Sustainable Biodigesters design for Low-income Communities

Sebastian Hugo Rimmele

Thesis to obtain the equivalent course from ITBA Buenos Aires, Argentina

Final Project

Supervisor(s): Doctor Ana Filipa da Silva Ferreira

Examination Committee

Chairperson: Professor Susana Isabel Carvalho Relvas

Member of the Committee: Professor Paulo Brito, Doctor Ana Filipa da Silva Ferreira

June 2022

Abstract

Economical, simple, and integrated technologies such as biodigesters are a great tool for developing countries that have yet to provide basic services such as gas, and electricity to all population. In the following thesis, a proposal for a *family size, single-stage, wet, co-digestive, semi-continuous, high-rate,* digestion system capable to supply gas basic needs for a family of four people is developed.

This dissertation explores and presents the basic principles and updated technologies involved in the biogas generation process that could be applied and implemented in areas of informal housing.

Specifically focusing on the north Argentinian region, where basic resources are scarce but organic waste abounds, the target user group is defined by a family of four members, the estimated gas basic daily consumption is considered as 600L per group and the annual temperature of the region is within the mesophilic range.

The mathematical model shows that under normal working conditions and feedstock availabilities, the maximum amount of gas that can be obtained per day for a fixed 400L volume digester is equal to 583L, just by using pig manure and fry fat/oil. Digester performance could be improved by adding a manual mixer by a 7,56%, thus, producing a daily amount of gas equivalent to 627L.

Families could save over 4% of their monthly income by having a biodigester, and the Argentinian government could save over U$S132 million a month in the long term. Unit cost is estimated at U$S460 without considering installation.

KEYWORDS: *Social impact, biodigesters, developing countries, informal housing, biogas, family size.*

Resumo

Tecnologias económicas, simples e integradas como os biodigestores são um grande instrumento para os países em desenvolvimento que ainda não forneceram serviços básicos como o gás, e electricidade a toda a população. Na tese seguinte, é desenvolvida uma proposta para um sistema de digestão de tamanho familiar, mono-estágio, húmido, co-digestivo, semi-contínuo, de alta taxa, capaz de suprir necessidades básicas de gás para uma família de quatro pessoas.

Esta dissertação explora os princípios básicos e tecnologias actualizadas envolvidas no processo de geração de biogás que poderiam ser aplicadas e implementadas em áreas de habitação informal.

Centrando-se especificamente na região norte da Argentina, onde os recursos básicos são escassos mas os resíduos orgânicos abundam, o grupo alvo de utilizadores é definido por uma família de quatro membros, o consumo diário básico estimado de gás é considerado como 600L por grupo e a temperatura anual da região está dentro da gama mesófila.

O modelo matemático mostra que em condições normais de trabalho, a quantidade máxima de gás que pode ser obtida por dia para um digestor fixo de 400L é igual a 583L, utilizando estrume de porco e gordura/óleo para fritar. O desempenho do digestor poderia ser melhorado adicionando um misturador manual em 7,56%, produzindo assim uma quantidade diária de gás equivalente a 627L.

As famílias poderiam poupar mais de 4% do seu rendimento mensal, e o governo argentino poderia poupar mais de U$S132 milhões por mês a longo prazo. O custo unitário é estimado em U$S460 sem considerar a instalação.

PALAVRAS-CHAVE: Impacto social, biodigestores, países em desenvolvimento, habitação informal, biogás, dimensão da família.

Table of contents

List of figures

List of tables

List of Acronyms and Abbreviations

AD anaerobic digestor

NGO non-governmental organization

LNG liquified natural gas

OLR organic loading rate

HRT hydraulic retention time

COD chemical oxygen demand

BOD biological oxygen demand

VFA volatile fatty acids

C/N carbon-nitrogen ratio

FW food waste

CM cattle manure

TS total solids

VS volatile solids

LHV lower heating value

WW wet weight

AR$ Argentinian currency

U$S United States dollar

CH_4 methane gas

CO_2 carbon dioxide

NH_4^+ ammonium

NH_3 ammonia

H_2O water

H_2 hydrogen

$CaCO_3$ calcium carbonate

C carbon

N nitrogen

P potassium

S sulfur

°C celsius degrees

HP horsepower

KWh kilowatt per hour

mm millimeters

cm centimeters

m meters

m^3 cubic meters (volume)

in inches (25,4 millimeters)

pH acidity and alkalinity of substances

kg kilograms

mg milligrams

GDP gross domestic product

IWA international workshop agreement

WBA world bioenergy association

WHO world health organization

ISO international organization standardization

IAP carbon

GHG greenhouse gases

INTA national institute of agriculture technology

IGN national geographic institute Argentina

GNEA northeast Argentine gas pipeline

SMN national meteorological service Argentina

DCV daily charging volume

BOD biological oxygen demand

1 Introduction

1.1 Motivation

The lack of infrastructure in the existent energy matrix of emerging countries is a reality that must be addressed. Using education, technology, and engineering applied to energy projects with charitable and social purposes can generate a great impact on the lives of families living in marginalized, low-income, and without access to basic resources areas. Bioenergy could be one of the main options to address these problems that are not only present in northern Argentina, but worldwide.

Anaerobic digestion has been gaining popularity around the world in recent decades. One of the main reasons is this technology brings the possibility for low-income families that are far from urban areas of being self-sufficient in energy matters to meet their basic daily needs. Other relevant factors, such as the education on how technology and engineering can simplify the way of living in these regions, taking care of global warming and water napas. Moreover, it is changing the perception of what is called “trash” that is being started to see it as a resource that could be converted into natural fuel to heat homes, water, and food.

Having had the possibility, to be part of works and activities with solidarity purposes, to get a closer look at the reality that people live every day in low-income regions without access to basic resources, and after being involved in two NGOs from different fields such as support education in low-income neighborhoods, charity events performance and visiting several neighborhoods from the northern Patagonian region, made biodigesters as a good alternative to address the problem of the lack of gas network structure in the country.

1.2 Introduction and Background of Biogas

Why the implementation and development of new technologies such as biodigesters are necessary? In most developing countries, cooking and heating in homes is a dirty and time-consuming job that involves burning solid fuels to produce fire. It is estimated that around the world, 3 billion people are burning solid fuels, including biomass, agricultural residues and charcoal, for their daily cooking and heating needs [1]. Worldwide, solid wood fuels used for cooking and heating, represent around the 55% of global wood harvest and 9% of primary energy source. However, about 50% of the wood fuel harvest is unsustainable [2]. Effects of utilizing solid fuels on a regular basis may have major consequences for its users. i.e. cooking in a home over a three-stone fire is comparable to smoking 400 cigarettes in an hour, releasing hazardous smoke and pollutants that mostly damage women and children. It is known that worldwide about 70,000 people is dyeing per year because of household air pollution [3]. Thus, cooking with solid fuels is also a difficulty, as inefficient cooking systems have a significant impact on health, the environment, and the economy. The overdependence on solid fuels as primary source of cooking fuel has led to global climate change, and environmental pollution, and thus leading to human health problems [4]. The continued use of solid fuels causes long-term health concerns, particularly among the household's women and children. In addition to major contribution to climate change, environmental pollution and health, global depletion of solid fuels has led to the search for alternative sources of energy. Improvement of renewable and sustainable energy source is the best strategy to meet developing countries energy demand.

According to studies, biogas has surpassed coal as the world's fourth largest source of energy [5] and has been used to address a variety of current social and environmental issues, including food security, waste management, water protection, soil health restoration, improved air quality, and health, sanitation, and education. As the world's population grows, the health of billions of people depends on properly managing trash in cities and urban regions, particularly food waste and sewage.

Biogas generation, in technical terms, is a natural process that occurs spontaneously in an anaerobic (i.e., oxygen-free) environment. Microorganisms create and trigger this process as part of the organic matter biological cycle, which involves the fermentation or digestion of organic matter to produce various gases and microbial-rich liquid fertilizers.

Bioenergy power generation may originate from a number of feedstocks and employ a variety of thermochemical methods. These range from well-established commercial types with a long track record and a diverse selection of vendors to less well-established and novel technology. The latter includes methods like atmospheric biomass gasification and pyrolysis, which are still in the early stages of research but are already being tested on a commercial scale. Direct combustion in stoker boilers; low-percentage co-firing; anaerobic digestion; municipal solid waste incineration; landfill gas; and combined heat and power are examples of mature technology.

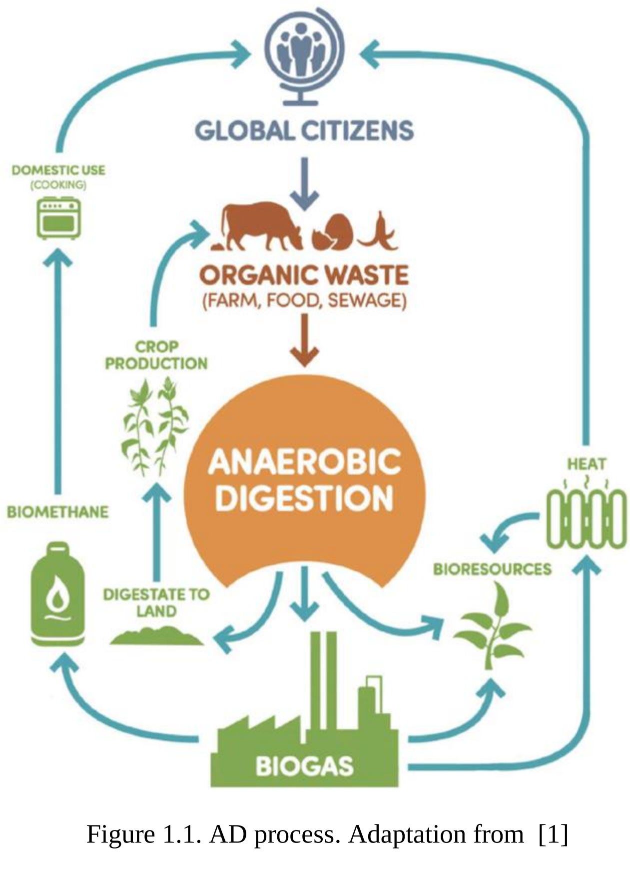

Figure 1.1. AD process. Adaptation from [1]

Composting and digesting are two common ways of processing biodegradable materials, such as organic wastes. Many people believe these are two separate procedures, however, they are both degradation processes carried out by living organisms that change the materials through chemical reactions. There are inputs, outputs, and by-products in every process. The materials being treated (feedstocks) are the inputs, which include sludges, manures, food scraps, and so on. The outputs are those products with real or potential revenue value (compost, energy captured from composting piles or derived from biogas, and some digests). The by-products are process outputs with real or perceived negative value (gases/odors, leachate, and some digests). The complete Anaerobic Digestion cycle can be seen in Figure 1.1.

Biodigesters are systems that maximize the generation of biogas from agricultural wastes, manure, or industrial effluents, resulting in clean, low-cost energy from a sustainable source. The use of this technology is not new, but over the last few years, it has gained interest due to the current energy crisis resulting from the exhaustion of fossil fuels. In addition, the use of biogas helps reduce emissions of greenhouse gases such as methane (CH_4), whose potential for global warming is 23 times higher than carbon dioxide (CO_2) [6].

Biogas is utilized as a car fuel in nations such as Germany and France. However, in countries like Costa Rica, Argentina, and other developing countries, the use of biogas has been limited to those locations where it is produced, where it may be used directly for combustion for cooking or lighting, or indirectly, to drive internal combustion engines that generate engine or electrical power [7,8].

1.3 Digester composting conditions

When building a biogas facility, selecting the correct biogas digester is critical. As a result, knowing the difference between aerobic and anaerobic composting conditions is critical. Both methods handle decomposition, which is carried out by biological creatures that use chemical reactions to change the materials. Each procedure has advantages and disadvantages, and they may be combined to improve the value proposition of recycling organic materials. Composting and digesting have different processes for converting inputs to outputs, according to the presence or lack of oxygen. Because composting is an aerobic process, oxygen is required for success. Digestion can be aerobic or anaerobic, although it is most commonly set up as an anaerobic process to produce and capture methane-rich biogas (aerobic digestion is used in some sewage sludge treatment schemes for stabilization and pasteurization, but is very energy-intensive).
As an example, the biodegradation of simple sugar (glucose) will be considered, both aerobically (eq.1) and anaerobically (eq.2) [9] :

$$\text{Biopolymer} + O_2 \rightarrow CO_2 + H_2O + \text{biomass (microbes)} + \text{intermediates/residues} \quad \text{(eq.1)}$$
$$\text{Biopolymer} \rightarrow CH_4 + CO_2 + \text{biomass (microbes)} + \text{intermediates/residues} \quad \text{(eq.2)}$$

In composting, glucose is converted to carbon dioxide and water; in indigestion, that glucose is converted to carbon dioxide and methane.

