganisms, or anaerobic oxidants.

Aerobic: In the presence of oxygen.

Alkaline: The condition in which there is a sufficient amount of alkali to give a pH above 7.0.

Anaerobic: Without the presence of oxygen.

Aerobic Bacteria: Bacteria that live and reproduce only in an environment containing oxygen available for breathing, such as atmospheric oxygen or dissolved oxygen in water.

Alternative daily cover: Material other than soil used to cover the surface of active landfills at the end of each day to control diseases, fires, odors, etc.

Anaerobic bacteria: Bacteria that live and reproduce only in an environment that does not contain oxygen.

Anaerobic contact digester: anaerobic digester in which the microorganisms are separated from the effluent suspension by sedimentation or other means and are returned to the digester to increase the rate of stabilization.

Anaerobic Digester: Reactor which is constructed to degrade organic matter by anaerobic bacteria.

Anaerobic Digestion: Process of degradation and stabilization of organic materials by the action of anaerobic bacteria with the production of biogas (biomethanation). The process is very slightly exothermic (heat- producing).

Active volume: The actual available volume in a digester for bacterial action. It is calculated by subtracting the volume occupied by grit and scum from the volume of the digester occupied by sludge.

Batch-Feed Digester: A digester which retains all the feedstock added in a single charge. Discharge of the entire batch occurs at the end of the retention time.

Benefits: Tangible benefits of a biogas system are those that are easily quantifiable and have a monetary value. Such benefits include the value of the gas and the digested produced. Intangible benefits are those that are not so easily quantified or related to a monetary value. Examples include the value of an improvement in environmental sanitation and odor prevention.

Biogas: Gas generated by composition of organic matter in the absence of oxygen by direct action of methanogenic bacteria, process known as anaerobic digestion. It is a mixture of gases, predominantly methane and carbon dioxide and traces of hydrogen sulphide and ammonia are present in varying quantities.

Biogas collection system: A system that collects the biogas inside the digester and leads to the gas handling system.

Biogas flow meter: The instrument used to measure the volume of the digester biogas flowing to the burner or motor-generator.

Gas handling system: Equipment that removes moisture pressurizes and quantifies volumetrically the biogas flow exiting the digester and goes to the burner and / or electric energy motor generator.

Biogas Plant: A plant used to process organic matter to produce biogas and sludge.

Bioreactor-landfill: A landfill operated as a bioreactor using leachate recycling (or other management schemes) to increase the rate of organic decomposition and biogas production.

Biodigester: Element that allows the anaerobic decomposition of organic matter and the formation of biogas.

Buffer Capacity: A measure of the resistance to changes in pH caused by the compounds in the sludge

Burner: System to carry out the complete combustion of methane, which is generated in the biodigester.

Calorific Value: The amount of heat that can be obtained from a fuel, usually expressed in terms of calories per unit weight (or volume) of the fuel.

Carbon/Nitrogen Ratio (C/N Ratio): The ratio of organic carbon to that of total nitrogen.

Cabutz: The solid fraction remaining after separation of digested slurry from the thermophilic anaerobic digestion of cow manure.

Carbon dioxide (CO_2): The gas resulting from burning or complete oxidizing of any carbon source.

Carbon monoxide (CO): The gas resulting from incomplete burning or incomplete oxidizing of any carbon source.

Compost: Compost here refers to stabilized and screened organic material ready for horticultural or agricultural use. If anaerobically digested material is used as compost, it must be biologically stabilized, typically through aeration and maturation.

Composting: Controlled decomposition of organic matter under aerobic conditions by which material is transformed to humid material. The process is exothermic resulting in a rise in temperature. The process is used to improve the quality of manure as organic fertilizer.

Condensation System: System that removes the moisture contained in the biogas.

Continuous-Feed Digester: A digester which is regularly charged continuously or with small amounts of fresh slurry at short intervals; the freshly charged slurry automatically displaces an equal volume of effluent and the process continues without interruption.

Continuously stirred tank reactor: A digester configuration in which the entire digester contents are mixed to create homogeneous slurry.

Cover Material: Soil used to cover compacted solid waste in a sanitary landfill.

Degradation: The breakdown of (organic) substances by chemical, physical, and/or biological action.

Denitrification: Anaerobic reduction of nitrogen compounds, such as nitrates, to elemental nitrogen.

Detention Time The theoretical period of residence in a given volume or unit. It is normally calculated by dividing the active volume of the unit by the rate of flow of the liquid through it.

Digester: Element that allows the anaerobic decomposition of organic matter and the formation of biogas, i.e. the microbiological process of decomposition of organic matter, in the absence of oxygen takes place in reactors, called digesters.