More complex polymeric molecules, such as proteins, carbohydrates, and lipids, are similarly biodegraded by several different types of microbes in each system. Composting systems use bacteria, fungi, and actinomycetes, with minor roles from other protists such as algae and protozoa. Digestion systems use fermentative microbes (acidogenic), hydrogen-producing, acetate-forming microbes (acetogenins), and methane-producing microbes (methanogens). These organisms excrete enzymes (lipases, proteases, cellulases, amylases, etc.), which hydrolyze their respective polymers into smaller molecules.

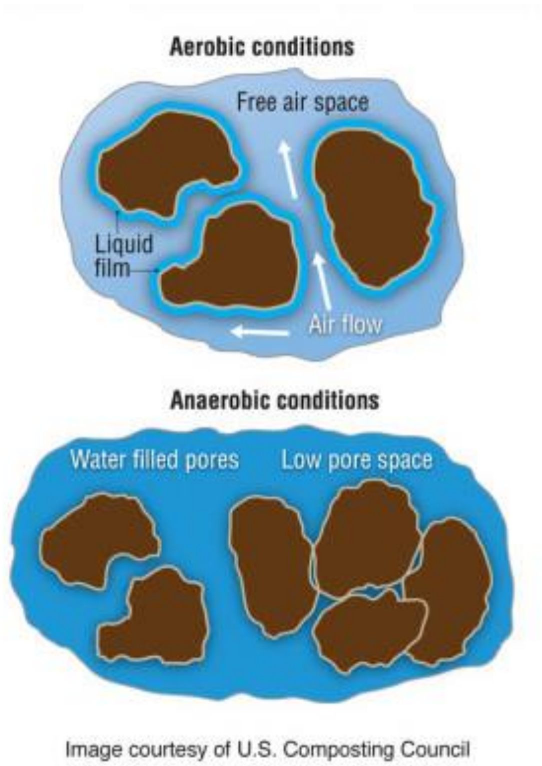

Figure 1.2. Aerobic and anaerobic conditions
(Image courtesy of U.S. Composing Council) [7].

Another major difference between aerobic composting and anaerobic digestion is moisture content. Composting is most efficient with a moisture content of around 50%, which enables the formation of a biofilm around each particle in the compost pile (Figure 1.2). Air moves through the structurally porous compost pile and transfers across the water layer boundary to provide air to the microbes living on the surface of the particle. Digestion systems operate best at 100 percent moisture content so that all pore spaces between the particles are filled and no air can get to the anaerobic microbes as seen in Figure 1.2. Composting is most efficient (with regard to processing times) at particle sizes between a half-inch (12,7 mm) and two inches (50,8 mm). Smaller particle sizes provide the best digestion efficiency (as measured by biogas production rates and volumes). One study measured a 20 percent increase in biogas production between ~0.4 inches (10 mm) and ~1.2 inches (30 mm) [10].

1.4 Clean and improved heating and cooking

Cooking solutions that reduce the negative health, environmental, and economic consequences of cooking with traditional solid fuel technologies, even if only somewhat. Clean and improved cooking solutions reduce emissions, improving people's health and the environment [1].

The IWA (International workshop agreement) tiers for indoor emissions are consistent with the WBA (World Bioenergy Association) and WHO (World Health Organization) indoor air quality guidelines. Cooking solutions with low total emissions (ISO Tier 3–4 for the total emissions indicator) are considered clean for the environment within the Global Alliance’s monitoring and evaluation framework [11–13]. These clean and improved solutions can include advanced biomass cookstoves, renewable fuel solutions, and modern fuel stoves.

Table 1.1 Negative impact of solid fuel cooking [14].

Health	Broad range of health conditions associated with IAP. Burns suffered by household members from traditional fuels/cooking appliances. Chronic and acute physical ailments due to firewood collection.
Environment	GHG emissions due to the use of inefficient fuel production and consumption. Catalytic warming effects of black carbon emissions tied to solid fuel cooking. Forest degradation and deforestation due to fuel collection and production. Foregone agricultural productivity due to habitat degradation and combustion of dung as fuel.
Economic	Avoidable spending on fuel due to reliance on inefficient fuels and stoves. Lost opportunities for income generation from time spent on fuel collection. Lost opportunities for income generation due to time spent cooking
Gender	Disproportional effects on women and young girls including: • Health effects including IAP, burns, and firewood collection injuries • Reduced leisure time • Reduced opportunities for market employment and resulting status in household • Violence during wood collection
Other Social Effects	Reduced access to education due to impaired child health and time spent on fuel collection. Negative aesthetic effects (e.g., poor lighting and soot-darkened home environment). Poorer nutrition due to partly prepared food or reduced food budgets Increased poverty due to diversion of scarce resources to pay for fuel.

Biofuel cookstoves powered by ethanol and other plant-based liquids, oils, or gels; biogas cookstoves; solar cookers; and retained heat equal to or even exceed the performance of modern fuel cookstoves in terms of environmental impact because of their very low emissions and reliance on renewable fuel sources. For climate and environmental impacts, the lifecycle effects of the production and distribution of renewable fuels should also be considered. Some of the renewable cooking solutions are supplementary in nature; they can augment existing household cooking solutions as part of an integrated cooking system but sometimes are unlikely to serve as primary stoves or fuels.

1.4.1 Solid fuels for cooking

Over half of the world's population lives in families that cook primarily with wood, charcoal, coal, agricultural waste, and dung, and this number is rising or remaining stable in most regions. Dependence on solid fuels, potentially harmful modern fuels such as kerosene, and inefficient and polluting cookstoves are one of the world’s major public health challenges, causing more premature deaths than HIV/AIDS, malaria, and tuberculosis combined [1].

Worldwide, solid fuels, including wood; charcoal; coal; animal dung; crop waste is the primary cooking and heating energy supply for more than 3 billion people, particularly rural poor households in developing countries. As can be seen and stated in Table 1.1, a high degree of reliance on conventional solid fuels and unimproved or marginally improved cookstoves imposes enormous health, environmental, economic, and social costs on developing nation households and economies.

1.5 Objectives

The role of engineering and innovation as a factor to solve human and environmental problems is known to be very important.

The aim of this thesis is to gain an understanding on how a simple model of a small sized familiar biodigester could help thousands of people living in rural areas, more specifically in northern Argentinian region, aiming to solve some of their daily problems like heating food, water, homes during winter, obtaining fertilizer, not contaminating their napas or avoiding diseases due to burning wood indoor and living in a healthier environment just by using the organic waste they are producing; to provide a critical analysis of the recent advancements in biogas and biomethane technologies, with special attention to the integration with low income communities and their possibilities.

The current development of biogas and biomethane resources can be addressed using a schematic approach which involves several aspects. The method used in this work is to analyze the most innovative solutions regarding the above-mentioned aspects of the biogas production and finally elaborate a possible and real implementation for an specific area situated in the north of Argentina considering its cost and benefits.

Some research questions were made to develop this work are:

1. What are the technologies (variants and materials) being used for small AD systems in rural areas to recover nutrients and energy?
2. What are the system models integrating production of gas/energy, clean water and nutrients, and where are they being used?
3. How do these models operate and how are they maintained, and consequently, which are the advantages and disadvantages of each of them?
4. How can this technology be applied to supply a low-income, rural located, four members family with a daily amount of gas equivalent to at least 600L?
5. Which would be the impact of implementing this kind of technology in the purposed areas?

1.6 Thesis structure

Figure 1.3. Organizational diagram for thesis development. Own elaboration.

The present thesis is divided into six chapters. Chapter 1, which is the current chapter, entitled Introduction, is where the motivation, topic overview, background, digestion classification and objectives and thesis structure are explained.

Chapter 2, Conventional (AD) biogas generation, contains some more detailed context about AD, theoretical background and literature review. This chapter is composed of six sections that cover all relevant background information. And at the end the state of art is introduced.

Chapter 3, Methodology, is where the procedure followed in this work is explained together with the results and the analysis of the results. It starts with spatial analysis, followed by design considerations and the mathematical model.

Chapter 4, technical aspects, introduce the daily working procedure and technical aspects to consider while working with the schematized model in the previous chapter.

Chapter 5, discussion, consists of the presentation of the results of this work as well as their interpretation and discussion. Energetic, economic, and social analyses are also done.

Lastly, in chapter 6, the Conclusions, the most important results are listed, and the main conclusions of this work are presented. Additionally, some recommendations for future work on this topic are made.

2 Conventional (AD) Biogas generation

2.1 Introduction

During this chapter an explanation of what is an AD will be made in order to understand how it works, what are the variables involved including a brief explanation of each one, how is the digestion process including all its phases and chemical reactions and the main properties of the biogas. A brief explanation on the design considerations to construct an anaerobic digesters as an introduction for the next chapter where the design of the equipment will be mentioned. At the end, a brief “state of art” will be developed for understanding the context where this report is situated compared with similar previous works and ideas and finally a comparison will be done to understand this project potential and innovative aspects.

2.2 Anaerobic Digestion

Anaerobic digestion technology is a worldwide know process that has been evolving for the last decades to convert biomass in renewable energy. In recent years, anaerobic digestion technology has received significant attention, this led to its application growing significantly because it represents an environmentally friendly technology and its relative cost is low. Allowing to convert organic waste (often unusable and representing sources of contamination) in renewable energy, can replace the use of fossil fuels, reducing thus the emission into the atmosphere of greenhouse gases.

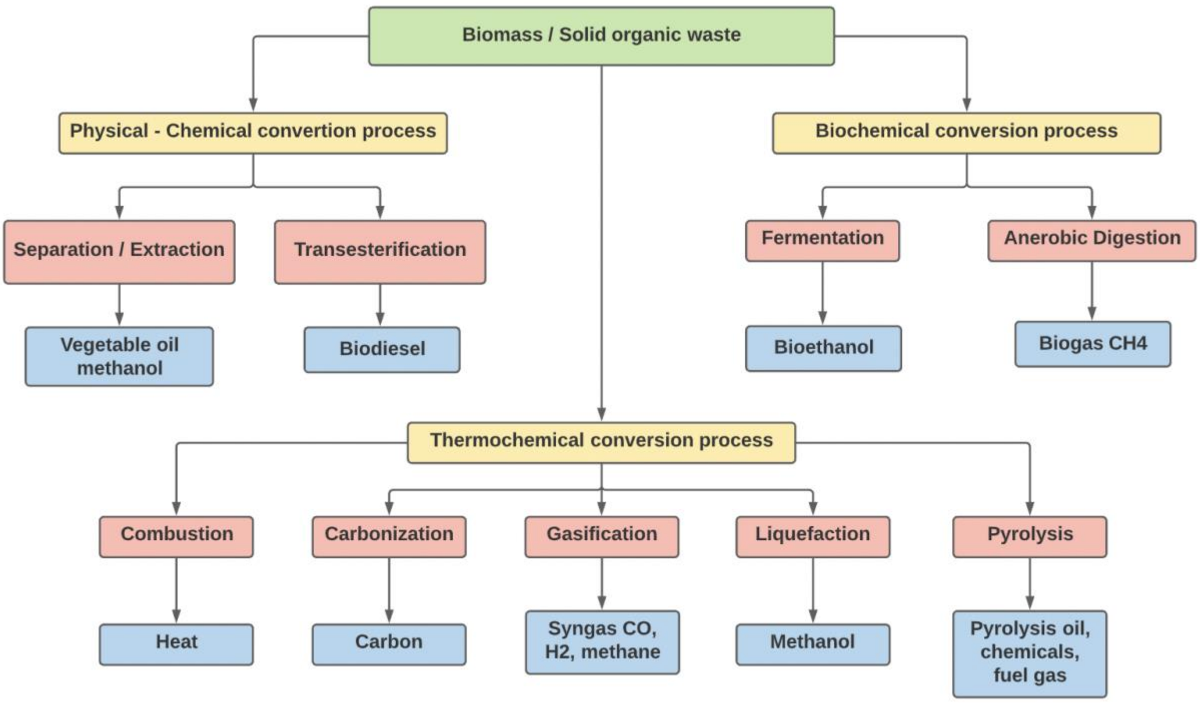

Figure 2.1. Biomass and solid waste conversion technologies. Own elaboration.

Biogas is the final product of anaerobic metabolism. The process occurs in an anaerobic environment (see section *"1.3 Digester composting conditions"*) through the consecutive biochemical breakdown of polymers to methane and carbon dioxide [14] and many other products as shown in Figure 2.1. This is a result of the metabolism of different microorganisms which include fermentative microbes (acidogenic); hydrogen-producing, acetate-forming microbes (acetogenins); and methane-producing microbes (methanogens) [15].

2.2.1 Methanogenic Fermentation phases

Anaerobic methane generation systems are known as methane bioreactors. The production of methane and growth of methanogenic microorganisms in the bioreactors depends on many factors, including temperature, pH, substrate kind and quality, the composition of specific groups of microorganisms, and their accumulation of toxic metabolic products. One of such final products of sulfate-reducing bacteria metabolism is hydrogen sulfide produced in the process of dissimilatory sulfate reduction [16]. In Figure 2.2 can be seen the four phases involved in the process of organic material degradation in AD.

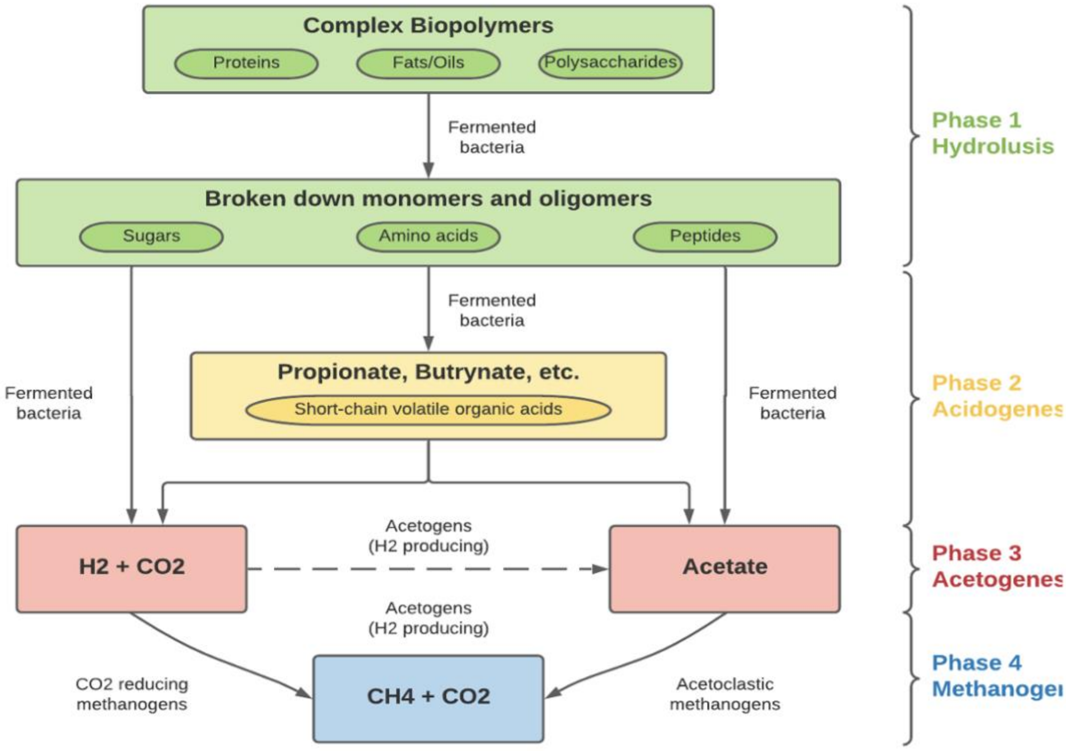

Figure 2.2. Phases of biogas production. Adaptation from [3].

2.2.1.1 Hydrolysis

Hydrolysis is a reaction with water. Acid and base can be used to accelerate the reaction. However, this occurs in enzymes as well.

$$\text{biomass} + H_2O \rightarrow \text{monomers} + H_2 \quad \text{(eq.3)}$$

The hydrolysis reaction, as given in (eq.3), explains how water and enzymes may break down cellulose, starch, and simple sugars. Exoenzymes (cellulose, protease, and other enzymes) from bacteria, protozoa, and fungus are used in anaerobic digestion. Monomers relate to mono-sugars [glucose, xylose, etc.] and fatty acids, whereas biomass refers to cellulose, starch, sugars, lipids, and oils. [3,30].

2.2.1.2 Acidogenic phase

During acidogenesis, soluble monomers are converted into small organic compounds, such as short-chain (volatile) acids (propionic, formic, lactic, butyric, succinic acids – see reaction (b)), ketones (glycerol, acetone), and alcohols (ethanol, methanol – see reaction (c)) [17,18].

$$C_6H_{12}O_6 + 2H_2 \rightarrow 2CH_3CH_2COOH + 2H_2O \quad (eq.4)$$

$$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2 \quad (eq.5)$$

2.2.1.3 Acetogenic phase

Acetogenesis is a carbohydrate fermentation process that results in the creation of H2 molecules, acetate, and CO2, which are then used by microorganisms to create methane [19]. Methanogens, which belong to the archaea domain, are the microorganisms in question. They can be found in wetlands, marsh gas, and the inside lining of ruminants' and humans' digestive systems. During the acid-forming step, the amount of hydrogen present is critical, and the reactions can only continue if the hydrogen level is very low.

Acetogenic bacteria assault the acidogenesis intermediates, resulting in the production of acetic acid, CO2, and H2. The reactions (eq. 6–9) depict the processes that take place during acetogenesis [17,18] :

$$CH_3CH_2COO^- + 3H_2O \rightarrow CH_3COO^- + H^+ + HCO_3^- + 3H_2 \quad (eq.6)$$

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2 \quad (eq.7)$$

$$CH_3CH_2OH + 2H_2O \rightarrow CH_3COO^- + 2H_2 + H^+ \quad (eq.8)$$

$$2HCO_3^- + 4H_2 + H^+ \rightarrow CH_3COO^- + 4H_2O \quad (eq.9)$$

2.2.1.4 Methanogenic phase

The methanogenesis phase is the final stage of anaerobic digestion. The intermediate products from the other phases are used in a number of processes, the most important of which being the formation of methane. The reactions (eq. 10–15) depict the frequent reactions that occur during methanogenesis.[17,18]:

$$2CH_3CH_2OH + CO_2 \rightarrow 2CH_3COOH + CH_4 \quad (eq.10)$$

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (eq.11)$$

$$CH_3OH \rightarrow CH_4 + H_2O \quad (eq.12)$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (eq.13)$$

$$CH_3COO^- + SO_4^{2-} + H^+ \rightarrow 2HCO_3 + H_2S \quad (eq.14)$$

$$CH_3COO^- + NO^- + H_2O + H^+ \rightarrow 2HCO_3 + NH_4^+ \quad (eq.15)$$

2.2.2 Parameters affecting anaerobic digestion

Anaerobic digestion is a complex multi-step process involving numerous types of microbes, each requiring specific conditions for survival and carrying out various activities. Even the slightest changes in factors could affect the efficiency of the digestion processes. Of these factors, the major ones are discussed below as can be seen in Figure 2.3.

Figure 2.3. Parameters affecting AD. Adaptation [3].

2.2.2.1 pH value range

The pH value of the food waste composition (taken into account) is critical for anaerobic digestion to take place effectively. It plays a crucial role in indigestion. The modern world's urbanization has resulted in an overabundance of food waste, which contains a considerable quantity of organic matter that may be degraded, allowing for the production of biogas.

T The pH value range, optimal operating temperature, retention period, loading capacity, and the nature of the organic waste employed all have a significant impact on biogas generation. It has been experimentally proven that substrates with an optimal range value of pH 7 have a greater biogas production yield and degradation efficiency than substrates with other pH range values. Because the microorganism, i.e., methanogens, is very sensitive to acidic ambient conditions, the pH value plays a crucial role. They can't develop or produce methane in an acidic environment[20].

On the other hand increasing the pH value more than 7.5 and towards 8 can lead to proliferation of methanogens which inhibits acetogenesis process. In order to keep the pH value in an equilibrium condition, a certain amount of buffer solution is added to the system such as $CaCo_3$ (base) or lime (acid).

Although the optimum pH value should be maintained between 7.5 to 8, in order to obtain higher yield of biogas [18].

2.2.2.2 Operating temperature

Operating temperature is a pivotal factor which determines the performances of the AD reactors because it is an important condition for the survival and optimum flourishing of the microbial association. Bacteria have two optimum ranges of temperature, termed as mesophilic and thermophilic temperature optimum. Mesophilic digesters have a very good output efficiency while operated in the temperature range of 25-40 °C and thermophilic digesters have a range of 50-65 °C.

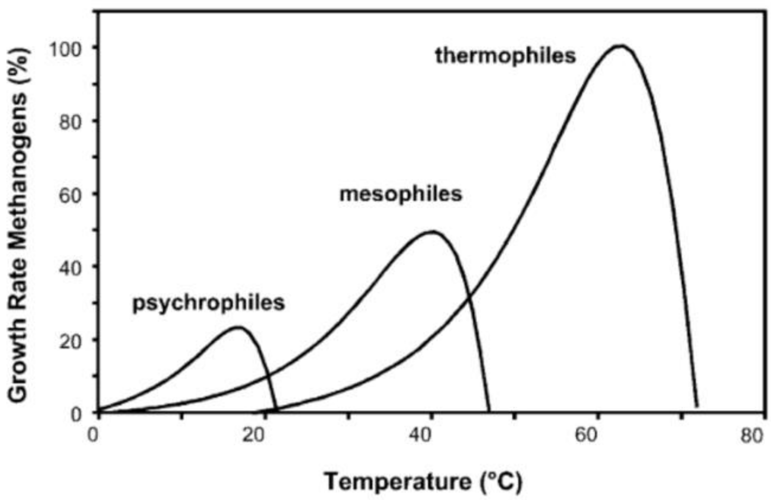

Figure 2.4. Relative growth rate of psychrophilic, mesophilic and thermophilic methanogens [4].

Thermophilic digesters allow for higher loading rates and produce more methane, degradation of the substrate, and pathogen eradication. By speeding up the processes of degradation of organic material, a higher temperature reduces the needed retention period. Toxins and tiny changes in the environment may quickly affect thermophilic anaerobic bacteria, and it takes time for them to go through a redox population. Because they require a secondary energy input for self-heating, the systems are less appropriate for commercial use.

Mesophilic AD reactors employ powerful microbial consortia which have a high tolerance towards environmental changes and have better stability and are easy to maintain. These systems don't need any additional energy input for heating. But they have the disadvantage of longer retention time and a low rate of biogas formation. However, these are more suitable for commercial-scale plants as they are easy to operate and maintain and have lower investment costs [18,21].

Figure 2.4 shows a graph presented by Van Lier et al. (1997) of the relative growth rate of methanogens as a function of temperature. This association is still widely used as a guide, and the appropriate temperature ranges are plainly visible. Because Figure 2.4 demonstrates, a temperature increase over the ideal range of each group will result in an exponential fall in methanogen's relative growth, this generalization should be used with caution. A safe conclusion is that any significant variation from a group's ideal temperature range may result in poor digester performance 4].

2.2.2.3 Organic loading rate

OLR is another essential parameter in the anaerobic digestion process. This parameter indicates the amount of organic matter introduced per unit volume and time. The organic loading rate (OLR) will depend on the type of organic substrate used. Low OLR values imply high hydraulic retention time (HRT) and/or low concentration of volatile solids (VS) in the influent, while increases in OLR lead to a reduction in biogas production. The optimum OLR should be determined for each facility and substrate to be used, to optimize the technical and economic operation of the biodigester. The loading rate of a system cannot exceed its maximum capacity, as it may result in a low or average biogas production. The overloading of a system usually happens due to the presence of degrading or inhibiting substances in the system such as insoluble fatty acids which can cause hindrances in the path of biogas production.

High loading in simple words causes an increase in the number of acidogenic bacteria which stimulates pH fall and hence results in the elimination of methanogenic bacteria or methane-producing micro-organisms hence causing the system to crash [18].

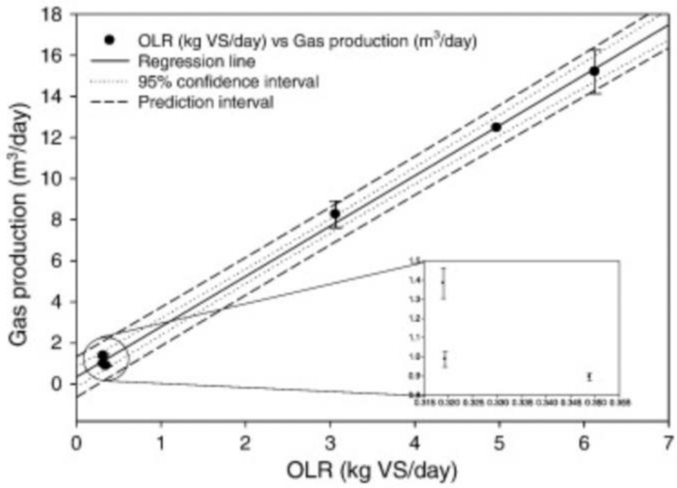

Figure 2.5. OLR vs Gas production [23].

It has been shown in different studies that for low-efficiency and small-sized that the admissible amount of VS that can be added in a digester has a high dependence on the kind of digester and its efficiency, and it has been estimated that the OLR would have a lineal impact over the gas production as shown in Figure 2.5 [23]. Other studies have shown that for the mesophilic temperature range, the OLR for low efficiency and small-scale digester varies between 2,43 ± 0,22 $\frac{KgVS}{m^3}$ [24].