Digestion: Controlled decomposition of organic substances, usually under anaerobic conditions¨.

Detention Time (or Retention Time): The theoretical period of residence in a given volume or unit. It is normally calculated by dividing the active volume of the unit by the rate of flow of the liquid through it.

Dewatering: Removal of water from solid material by evaporation, filtration, centrifugation or similar techniques, Sludge dewatering is typically the final step for industrial wastewater treatment processes and plants.

Digestate (Digested): Semi-liquid-product resulting from the anaerobic digestion. It has a potential use as organic fertilizer. It can be applied directly, or after separation into two fractions, solid and liquid.

Digester heating system: heat exchanger that allows heat injected into the system to maintain a temperature suitable for the production of biogas.

Digester Slurry: Mixture of fermented organic matter and water.

Dump: A place where waste is dumped in the open in an uncontrolled manner without receiving any sanitary treatment.

Dump controlled: Place for disposal of solid waste, which has the infrastructure befitting a landfill, but with some control measures.

Economically active population: the people who have an occupation or who have not it but are actively looking for it. It is composed of the employed population plus the unemployed population.

Effluent: The sludge or spent slurry emerging from a digester.

Electrical Installation: Set of elements that lead, distribute and use electrical power.

Electricity generation: The process of generating electricity through generator sets that use as fuel the gas mixture (biogas) produced by the digester.

Endothermic reaction: The chemical reaction in which energy is needed (or absorbed from the surrounding) in order it to take place.

Environmental Monitoring: A set of actions for the periodic verification of compliance with the requirements established to prevent environmental pollution.

Exothermic reaction: The chemical reaction in which energy is liberated when takes place.

Enzyme: A complex organic substance (mostly a protein) produced by living cells and having the property of accelerating transformations such as digestion processes.

Facultative: The ability of microorganisms to live under either aerobic or anaerobic conditions.

Fill rate: Approved rate of waste accepted into the site, expressed on a daily operating basis or annual basis (usually in tons).

Final disposal: To deposit or confine waste permanently in different sites and facilities.

Floating gasholder: A biogas container consisting of an inverted open top tank floating over a liquid such as digester slurry or water; it rises when it fills with biogas and sinks as the gas is depleted. The weight of the floating cover controls the pressure of the gas which is discharged from the gasholder.

Footprint: Actual area of a site designated to be filled with wastes.

Gas measuring system: An instrument used to measure the volume of the digester biogas flowing to the burner or motor-generator.

Gasholder: A separate system that receives and stores the gas produced in a digester.

Geomembrane: Synthetic material used as insulation.

Grey waste: The material left over after separation of recyclables and putrescible material from the mixed waste stream. Composed mostly of inorganic material, grey waste usually contains a significant amount of organic material. Depending on its composition, grey waste can be treated biologically or burned prior to final disposal.

Grit: Heavy mineral matter such as sand, gravel, and cinders, often present in digester feedstock which accumulates in the bottom of the digester.

Household solid waste: Solid or semisolid waste exclusively residential home, generated by human activity inside the home.

Hydrogen sulfide: Inorganic acid formed by dissolution and dissociation in water of hydrogen sulfide (H_2S). In gaseous state is known as hydrogen sulfide.

Hydrolysis: Reduced high molecular content biopolymers as polysaccharides, lipids and proteins to simple molecules such as simple sugars, organic acids and amino acids by the action of enzymes produced by facultative aerobic microorganisms in the presence of water.

Hydraulic Retention Time: The average time that a liquid stays in a reactor before it is discharged. It is equal to the active volume of the reactor divided by the flow rate of the liquid entering it. It is usually expressed in days but may be as short as hours.

Hydrogen sulfide: Toxic gas produced by sulfate-reducing bacteria under anaerobic conditions.

Infiltration: Penetration of a liquid through pores or interstices of a ground, underground, or any natural or synthetic material.

Influent: The feeding materials or slurry incoming to a digester.

Inoculant, Inoculum: Any material, such as digested feedstock, that is added to a newly started digester to start the degradation of organic matter and the production of methane.

Inorganic Matter: Material in solution or suspension, such as sand, salt, iron, calcium, and other minerals, which are not degraded by microorganisms.

Liners: An impermeable barrier of plastic and/or dense clay designed to keep leachate inside a landfill.

Lifespan: Period of time in which a process, system or material is capable of providing the service for which it was designed, built or manufactured.

Loading digester: Feeding of digestion process.

Sludge Digester: Fermented organic matter and water Mix. **Manure:** Animal excrete normally fecal matter from livestock.