2.2.2.4 Retention time

Retention time or "hydraulic retention time" (HRT) in the AD systems is the amount of time a feedstock resides in an anaerobic digester. It is calculated in terms of the number of days as in the case of the following equation (eq.16).

$$HRT = \text{Operating volume } V / \text{Flow rate } Q \quad \text{(eq.16)}$$

It is the average time it takes for organic waste to degrade in a digester, taking into account the COD (chemical oxygen demand) of the influent or particles, as well as the BOD (biological oxygen demand) of the liquid waste materials. The better the breakdown of organic stuff, the longer the retention time period [25]. The operating temperature and composition of the solid waste material in an AD system can affect retention time. Dry systems or extremely solid wastes often have a longer retention duration than wet systems or liquid-type wastes.

The residence time for a digester is designed in a way keeping in mind the microbial communities present in the digester that operates at different rates and at different times [18].

2.2.2.5 Composition of the food waste

This is another parameter considering the content of the food waste or its composition which may affect the anaerobic digestion in a different way. The content of the organic material generally depends on the time of year, cultural habitat, environmental conditions, abiotic and biotic factors, and also the region [26]. It is important to know the composition in order to predict the course and rate of the reaction also keeping in mind the amount of biogas yielded.

The bio-methanization potential or rate of methane synthesis is determined by four key concentrations: lipids, proteins, carbs, and cellulose. The bio-methanization efficiency of AD systems with high lipid content is generally high, but due to their complicated structure, they require a longer retention time period. Proteins have the shortest retention time duration, followed by carbs and cellulose [27]. However, systems with an excess of proteins or lipids may have inhibitory effects owing to ammonium and nitrogen buildup, which has a significant impact on bio-methanization yield. [18].

2.2.2.6 Volatile fatty acids

Volatile fatty acids are the absolute most essential intermediate in the anaerobic biogas handle. The transformation from VFA into methane and carbon dioxide is the most imperative phenomenon [19]. The expansion of VFA focus in the biogas procedure is well known, as an aftereffect of process disparity. In this way, it has been normally recommended as an indicator in the anaerobic digester.

2.2.2.7 Carbon and Nitrogen content

As a matter of fact, carbon constitutes the energy source for the microorganisms and nitrogen serves to enhance microbial growth. If the amount of nitrogen is limited, microbial populations will remain small and it will take longer to decompose the available carbon [28]. On the other side, too much nitrogen slows down the anaerobic digestion process. Because microorganisms use carbon 25-30 times quicker than nitrogen, a carbon/nitrogen ratio of 20-30:1 has been proposed as the optimal carbon/nitrogen ratio for anaerobic digestion. [29]. Elsewhere, a nutrient ratio of the elements C:N:P:S (carbon: nitrogen: phosphorous: sulfur) at 600:15:5:3 was reported sufficient for methanization [30]. A low C/N ratio, or too much nitrogen, can lead to ammonia buildup, resulting in pH levels exceeding 8.5. The co-digestion of several organic mixes has been used to increase nutrition and C/N ratios. [31]. In studies based on anaerobic biodegradability of food waste (FW) [32], waste activated sludge (WAS) in a single-stage anaerobic digester operating at 35°C. Studies reported that as the FW proportion of the mixture increased from 10 to 90%, C/N ratio of the mixtures improved biodegradation of the mixture increased and the methane production increased.

In another study [33], the mesophilic anaerobic co-digestion of food waste and cattle manure was tested. The results indicated that the total methane production was enhanced in co-digestion, with an optimum FW to cattle manure (CM) ratio of 2:1. The improved biogas generation was mostly due to a greater C/N ratio and increased lipid biodegradation. Because nitrogen helps to the stability of the pH value in the reactor in the form of ammonium, nitrogen plays a significant function in anaerobic digestion. Because of its metabolic products (ammonia/ammonium), nitrogen can cause issues in anaerobic digestion [34]. The ammonium ion may directly block methane-producing enzymes, whereas the ammonia molecule may penetrate into bacterial cells, causing an internal pH shift and, as a result, inhibition of certain enzyme processes. pH and temperature affect the NH3 proportion of total ammonia nitrogen. For three different operating temperatures, the dissociation balance of ammonia and ammonium with change in pH is plotted in Figure 2.6, showing that at a high value of pH rapid conversion of ionized ammonia nitrogen (NH_4^+) into free ammonia nitrogen (NH_3) occurs [31].

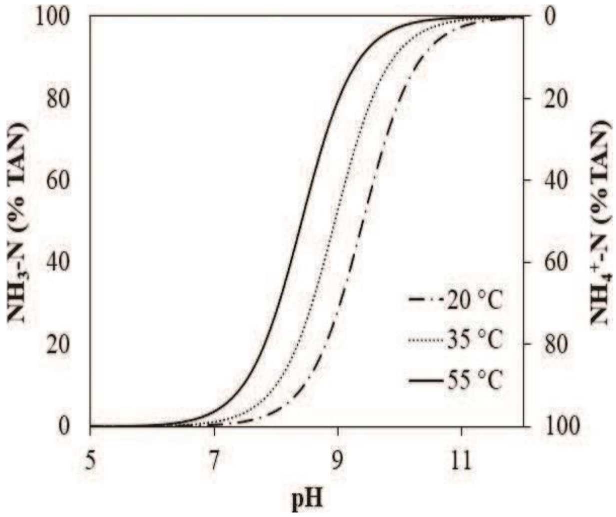

Figure 2.6. Dissociation balance between ammonia at different operating temperatures [6].

The increased concentration of NH_3 inhibits the methanogenic microflora, resulting in the buildup of VFAs, which causes a drop in pH and, as a result, a fall in NH_3 concentration. Lower methane output may result from the interplay of NH_3, VFAs, and pH. Anaerobic digestion can be more quickly inhibited and less stable at thermophilic temperatures than at mesophilic temperatures due to the influence of temperature on the dissociation of ammonia/ammonium. [31].

The ammonia-induced inhibition was reported to occur during the anaerobic digestion of organic waste materials rich in proteins. The inhibiting concentrations were found between 30 and 100 mg/L ammonia or 4000 and 6000 mg/L ammonia (at pH value ≤7 and temperature ≤30°C) [34].

Different strategies such as pH and temperature control, acclimation of microflora, and diluting reactor content were suggested in order to prevail over the ammonia inhibition during the anaerobic digestion process [31].

2.2.2.8 Total solids

Water content is one of the most crucial factors that might influence the entire AD process [18]. As a result, the total solids (TS) content of the medium is commonly employed to distinguish between two types of processes: wet digestion for TS of 15% and dry digestion for TS > 15% to 20% [35]. Operating AD under dry circumstances has the benefit of minimizing reactor size, liquid/solid separation systems, and bioprocess heating energy usage. The early industrial development of digesters operating between 20 and 30 percent TS, and up to 40 percent TS for specific technologies, was prompted by the intrinsic benefits of dry AD bioprocesses. [35]. However, this technical development was mainly based on empirical knowledge. Among the few studies dealing with the effect of TS content, Brown D. showed significant differences in anaerobic kinetics between wet and dry digestion, but no impact on methane yields [36].

2.2.3 Biogas properties

Biofuels have a biological and renewable origin because they are made from biomass. Solid biofuels, such as firewood, coal, and agricultural waste, are available. Biodiesel and ethanol are liquid biofuels, whereas biogas and biohydrogen are gaseous biofuels. Biofuels are classified into three categories based on the raw material and technology utilized in their production:

1. First-generation biofuel: produced from oils, sugars, and starches that originate from food crops (corn, sugar cane, etc.)

2. Second-generation biofuel: from non-food crops and inedible portions of food crops (perennial grasses, crops, etc.)

3. Third-generation biofuels: they are produced from algae.

Biogas is primarily composed of methane, as well as carbon dioxide and other gases, the quantities of which vary depending on the production environment and procedures used. Hydrogen sulfide, ammonia, and nitrogen gas may also be present in trace amounts. Water vapor drenches biogas in most cases. Pure methane has an energy value of 9.81 KWh/Nm^3. The energy value of biogas ranges between 4.5 and 8.5 KWh/Nm^3 when the relative volumes of methane, carbon dioxide, and other gases are taken into account. The odor of biogas is caused by the presence of sulfur compounds. [19].

It should be considered that biogas is generated by a natural biological process, therefore, its composition depends largely on factors such as the type of raw material used, the anaerobic digestion system, and in addition to operational parameters such as temperature, which were discussed in greater detail in section 2.2.2.2 from this same chapter. It is interesting to note that few authors specify the conditions (standard or normal) under which the volume of the biogas is expressed or other characteristics such as its calorific power.

Table 2.1 shows the most relevant properties of the biogas and Table 2.2 shows the average composition of the biogas, as well as the calorific value of its components, at the indicated temperature and pressure. In Table 2.2 it can be seen that apart from methane, the rest of the gas components have practically no energy contribution to the biogas due to its almost zero presence in it (<1%) and its low calorific value.

One cubic meter of fully combusted biogas is sufficient to [37]:

- Generate 6 hours of light equivalent to a 60-watt light bulb.
- Run a 1 m^3 capacity refrigerator for 1 hour.
- Run a 1 m^3 capacity incubator for 30 minutes.
- Run a 1 HP motor for 2 hours.

Table 2.1. Biogas properties for organic waste. Adaptation from [37].

Property	Description
Composition [%]	55 - 70% methane (CH_4) 30 - 40% carbon dioxide (CO_2) and some other gases
Odour	Low odour, rotten egg (smell of desulfurazed biogas is imperceptible)
Agitation	Self agitated by Biogas pressure
Sizing [m3]	6 to 124 m^3 digester vol
Methane emission	High
Calorific Value [Mj/Kg]	20,02
Density [Kg/m3]	1,2
Ignition Temperature [°C]	650 - 750 °C (according to mentioned methane amount)
Molar Mass [Kg/Kmol]	16,043
Energetic content [Kwh/m3]	6,0 - 6,5

Table 2.2 Biogas composition [38].

Average biogas composition and internal calorific power of it's components (15,55°C and 1atm)		
CH_4	60 - 80 %	8145 kcal/m^3
CO_2	20 - 40 %	-
H_2	1 - 3 %	2441 kcal/m^3
O_2	0,1 - 1 %	-
CO	0 - 0,1 %	2868 kcal/m^3
N_2	0,5 - 3 %	-
SH_2 , NH_3	0,5 - 1 %	5552 kcal/m^3
H_2O	Variable	-

2.3 AD technologies and design considerations

Anaerobic digesters come in a variety of shapes and sizes. Depending on the primary feedstocks being processed, these differ in terms of configuration, retention duration, pre- and post-treatment requirements, and operation temperature, among other factors. During AD, a diverse range of bacteria and archaea work together to break down organic molecules (microbes). The biomass added to the digester is broken down into sugars, amino acids, and fatty acids (hydrolysis), fermented to produce volatile fatty acids and alcohols (acidogenesis), then converted to hydrogen, carbon dioxide, and ammonia (conversion), and finally, methanogens produce biogas from acetic acid and hydrogen (methanogenesis).

Based on the constituents and consistency of the food waste treated, an anaerobic digester can be designed as a ‘wet’, ‘dry’, ‘liquid’ or ‘co-digestion’ system. Figure 2.7 below provides information about these configurations [39]. The choice of the basic AD design is influenced by the technical suitability, cost-effectiveness, and availability of local skills and materials. In developing countries and particularly in rural areas, the design selection is largely determined by the prevailing and proven design in the region, which in turn depends on the climatic, economic, and substrate-specific conditions.

The fixed-dome digester, floating-drum digester, and tubular digester are the three primary types of digesters used in poor nations. They are all wet digesting systems that work in a continuous mode under mesophilic conditions. These three varieties are low-cost, made of locally available materials, simple to handle, and have few moving components, making them less prone to failure. These three technologies will be discussed in further detail in later sections of this paper.

A biodigester can be useful in several aspects for a rural family, but mainly in two ways: the amount of gas it can generate and the volume of waste that can be treated in it.

Regarding the first criteria, the household's demand and the type of energy to be replaced should be evaluated. In the case of using biogas to generate electricity, the necessary volumes of waste are high, and a biodigester sizing is required which, in the case of a family, can be complicated. This does not mean that with good ideas, training and assistance a family can implement it at home.

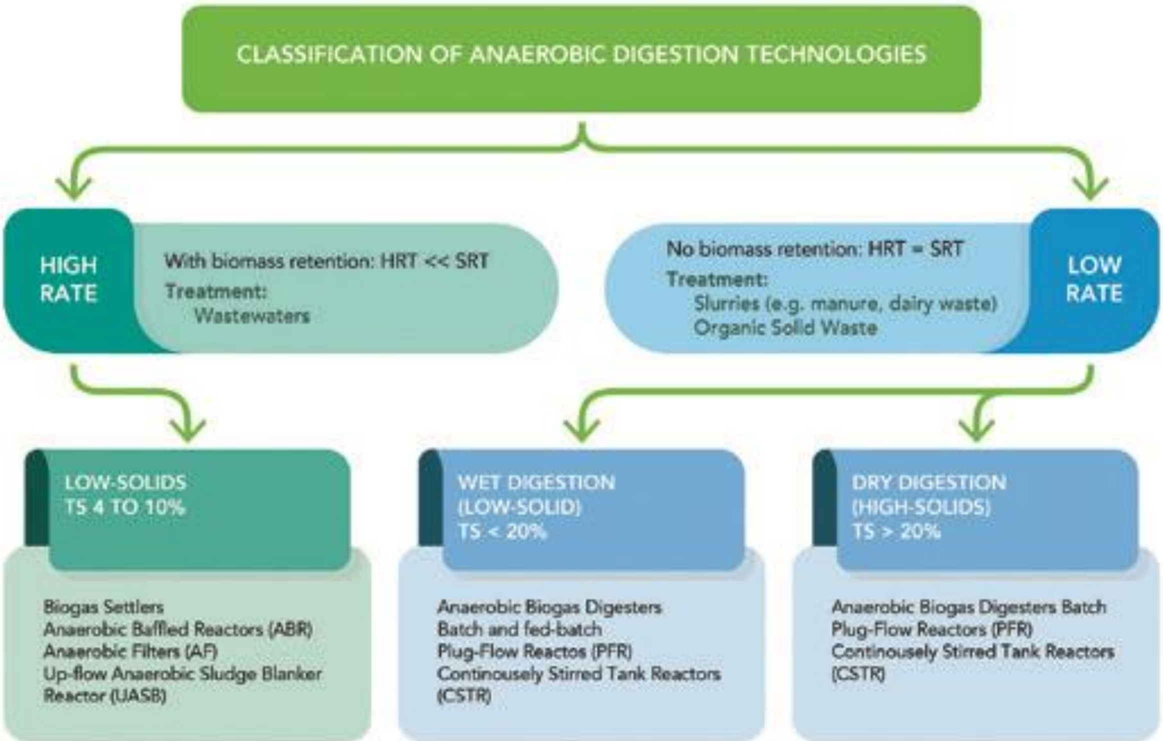

Figure 2.7. Classification of AD technologies [1].

It is easier to utilize biogas as a substitute for firewood, bottled gas, or mains gas, albeit the latter is not economically viable due to its low cost. It is vital to investigate the distribution of energy usage in the home for these applications (daily, monthly and yearly). This can lead to conclusions before building begins, such as:

- If there is a high gas consumption during the winter months, a high efficiency biodigester (heated, insulated and agitated) should be designed so that the biogas production replaces the fuel used.

- If the consumption is stable during the year (for example, in a production process), in this case, during the months of higher temperature biogas can be used to supply the demand.

2.3.1 Classification of AD technologies

Biogas systems can be classified according to critical operating parameters and elements of reactor design. This thesis does not cover all design options but rather focuses on those that are considered appropriate for the developing country context and for a biowaste feedstock. The following sections discuss the main distinguishing features of selected AD systems.

2.3.1.1 Total solids content (wet/dry systems)

Digester designs are classified as wet or dry depending on the TS content of the substrate fed into an AD system. Wet bioreactors have a TS percentage of less than 16 percent [29], whereas semi-dry and dry bioreactors have a TS content of 22 to 40% [30]. Dry systems are preferred over wet AD for a variety of reasons. Dry digestion necessitates a smaller reactor space, less energy (if heating is needed), and little material handling. Due to the low moisture content of the digestate after dry AD, it can easily be used as fertilizer or be pelletized and serve as biomass fuel. Despite the obvious benefits of dry AD and the ongoing advancement in system design, a number of practical challenges still stand in the way of its adoption in underdeveloped countries. The conventional batch-wise method (described in the next section) is one barrier, while the filling and emptying process, which requires a large enough opening and must be sealed in a gastight manner on a regular basis, is another.

2.3.1.2 Feeding mode

Anaerobic digesters can be fed continuously or batch-wise. In a continuous feeding mode, the new feedstock is added at regular intervals while an equivalent volume of slurry leaves the digester, thereby providing a continuous process of digestion.

In batch-fed digesters, the reactors are filled with a feedstock, closed, and left for a period of time (i.e., the retention time), then opened again and emptied state that batch systems represent the lowest-technology of all systems and are also the cheapest [30,40]. Batch systems are recommended for use in underdeveloped countries due to their simple design and cheaper investment costs. However, experience has shown that nuclear reactors have significant drawbacks. Once closed, each batch goes through the entire start-up phase of the methanogenic process. This means that until the system is stable, there will be significant swings in gas production. The quality of the gas varies as well. The height of the reactor is limited to ensure good infiltration of the percolate. Furthermore, gastight sealing of inlet /outlet can be challenging especially as the doors are regularly closed and opened after each batch sequence. This may result in biogas losses and the risk of explosion when emptying as residual methane in the reactor mixes with air [40].

2.3.1.3 Operating temperature

As described previously in section *"2.2.2.2 Operating temperature"*, the temperature is an important operational parameter and can also be used to classify AD systems into two categories: mesophilic (25–40°C) and thermophilic (45–60°C) systems. The temperature range below 20°C is referred to as psychrophilic, and it is not suited for anaerobic digestion due to the slow reaction rate. Mesophilic digestion systems are more stable than thermophilic digestion systems and require less energy input. The increased temperature of thermophilic digestion systems, on the other hand, allows for faster reaction rates and gas output. The cleanliness of the digestate is also aided by operating at higher temperatures. Because the predominant systems in developing nations with tropical climates are not heated, they are often operated in the mesophilic temperature range [41].

2.3.1.4 Number of stages

Another approach to categorize the process is by how many steps it has. It could be a single-stage or multi-stage procedure. All four phases of anaerobic digestion take place in the same reactor in a single-stage process. A multi-stage process, on the other hand, divides some of the phases in order to customize circumstances to each of them. When going the multi-stage way, the most common setup is a two-stage system, with hydrolysis and acidogenesis in the first reactor and acetogenesis and methanogenesis in the second. This is very beneficial when determining the pH level that is best for each step. Even though multi-stage systems are more efficient at producing biogas, they have substantially higher costs and complexity than single-stage procedures. [42].

2.4 Feedstock Description in rural areas

Before the start of an assessment, it is essential to define the feedstock to be assessed, but this is not seen as a key area. This definition can be further specified during the assessment when learning more about important aspects. For example, the following information can be of importance:

- Name.
- Type; agriculture, aquatic, forest, etc.; and primary, secondary, residue; etc.
- Key components.
- Dry matter content or Total Solids (DM in TS in % mass).
- Volatile solids (VS in TS in % mass).
- C/N ratio.
- HRT – Hydraulic retention time.
- Agitation.
- Heating.

External users and reviewers of the evaluation results will, of course, want this information.

Agricultural and animal wastes, organic component of solid home waste, and domestic sewage sludge are all good substrates for biogas production in rural settings (i.e., human excreta and wastewater). The quality, quantity, and delivery rate (continuous or semi-continuous) of feed materials determine the biogas yield. The pressure of each digestor's headspace can be used to directly quantify biogas output [58].

2.4.1 Biogas yield

Naturally, it is required that the feedstock is anaerobically digestible and has a good biomethane yield.

Table 2.3 contains information about the methane yield for a few selected feedstock categories, which is useful when suggesting and reviewing scales for this key section. However, one needs to be careful when trying to find information. There are yield data for many types of feedstock categories, but it might be difficult to value it, for example, to identify what type of yield is indicated and if it is reliable. The biomethane yield is expressed as the volume of gas per unit of weight for each feedstock, but there may be some ambiguity in the literature because the gas volume may refer to pure methane or include additional content (CO_2, etc.), i.e., more biogas, and tests may have been performed at different temperatures and pressures. The weight can then be expressed as Wet Weight (WW), Dry Matter (DM), Total Solids (TS), Organic Dry Matter (ODM), or Volatile Solids (VS) (VS). In addition, the values given might be within a range from theoretical values, calculated based on the chemical composition of the substrate, to values from small-scale lab tests, pilot-scale tests to full-scale practical applications. When comparing experimental methane potential to a theoretical, a maximum of 90-95 % can be expected in a batch assay since the rest of the substrate is used for the growth of the microorganisms [43]. For a continuous process, the methane yield maybe only 50-70 % of the theoretical yield (biogas yield) [44].

Table 2.3. Biogas yield for different substrates. Adaptation from [45].

Typical Feedstocks					
Manure	**Source of nutrient; high buffet capacity. Usually in co-digestion with straw.**				
Type	Organic content	DM%	VS% of DM	C:N ratio	Biogas yield [m^3/kg VS]
Pig	Carbohydrates, proteins, lipids	3–8	70–80	3–10	0.25–0.50
Cattle	Carbohydrates, proteins, lipids	5–12	80	6–20	0.20–0.30
Poultry	Carbohydrates, proteins, lipids	10–30	80	3–10	0.35–0.60
Agriculture residues	**Source of cellulose, lignin, and starch. Need pre-digestion.**				
Type	Organic content	DM%	VS% of DM	C:N ratio	Biogas yield [m^3/kg VS]
Straw	Carbohydrates, lipides	70–90	80–90	80–100	0.15–0.35
Grass		20–25	90	12–25	0.55
Organic household waste	**High variability of composition. Easily digestible. May inhibit the process for acidification.**				
Type	Organic content	DM%	VS% of DM	C:N ratio	Biogas yield [m^3/kg VS]
Fruit waste		15–20	75	15–20	0.25–50
Food residues		10	80	—	0.50–0.6

Overall, animal manure is an ideal feedstock because of its high moisture and volatile solids (VS) content and the buffering capacity, and also its variety of microbial strains. The animal manures used in anaerobic digestion may vary according to the geographical area and local livestock practices [46]. In later sections, this topic will be taken up again specifying the type of manure and biomass available in the region of interest and it may be replicated in any region with similar characteristics.

In Ethiopia, the potential of cow dung, sheep manure, and pig manure in the plastic reactor was investigated, with results showing that after 20 days of retention at 25-28°C, a burnable gas with more than 60% methane was obtained from cow dung and sheep manure, while pig substrate required more time [47]. In a modified floating model with a volume of 11.3 m^3, the biogas output per kilogram of goat dung was 54 L/kg in northern Brazil [48].

2.5 Biogas against natural gas

Due to its methane content, biogas, also called lean or low energy gas, has characteristics similar to natural gas, but with a slightly lower calorific value greater than half the calorific value of this fossil fuel. For example power, lower heating value (LHV) of natural gas can fluctuate between 8,2 and 11,1 kWh/Nm^3, while the LHV of biogas is between 4,5 and 7 kWh/Nm^3. This value, as mentioned before, depends on its methane content. If biogas with a methane content of 60% is considered, this will have a lower calorific value of about 5500 kcal/Nm^3 o 6,4 kWh/Nm^3 [49].

On the other hand, it is a non-polluting green and clean renewable energy since it is generated from organic waste. Between 50–70% of LNG usage could be reduced by installing biogas plants in homes [50]. In Table 2.4 technical differences between biogas and conventional gas can be seen.

It is important to notice that like any other barely "new" renewable energy, biogas is still evolving day to day and under the efficiency concept it cannot reach conventional gas standards.

Table 2.4 Biogas vs Natural gas. Adaptation [18].

Properties	Biogas	Natural gas (LNG)
Lower calorific value	6.5 kWh/Nm3, 20 MJ/kg	11kWh/ Nm3, 48 MJ/kg
Density	1.1 kg/Nm3	0.82 kg/Nm3
Relative density	0.9	0.63
Wobbe index, upper	27 MJ/Nm3	55 MJ/Nm3
Methane number	>135	>73
Methane	65 Vol.%	90 Vol.%
Methane, range	60–70 Vol.%	85–92 Vol.%
Heavy hydrocarbons	0 Vol.%	9 Vol.%
Hydrogen	0 Vol.%	–
Carbon dioxide	35 Vol.%	0.7 Vol.%
Carbon dioxide, range	30–40 Vol.%	0.2–1.5 Vol.%
Nitrogen	0.2 Vol.%	0.3 Vol.%
Nitrogen, range	–	0.3–1.0 Vol.%
Oxygen	0 Vol.%	–
Oxygen, range	–	–
Hydrogen sulfide	>500 ppm	3.1 ppm
Hydrogen sulfide, range	100 ppm	–
Total chlorine as Cl−	0–5 Mg/Nm3	–

2.6 State of art

Energy production from renewable sources showed an exponential growth in the last 20 years and more and more solutions are being explored [51]. This new worldwide involvement makes biogas a strategic resource for developing countries, where there is a large availability of agricultural wastes and animal wastes [52]. Several studies for these countries show the high potential for electricity production from biogas [53] and highlight the various economic, social and political constraints [54]. Amongst the innovative solutions, biogas is establishing itself as one of the most promising technologies. The increasing interest in such technologies is also shown by the number of research works in the last 20 years as shown in Figure 2.8.