Manure Slurry: The mixture of manure and water coming from livestock pens.

Organic Matter: Materials which come from animal or vegetable sources. Organic matter generally can be degraded by microorganisms.

Mesophyll: Moderate temperature range, normally between 30-40°C.

Metabolism: The biochemical changes in living cells by which energy is provided for vital processes and activities, and new material is synthesized (catabolism + anabolism).

Methane (CH_4): A colorless, odorless, flammable gas and the main constituent of natural gas, coal gas and biogas.

Methane-forming Bacteria: Group of bacteria in a digester that produce methane using acetate and H_2 as an energy source.

Methanogenesis: Final stage of anaerobic biodigestion process that involves the conversion of carbon compounds to methane by action of methanogenic bacteria.

Motogenerator: Electromechanical device generating electricity using the biogas as fuel.

Motogenerator security booth: Construction that protects wiring and equipment energy use of biogas.

Municipal solid waste: MSW includes all of the solid wastes that are generated from residential (homes and apartments) sources, commercial and business establishments, institutional facilities, construction and demolition activities, municipal services, and treatment plant sites. Hazardous wastes are generally not considered MSW.

Operation Manual: A document that describes the various activities involved in the operation of anaerobic bio-digestion system.

Organic fraction of municipal solid waste: The biogenic fraction of MSW. OFMSW can be removed from the waste stream at the source (source-separation), or downstream by mechanical separation, picking lines a combination of the two. The wood and paper fraction is more recalcitrant to biological degradation and is therefore not desired for biochemical conversion feedstock.

Plug Flow: Movement without mixing in the axial (longitudinal) direction in a digester.

Plug flow digester: A digester in which materials enter at one end and push older materials toward the opposite end. Plug flow digesters do not usually have internal mixers, and the breakdown of organic matter naturally segregates itself along the length of the digester.

Recyclable material: Materials that after serving their original purpose have physical properties by which they can be reused or transformed into new products.

Recycling: An activity, in which certain solid wastes from urban sanitation services are separated, collected, sorted and processed, to reinstate a domestic cycle, commercial or industrial.

Retention filter of hydrogen sulfide: biogas purification system of traces of hydrogen sulphide which contaminates it.

Retention time: The number of days that organic matter or bacteria remain in the digester. See also detention time.

Sanitary landfill: Engineering technique for containment of municipal solid waste. Includes recreation, accommodation and compaction of waste on a bed waterproof, coverage with soil or other inert material at least daily, to control the proliferation of vectors and proper handling of gas and leachate, in order to avoid contamination of the environment and protect the health of the population. The sanitary landfill has engineering project, control at the entrance, weigh and there are no scavengers on the site.

Secondary lagoon: Element for reception and temporary storage of the digester effluent.

Security: Protocol and procedures to follow to install equipment to prevent accidents during operation of anaerobic bio-digestion system.

Side slope: The slope of the walls of the excavation of the digester to the ground.

Sludge: The slurry of settled particles resulting from the process of sedimentation. Mixture of fermented organic matter and water,

Sludge removal: The procedure used to download the digester of settled solids in the process.

Slurry: A mixture of manure and water from livestock pens.

Solids retention time: The average length of time solid material remains in a reactor. SRT and HRT are equal for complete mix and plug flow reactors. Some two-stage reactor concepts and UASB reactors decouple HRT from the SRT allowing the solids to have longer contact time with microbes while maintaining smaller reactor volume and higher throughput.

Suspended Solids: Solids that are in suspension in water or other liquids.

Specific gas volume: Daily volume of biogas produced per unit volume of digester.

Stirring system: System which causes turbulence in the digester.

Supernatant: Liquid removed from settled sludge. Supernatant commonly refers to the liquid between the sludge in the lower portion and the scum on the surface of an anaerobic digester or the liquid material left after separation of the slurry.

Technical specifications: Set of technical elements that regulate the design, construction and operation of systems Biodigestion. Technical Specifications Biodigestion Systems.

Thermophilic: Digestion at a relatively high temperature, normally in the range of 50-70°C.

Thermofusion: Phenomenon of heat welded of in sanitary landfill geomembrane.

Toxicity: A condition that will inhibit or destroy the growth or function of a living organism.

Total Solids: The sum of dissolved and suspended constituents in a sample; i.e. the amount of solid material (or dry matter) remaining after removing moisture from a sample. Usually is expressed in milligrams per liter or as a percentage of the as-received or wet weight. Moisture content plus TS (both expressed as percentage of wet weight) equals 100 percent.

Volatile Acids: Short chain (Cl - C2) fatty acids which are produced by acid forming bacteria.