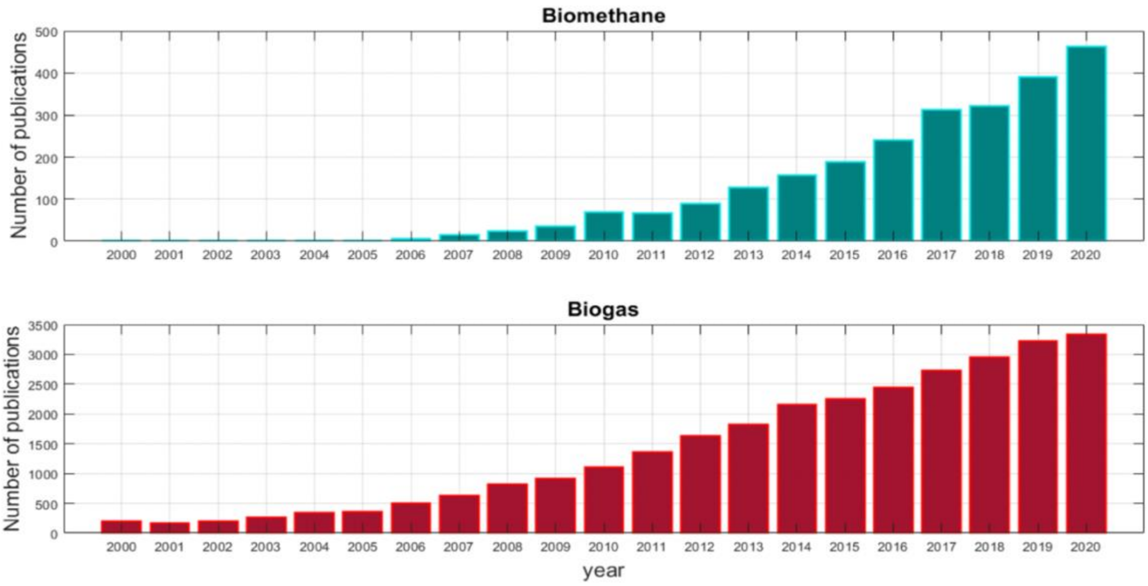

Figure 2.8. Number of studies published per year with the terms “biomethane” (a) or “biogas” (b) [7].

In order to draw insights and conclusions on AD technologies, it is necessary to document the design and management parameters followed in different models around the world. Brief information may be gleaned from case studies and review articles that are likely to outline the main characteristics of each design. A structured review process was conducted to review articles based on closed-loop rural small AD technology. The research questions were previously defined in section “*1.4 Objectives”.*

2.6.1 Small-scale biodigester investigation

In poor nations, three types of residential biodigesters are popular: fixed dome, floating drum, and plastic tubular/inflate balloon. These are small (5-10 m3) and are mostly used to supply the energy needs of households for cooking and lighting. Because of its dependability, low maintenance requirements, and extended lifespan, the Chinese fixed dome digester is frequently the design of choice. [35].

The Floating-drum reactor (Figure 2.9.) consists of a cylindrical or dome-shaped digester with a movable drum on top which has external guides to keep it upright. When gas accumulates in the drum, it rises, increasing the volume while keeping the pressure constant. The drum decreases as the gas is withdrawn, reducing the volume while maintaining pressure. It's a simple method that maintains consistent pressure in the digester, but the drum is pricey and requires regular repair [57,58].

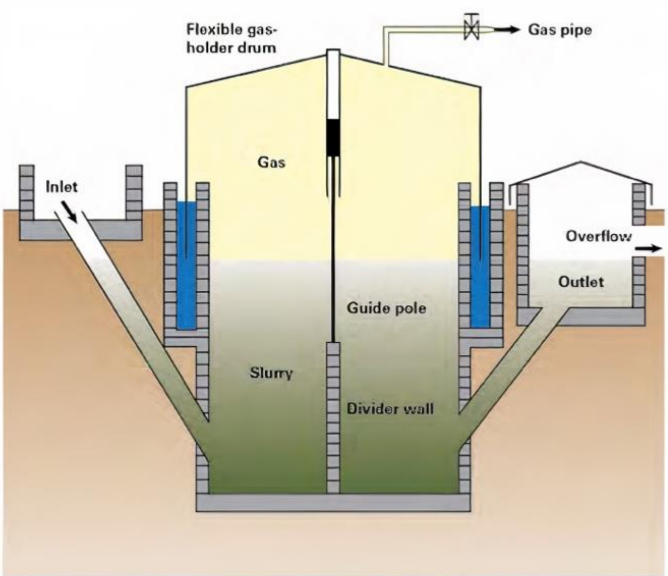

Figure 2.9. Scheme of a floating-drum reactor [58].

Fixed-dome reactors (Figure 2.10.) are dome-shaped and both the digester and gasholder are rigid and immovable. As the pressure inside the reactor rises, some of the substrates will be pushed into a displacement pit, where they will be temporarily stored. When the gas is evacuated, a corresponding amount of substrate flows back into the digester from the displacement pit. This design is compact, well-insulated, low-cost to start, and has a long usable life. The drawbacks are that cracks usually lead to irreparable leaks and the fluctuating pressure may make it harder for users to understand the system [57,58].

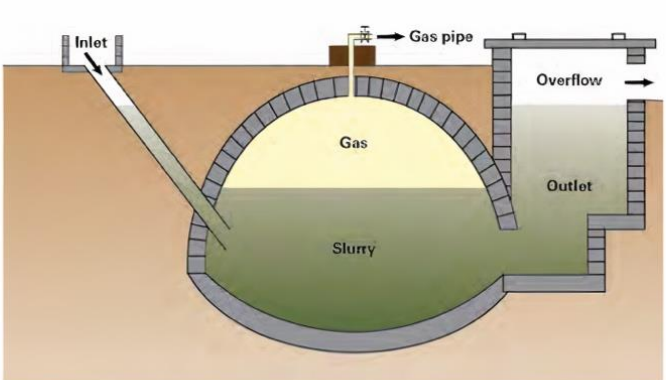

Figure 2.10. Scheme of a fixed-dome react [7].

Inflatable balloon reactors (Figure 2.11.) are plastic or rubber bags for which the bottom part serves as the digester and the top part as the gasholder. The balloon inflates as the biogas is created, and the needed gas pressure is achieved by placing weights on the bag. Although it is a low-cost system, its useful life is only about 5 to 10 years [57,58].

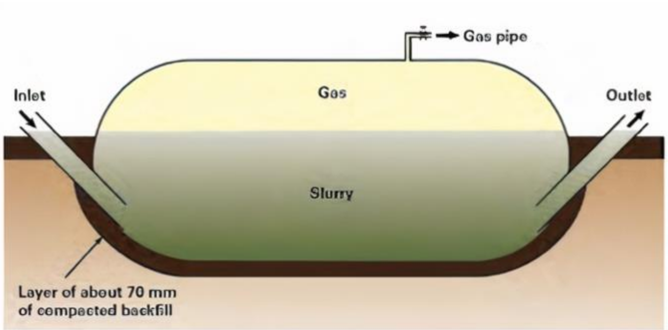

Figure 2.11. Scheme of an inflatable-balloon reactor [57].

A very important fact to be considered is that all the reactors previously mentioned are generally placed underground, this helps isolate and maintain a constant temperature of the reactor using only geothermal energy most often of low intensity [57]. In Table 2.5 main characteristics of each digester technology are listed together with a brief explanation that could assists in decision making through information gathered from actual implementations in different countries with different conditions around the world.

Table 2.5. Principal household designs used in developing countries [46,59–64].

Properties	Floating drum	Fixed dome	Inflatable - Balloon
Modifications / Models	-	Janta Deenbandhu French	Pre-built and low-cost digester
Construction / Fabrication Materials	Bricks and concrete for digester Metal or Mild steel for drum Reinforced fiber plastics high-density polyethylene (HDPE)	Bricks, Cement, Concrete, Polymers Glass-fiber-reinforced plastics	PE PVC HDPE Glass fiber reinforced plastics
Advantages	Easy construction Visible storage volume Gas at constant pressure	Low initial cost long-life span (if appropriately built) Less land required	Low cost Easy transportation Easy installation Low maintenance
Disadvantages	High installation and operational costs High payback. Short life span (corrosion of drum) High maintenance	Requires high construction skills Built with heavy materials Gas leakage due to cracks	Short life span. Requires insulation in a cold climate. Requires a high amount of water. Low gas pressure
Geographical Diffusion	India	China, India, Nepal, Uganda Tanzania	South America, Africa South Asia
References	[59]	[60–62]	[46]

Daily operation and maintenance are required for all rural small-scale and household digester models. Feeding, digestate handling, and biogas outflow control are all part of day-to-day activities. Organic waste is mixed with water in various amounts and fed to both brick and plastic tube digesters. Sludge removal from the digester, plugging probable cracks in fixed digesters, and repairing damages in plastic systems are the most difficult maintenance tasks for users [65]. Because installed digesters functionality depends on continuous management and supervision of operation and maintenance, specific programs are often put in place to develop ownership and participation in using the biogas systems [63]. Sensitivity analyses demonstrated that small-sized digesters are more environmentally sustainable if biogas leakage and release are avoided [64].

2.6.2 Northern Argentinian investigation

To the best of my knowledge, there has not been an exhaustive and updated work in the literature that critically reviews biomethane small-sized design and operation criteria, paying special attention to the integration of the process with low-income families from rural areas especially located in the northern Argentinian region. The present work aims to cover this gap and to provide these families with the possibility of administrating their own resources in order to generate biogas from their organic waste.

To be able to understand which are the main parameters and ideas around this way of obtaining energy, research has been made over the interesting area, the northern Argentinian region.

Trials and workshops have been made by the most popular institution advocating the development of agricultural technologies in the country, the national institute of agricultural technology, INTA (Instituto Nacional de Tecnologia Agropecuaria), and the department of agriculture under the program called "Energetic efficiency and renewable energies for families in rural areas" [66,67]. In this case, the technology used to build the biodigester is different from the traditional ones that were listed in the previous section "*2.6.1 Small-scale biodigester investigation* ", since the main purpose of this kind of workshop is that people could be able to build the biodigester by themselves in an easy and low-cost way.

On the other hand, other workshops were made by different institutions like the rural engineering institute, IIR (Instituto de Ingeniería Rural), universities, and the private sector under the same working concept, low-cost construction for low-income communities [67,68]. All these projects have in common that they were destinated for rural areas and their main purpose was to treat and receive as input different kinds of animal manure and agricultural waste is considerably big amounts, therefore, biodigesters were dimensioned and designed to receive the manure coming from fields with main cows, pigs, chicken, etc. Since the volume of the digester is directly proportional to the amount of fresh feedstock available per day, in most cases the dimensions of the digesters were between 2-8m^3 (2000-8000lt) mainly made from plastic tanks and tubular polyethylene bags receiving daily amounts of feedstock that goes from $20\ to\ 80\,\frac{kg}{day}$.

Throughout this thesis, some considerations from what was mentioned before will be taken into account, but they will differ in terms of the purpose and main objective of the development and use of biodigester technology. What is called as a "family-size biodigester" will now be redefined as a rural family that does not necessary owns animals or a crop field, this means that their feedstock available per day may have the same characteristics as the mentioned in the previous paragraph but the daily amounts available will be significantly smaller, but enough to allow these families with low income and far from cities to supply they daily cooking needs using biogas obtained from their organic waste. In the following chapter the new concept of "family-size biodigester" will be introduced and defined, together with the feedstock characteristics and expected daily feedstock quantities.

3 Methodology

The methodology used in this work includes two main parts, the spatial analysis where the background study is done obtaining as result the variables, parameters, and constraints for the area of interest, and the design considerations where the mathematical model is introduced and the results are analyzed.

3.1 Spatial analysis

The following analysis aims to explain and illustrate why this work is based on the northern Argentinian region, more specifically in northeast Santiago del Estero province and the northwest part of Chaco province.

The spatial analysis in the current section will be developed first through the implementation of a macro analysis with the objective of making the first filter and focus on a more specific region, and then move to a microanalysis and characterize in more detail the area of interest that could also be the starting point to implement the biodigester proposal presented in this work in regions with similar characteristics and thus ensure similar results.

Throughout the macroanalysis section, indicators such as the poverty index, urban density distribution, and the existence of basic public services of interest to the work (i.e., the scope of the national natural gas network) will be addressed.

On the other hand, in the microanalysis, more specific aspects of the target region will be addressed, such as the climatic specifications that will allow for determining the average working temperature of the digesters, the size of the families that will be the target public, and the identification of the main activities that are developed in order to determine the available feedstock per agglomerate.

After introducing the selected region, an investigation of the organic matter produced by people in the already mentioned areas will be done in order to identify the main inputs available for the biodigester, such as the characterization of waste and amount produced.

3.1.1 Macro-level analysis

For developing this section, a free and open-source geographic information system QGIS 3.22 [69] will be used in order to visualize all the information that is presented in table format in a resumed and easier way for the reader. GIS software work with layers of information in a "shapefile" format better called ".shp", therefore much of the information obtained from statal or regional sources had to be manipulated and readapted to be displayed in a convenient way in each of the cases. This software understands and analyzes the information in three different ways: as lines, polygons, or points, each of them has its own properties and ways to be analyzed and visualized.

3.1.1.1 The country

Argentina is a worldwide known country for its diversity of people, cultures and landscapes. When it comes to analyzing and studying its diversity, it is easy to figure out that as in many other developing countries, its richness is mainly concentrated in the capital city. Argentina is one of the largest economies in Latin America, with a Gross Domestic Product (GDP) of approximately US$450 billion and a population of 46 millions [70].

With abundant natural resources in energy and agriculture, in its territory of 2.8 million square kilometers, the country has extraordinarily fertile agricultural land, important reserves of oil, gas and lithium, and an enormous potential in renewable energy. Argentina is a leading country in food production, with large-scale industries in the agriculture and cattle ranching sectors. It also has great opportunities in some manufacturing subsectors and in the innovative high-tech services sector [70].

However, the historical inflation and financial volatility of the country, the COVID-19 pandemic, and social isolation as a way to deal with it have aggravated the situation.

3.1.1.2 Poverty

Urban poverty has increased during the latest years, and after the pandemic, it reaches 40,6% of the population in the first semester of 2020, which is equivalent to 2,9 million families earning less than AR$25.759 equal to 393usd[1] [71] per family and 10,7% of Argentines are under the level of poverty, having an average monthly income under the 157usd. Child poverty, among children under 14 years of age, reaches 54.3% [70].

What is notorious to see is that the poverty of the country is mostly concentrated in the northern region as can be seen in Figure 3.1. Provinces like Santiago del Estero, Chaco, and Santa Fe have the highest poverty rate when compared with the rest of the country.

Figure 3.1 shows the superposition of different layers of data like the country's political delimitations, its provinces' delimitations, names, and poverty index. Information has been mainly obtained from the IGN (National Geographic Institute of Argentina) [72] together with self-made layers with information obtained from the INDEC like the poverty percentage per each province for the first semester of the 2020 year [73]. Said data was available in the form of a table and introduced to the QGIS 3.22 software as a shapefile.

[1] Using as reference the rate provided by the Argentinian Republic Central Bank (BCRA) for the end of the first semester of 2020 1 USD = 65,5 AR$.

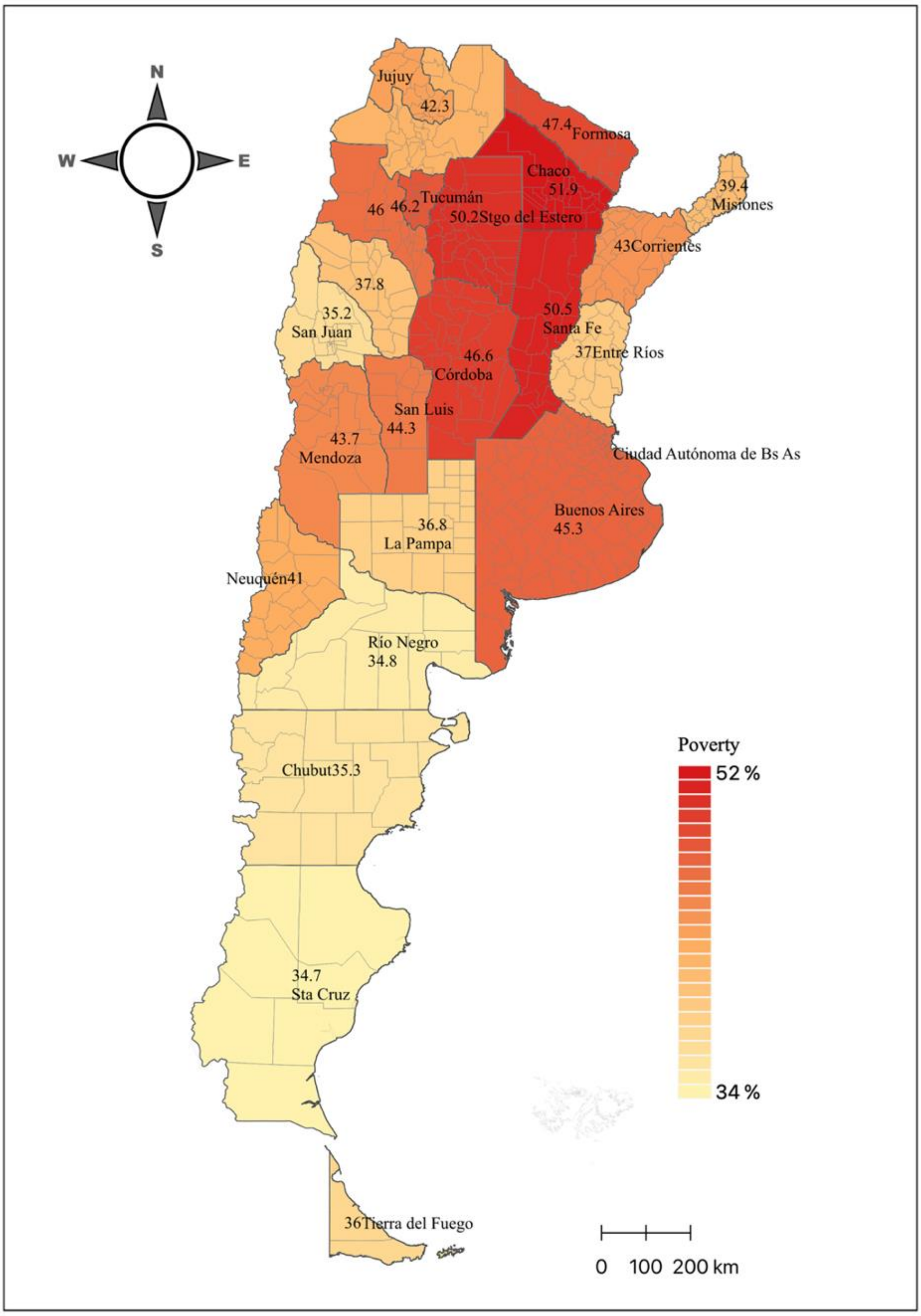

Figure 3.1. Argentine poverty by province. Own elaboration.

3.1.1.3 Population

The following analysis will be focused on discovering the undeveloped/non-urbanized areas of the poorest provinces of the country, where people counts with less access to basic needs such as water, electricity, or conventional gas network.

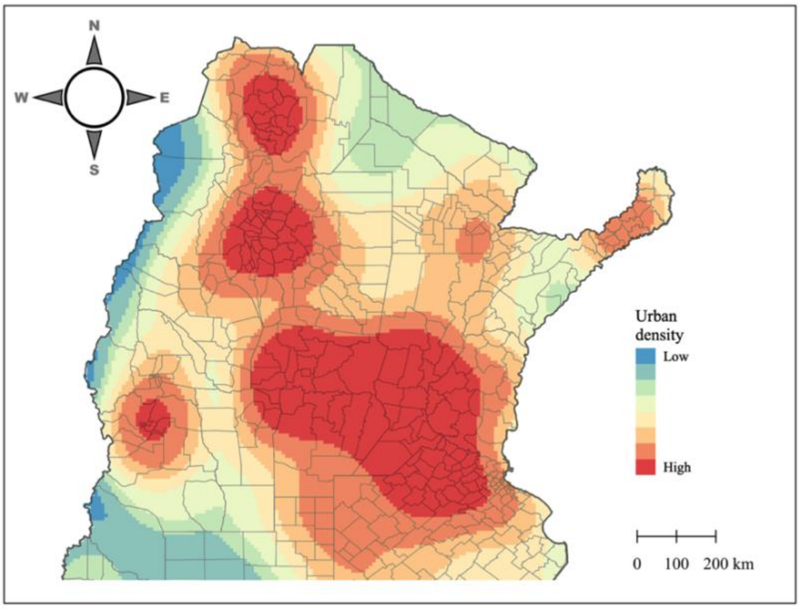

Figure 3.2. Urban density distribution in northern Argentina. Own elaboration.

For each location in the north part of the country the Figure 3.2 shows in a graduated way, using a native QGIS tool named "heat map" how the concentration of people is distributed in a range that goes from "low" to "high" depending on the density/concentration of urbanization in a delimited area located in a specific region. The information to make this figure was obtained from the IGN in the ".shp" file format. The information was found in the layer under the name "urbanized areas" and was in a polygon format, showing different sized areas directly proportional to the most densely populated regions all over the country. In order to obtain valuable information for the purpose of this section the polygon information was translated to a numeric area value in square kilometers (km^2) and at the same time this value was designated to a point that was located by a QGIS mathematical native tool in the middle of the polygon, finally a convenient iteration was made with a radius that allowed to cover the whole region of the Argentinean soil and at the same time to establish a distance relation between all the points presented in the map, as can be seen in Figure 3.2.

From this figure can be seen how the population is mainly distributed in the middle and northern Argentinean regions. It can be seen how in provinces with the greatest poverty mentioned in the previous section *"3.1.2.1 Poverty"* the concentration of urbanized areas is lower compared with the rest of the provinces. A closed-loop can be located over the mentioned region, more specifically in north-east Santiago del Estero, north part of Chaco, and north Formosa.

After analyzing where is located the urbanization in the specified area, it can be said that overlapping the Figure 3.1 and Figure 3.2 the potential region of interest to develop an energy project which purpose is to assist people that cannot satisfy its basic needs or that do not have access to basic needs could be north-east Santiago del Estero, north part of Chaco.

3.1.1.4 Basic public services

In recent censuses, INDEC shows results on the availability of basic public services such as running water, natural gas, and sewage networks. As can be seen in Figure 3.3, 33.8% of Argentinian homes do not have access to the public gas network [74], which means that they have to satisfy their basic needs such as cooking using gas bottles that are sold in urbanized areas, or solid fuels such as firewood or charcoal that people typically collect itself.

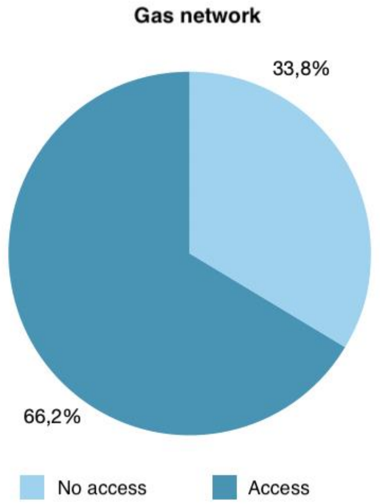

Figure 3.3. Reach of homes of the Argentine gas network [10].

With the objective of further deepening this lack of basic resources and visualizing the potential location of this 33.8% of Argentinian homes, information about the main gas pipelines and their ramifications can be seen in *Figure 3.4*. Cartography in this case was downloaded in PDF format directly from the web page of the national gas regulator ENERGAS since it is not available in shapefile format.

As can be seen in Figure 3.4. the pipeline system in the country does not cover all the territory, leaving the 33.8% of homes still not having access to conventional gas to heat their homes or cook their foods. Two main natural gas networks extend across the northern part of Argentina's territory, the “Main Gas Pipeline System” which covers a large portion of the country from south to north and has many branches that supply natural gas all the locations marked with red dots and at the northeast part the GNEA “North East Argentine Gas pipeline” as a branch of the main gas pipeline system extends across two provinces, Santa Fe and the east part of Chaco, supplying the demand of the main cities that can be located by the red dots. The purple line that follows the province of Chaco and extends across the province of Formosa from east to west, is a dotted line because it is a state-approved project that has not yet been started, which means that people still do not have access to a basic resource such as natural gas.