Volatile solids: The amount of combustible material in a sample (the remainder is ash). The value is usually reported as a percentage of the TS, but may occasionally be given as a fraction of the wet weight. VS are used as an indicator or proxy for the biodegradability of a material, though recalcitrant biomass (i.e., lignin) which is part of the VS is less digestible. Because of the simplicity of the measurement procedure, it is commonly reported in the AD literature.

Waste collection system: Pipes system installed to drive waste to the digester.

WAAR ACT 2001 No 58= An Act to promote waste avoidance and resource recovery; to establish Resource NSW; to repeal the Waste Minimisation and Management Act 1995; to amend the Protection of the Environment Operations Act 1997; and for other purposes.

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Acronyms

A

AD= Anaerobic digestion.
ADEME = Environment Agency and Energy Management (Agence de l'environnement et de la maîtrise de l'énergie).
AEBIG = Spanish Association of Biogas (Asociación Española del Biogás).
AEE = Energy Agency of Extremadura (Agencia Extremeña de la Energía)
AEMA = European Environment Agency (Agencia Europea del Medio Ambiente)
AIDIS = American Association of Sanitary and Environmental Engineering (Asociación Interamericana de Ingeniería Sanitaria y Ambiental).
AIMS = Africa, Indian Ocean, Mediterranean and South China Sea
ALC = Latin America and the Caribbean (América Latina y el Caribe).
APD = Absolute pressure in the digester.
APHA = American Public Health Association.
ASAE = American Society of Agricultural Engineers.
ASTM = American Society for Testing and Materials.
AWWA = American Water Works Association.

B

BID = Inter-American Development Bank (Banco Interamericano de Desarrollo).
BMP = Biochemical Methane Potential.
BOD = Biochemical Oxygen Demand.
BOD5 = 5-day Biochemical Oxygen Demand. The standard oxidation (or incubation) test period for BOD is 5 days at 20 degrees Celsius (°C).
BTU = British thermal unit (a standard unit measure of energy).

C

CAA = Clean Air Act.
CARICOM = Caribbean Community.
CDM = Clean Development Mechanism.
CEDECAP = Demonstration and Training Center in Technology (Centro de Demostración y Capacitación en Tecnologías Apropiadas)
CEPAL = Economic Commission for Latin America and the Caribbean (Comisión Económica para América Latina y el Caribe).
CERs = Certified Reduction Emissions.
CHP = Combined heat and power.
CIPAV = Centre for Research on Sustainable Agricultural Production Systems (Centro para la Investigación en Sistemas Sostenibles de Producción Agropecuaria).
CMNUCC = Convention United Nations Framework on Climate Change (Convenio Marco de la Naciones Unidas sobre el Cambio Climático).
C/N = Carbon/nitrógen ratio.
COD = Chemical oxygen demand.
CS = Colloidal solids.
CSTR = Continuous stirred-tank reactor.

D

DM = Dry matter.
DS = Dissolved solids.
DSW = Domestic solid waste.

DW= Domestic waste.

E
EC = European Community.
EGBS = Esxpanded Granular Sludge Bed.
EPA = Environmental Protection Agency of the U.S. federal government (USEPA).
EPER = European Pollutant Emission Register.
EWB = Engineers without borders.

F

FAO = Food and Agriculture Organization.
FMAM= Fund for the Global Environment (Fondo para el Medio Ambiente Mundial).
FSM = Federated States of Micronesia.
FvB = German biogas association (Fachverband biogas).

G

GHG = Greenhouse gas.
GEF = Global Environment Facility.
GPA = Global Programme of Action.
GTZ = German Organization for Technical Cooperation (Deutsche Gesellschaft für Technische Zusammenarbeit).
GWP = Global-warming potential.

H

HDI = Human development index.
HDPE = high density polyethylene.
HLB = Huanglongbing (also known as citrus greening, is a serious bacterial disease that affects citrus).
HRT = Hydraulic retention time.

I

IC = Internal Circulation.
ICV = Inferior Calorific Value.
IDAE = Institute for Diversification and Saving of Energy (Instituto para la Diversificación y Ahorro de la Energía).
IDB = Inter-American Development Bank.
IFPRI = International Food Policy Research Institute.
IICA = Inter-American Institute for Cooperation on Agriculture (Instituto Interamericano de Cooperación para la Agricultura).
ILRI = Internatinal Livestock Research Institute.
INIA = National Institute of Agricultural Innovation Cajamarca – Peru (Instituto Nacional de Innovación Agraria de Cajamarca – Perú).
IOC= Indian Ocean Commission.
IPCC= Intergovernmental Panel on Climate Change.
ISF = Engineers without borders (Ingenieros sin fronteras).
ISIS = Institute of Science in Society.
ISWA = International Solid Waste Association.
ITDG = Diversified Technical Institute Grajales (Colombia) (Instituto Técnico Diversificado Grajales (Colombia).
ITRC = Interstate Technology & Regulatory Council.

L

LAC = Latin America and the Caribbean.
LFGE= Landfill gas energy.

M

MS = Mineral solids.
MSS = Minerals suspended solids.
MSW = Municipal solid waste.
MWW = Municipal waste water.

N

NGDOs = Non-governmentals Development Organizations.
NGO = Nongovernmental Organizations.
NMOCS = Non-methane organic compounds.
NREL = National Renewable Energy Laboratory.
NSS= National Statistical Systems.
NSW= New South Wales

O

AOSIS= Alliance of Small Island States.
OFMSW = Organic fraction of municipal solid waste.
OLR = Organic loading rate (kg VS/(m3.d)).
OPS = Pan American Health Organization (Organización Panamericana de la Salud).

P

PAHO = Pan American Health Organization.
PIF = Pacific Islands Forum.
PFR = Plug-flow reactor.
PNG = Papua New Guinea.
PVC = Polyvinyl chloride.

S

SIDS = Small Island Developing States.
SRT = Solids retention time.
SRTlim min = Solids residence time minimum.
SS = Suspended solids.
STP = Standard Temperature and Pressure.
SWD: Solid waste disposal.
SWH= Solid waste home.

T

TOC = Total organic carbon.
TPC = Technology Performance Certificate.
TS = Total solids.

U

UASB = Upflow anaerobic sludge blanket.
UN= United Nations.
UNDP = United Nations Development Programme.
UNEP= United Nations Environment Programm.

UNO: United Nations Organization.
UPC = Polytechnic University of Catalonia (Universidad Politécnica de Cataluña).
US = United States.
USAID = United States Agency for International Development.
USEPA = United States Environmental Protection Agency.
UV = Ultraviolet.
UW = Urban waste.

V

VFA = Volatile fatty acids.
VOC's = Volatile organic compounds.
VS = Volatile solids.
VSS = Volatile suspended solids.

W

WAS = Waste activated sludge.
WARR = Waste Avoidance and Resource Recovery
WAAR ACT 2001 No 58= An Act to promote waste avoidance and resource recovery; to establish Resource NSW; to repeal the Waste Minimisation and Management Act 1995; to amend the Protection of the Environment Operations Act 1997; and for other purposes. This Act promotes waste avoidance and resource recovery to achieve a continual reduction in waste generation. The Act provides for the development of a state-wide Waste Strategy and introduces a scheme to promote extended producer responsibility for the life-cycle of a product.

WBG = World Bank Group.
WH = Waste house.
WPA= World Program of Action.
WWTP = Wastewater treatment plant.

Symbols and Abbreviations

y = year
aprox. = approximately
ºC = grades Celcius
cal = calories
d = day
D = diameter
ºF = degrees Fahrenheit
ΔG^o = Standard Gibbs free energy
(g) = gas
g = gram
H= height
inhab. = inhabitant
% = percentage
J = July
kg = kilogram
kcal. = kilocalories
kg VS = kilograms of volatile solids
L o l = litter
log = logarithm base 10
m = metro
m.a.s.l. = meters above sea level
mg = milligram
MJ = July mega
m.o. = microorganisms
µg = micrograms
µm = micrometer
N = newton
n.d. = not determined
Qw = volumetric flow rate, out (m^3/d)
Q = flow (m^3/d)
ρ = density (kg/m^3)
P = pressure
ppm = parts per million
s = second
T = temperature
temp. = temperature
V = volume

Formulas and chemical symbols

C = carbon
Cu = copper
CO_3^{2-} = carbonate ion
CO_2 = carbon dioxide
CH_4 = methane
CH_3OH = methanol
C_2H_5OH = ethanol
$C_3H_6O_3$ = lactic acid
CH_3COOH = acetic acid
CH_3CH_2COOH = propionic acid
$CH_3CH_2CH_2COOH$ = butyric acid
C6H12O6 = glucose
N = nitrogen
NH3 = ammonia
P = phosphorus
S = sulfur
H2 = hydrogen gas
O2 = oxygen gas
H2O = water
H2S = hydrogen sulphide
K2O = potassium oxide
P2O5 = phosphorus pentoxide
SO2 = sulfur dioxide
CaCO3 = calcium carbonate
NaCO3 = sodium carbonate

Carreras, N.