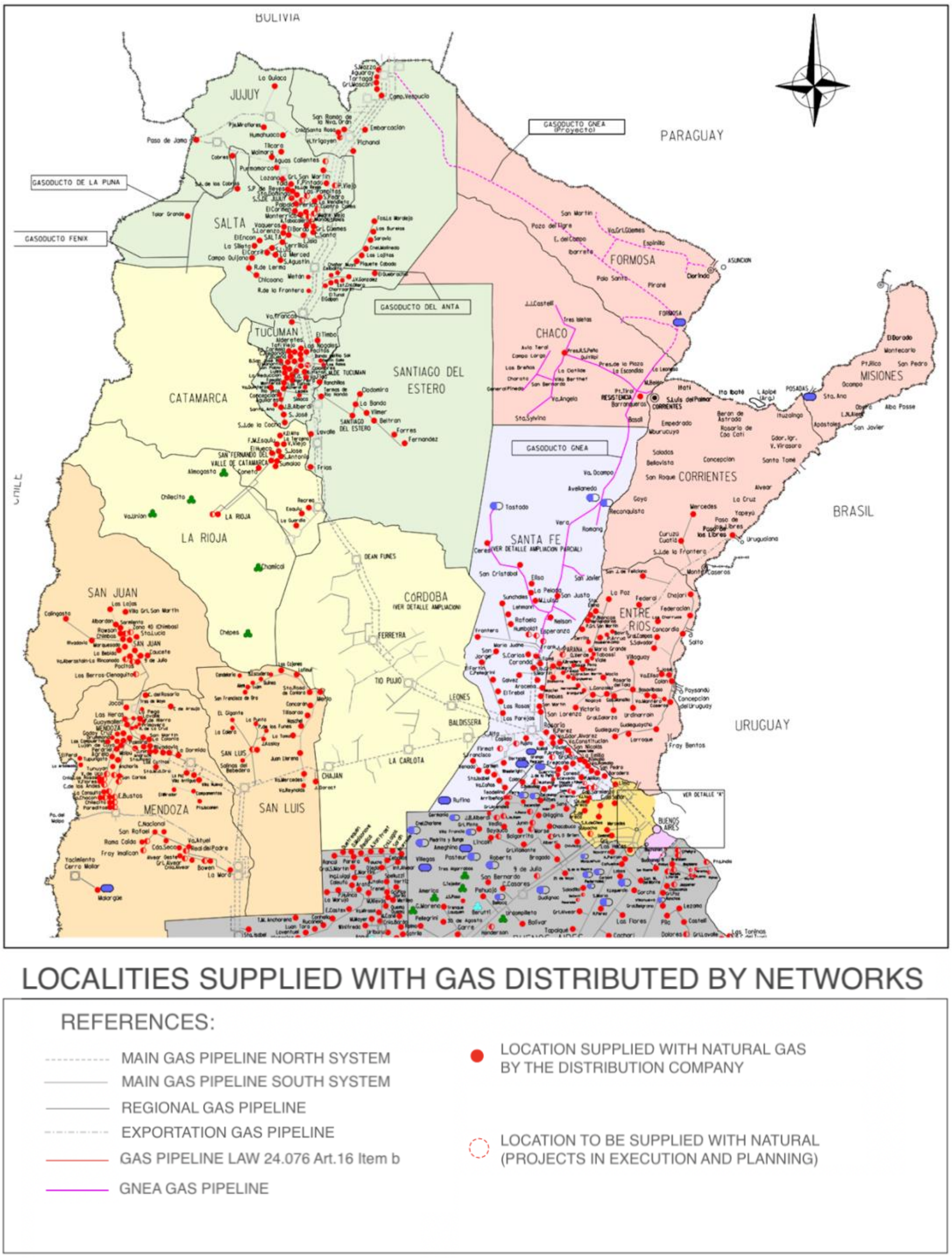

Figure 3.4. Argentine gas pipeline network [11].

Going back to the region of interest, it can be seen how in the mentioned close loop that englobes the north-east Santiago del Estero and north part of Chaco province there are any locations supplied with natural gas. This can be seen in a detailed way in Figure 3.5. In this figure can be seen that two different colors are used to demarcate the gas pipelines; purple color refers to existing pipelines as it is the case of Santiago del Estero and orange color if the gas line is a project to be carried out in the future as is the case of Chaco and Formosa.

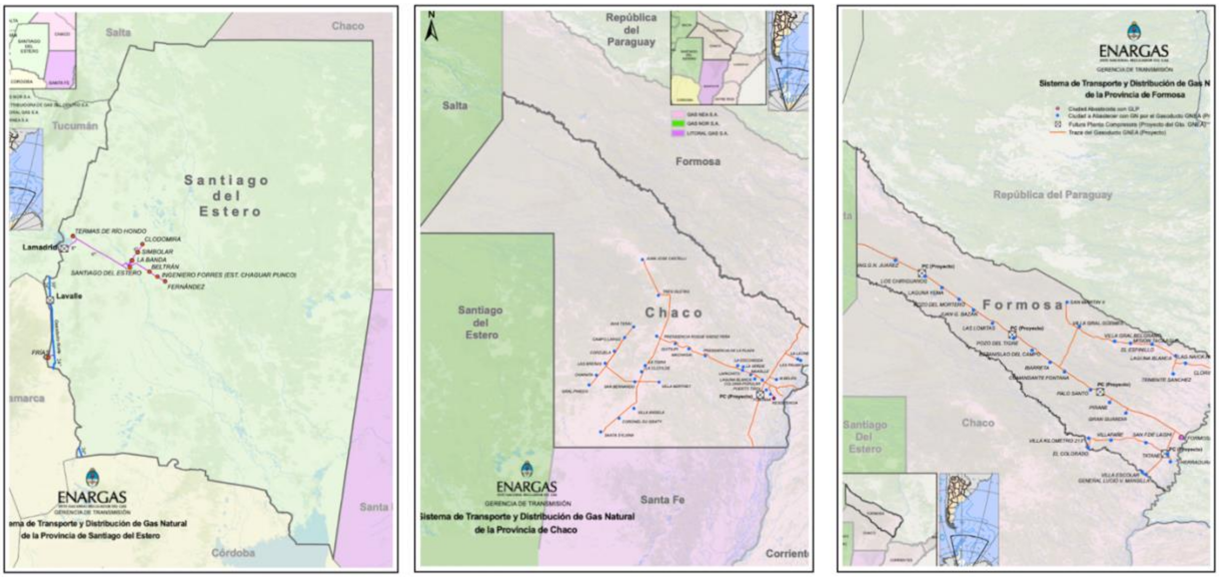

Figure 3.5. Locations whit gas network access [75].

3.1.2 Micro-level analysis

3.1.2.1 Weather specifications

Temperature is a relevant and influential topic when talking about organic fermentation. Temperature can play a very important role in digesting since it accelerates the methanogenic process. As it was said in the section *" 2.2.2.2 Operating temperature"* the relative growth rate of methanogens is a function of the temperature, and it is commonly used as a reference to indicate the optimal temperature ranges.

To determine the average weather in the mentioned region information was provided by the SMN (National Meteorological Service) from Argentina [76]. Information was in Excel format ".xlsx" and contained for the 71 (seventy one) meteorological stations from the country daily temperatures measurements from the beginning of the year 2000 until the end of the 2021.

In order to show the information of relevance for this case, in the first instance work was carried out on the xlsx file to extract by meteorological station the average temperature of the winters and summers for the last 21 years and in this way estimate the extreme temperatures to which the biodigester system will be subjected. The criteria used to define winters and summers periods were relative to the southern hemisphere:

- Winters from June to August
- Summers from December to March

In order to simplify calculations, in both cases the extremes were included in their total number of days, i.e. winter goes from 01/06 until 30/08 (format dd/mm). Secondly, after obtaining the temperature averages for each meteorological location for winters and summers, the shaped information was entered in the QGIS program in the form of georeferenced points in order to make the heat maps that can be seen in the Figure 3.6.

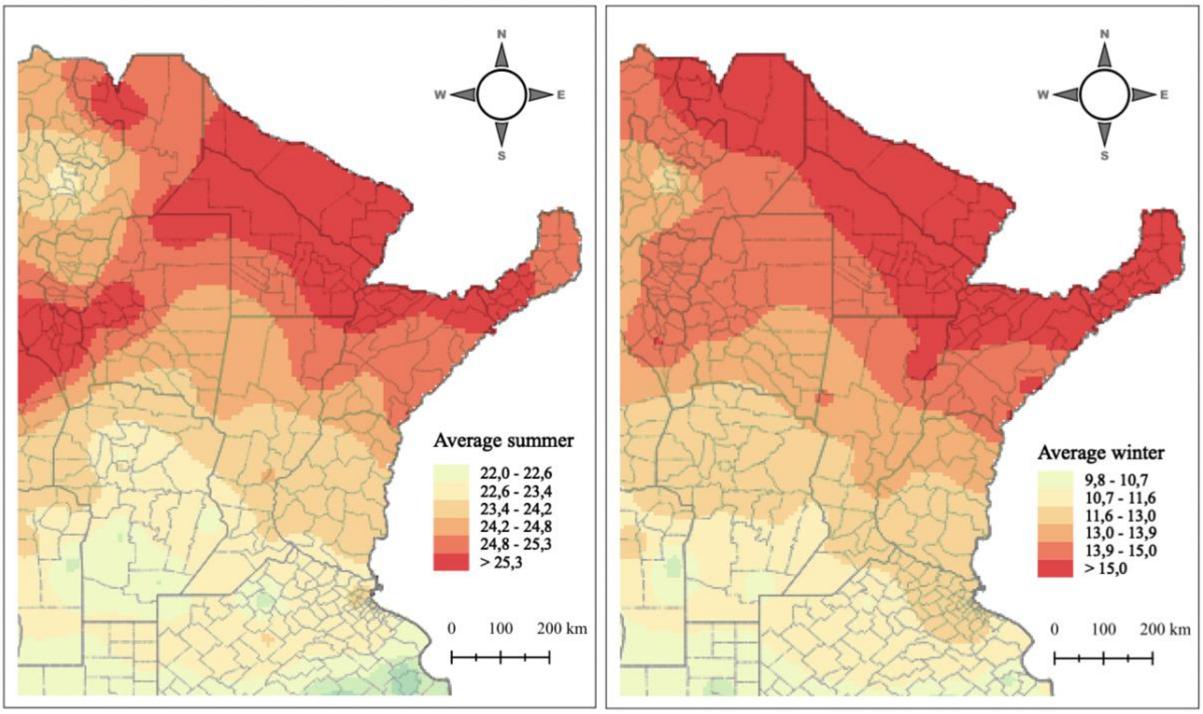

Figure 3.6. Extreme temperatures average (ºC) in QGIS. Own elaboration.

3.1.2.2 Target size definition

According to INDEC, the average size of an Argentinian family is between four and five people [73]. The definition of “family” to calculate the family size, refers to how it is composed from the point of view of kinship relations between the members and the presence, or not, of both spouses. Thus one can distinguish between family households (those representing relationships of kinship between its members) and non-family members (when there is no kinship relationship between its members); the latter includes the single-person households. On the other hand, nuclear home households are recognized (the couple lives together, with or without children) and the incomplete nuclear (one of the spouses is absent). Extended households are also contemplated (nuclear plus other relatives) and household compounds in which are also found other non-relatives [77]. Since there is no further or more specific information about the region, the family size will be established by the national measurements and criteria of the state entity INDEC.

Since the areas of interest are rural regions, in this specific case the input aims to be similar but the daily amount of feedstock will differ from the commonly used. Unlike other projects, now the main objective will be to provide small families of low income, located in the region mentioned in previous sections of this paper, that do not necessarily own large extensions of territory to cultivate or raise livestock but may have a small vegetable garden and some animals to supply their daily food needs, with a basic amount of biogas to cook food for an average family size of five people.

3.1.2.3 Feedstock available

As mentioned in previous sections, due to the extensive length of Argentina's territory, different economic activities and wastes can be found depending on the geographical location and factors such as temperature, altitude, dryness, and humidity, population size, etc. Having already focused on the north-central region of the country, it now remains to identify the main activities that take place in that region in order to identify which of them are potential creators of outputs that can be used as feedstock in a biodigester that will later allow knowing the potential efficiency and biodigester characteristics.

In the following section, a full study regarding the available feedstock will be done. Argentina's diversity, usually makes it difficult to characterize and find homogeneous activities. In this specific case, the main activities of the people who live and work in the region will be considered, therefore and based on that, a characterization of all the organic waste produced by carrying out these activities will be made, whether it be livestock/pork/goat, agriculture and even domestic organic waste. This yearly amount of units (UM) regarding each activity in some cases will be calculated using approximations suggested by the government statistics entities and using linear approximation due to lack of data. Information regarding the main productive activities in each region was obtained from the Ministry of Economy of the Argentine nation [78].

As can be seen in Table 3.1, the main economic activities in the provinces previously characterized as having the highest poverty rate and the lowest availability of basic resources are crop and livestock-related activities.

Knowing the main activities and the distribution within each province specified above is important to determine the main inputs available for the biodigesters.

Table 3.1. Santiago del Estero and Chaco main activities per year [26,27].

	UM	2017	2018	2019	2020	2021	% Nat Particip
Santiago del Estero							
Soybeans	Thousands tn	2737	1915	2498	3160	2356	6,2%
Corn	Thousands tn	4634	2408	4262	4484	3662	8,4%
Sorghum	Thousands tn	361	309	484	304	151	9,7%
Bobbin	Thousands head	1294	1390	1517	1604	1656	3,1%
Caprine	Thousands head	607	608	567	569	575	12,5%
Chaco							
Soybeans	Thousands tn	1200	1100	1280	1367	1404	3,8%
Corn	Thousands tn	975	1233	1330	1280	1307	2,9%
Sunflower	Thousands tn	580	663	750	695	706	16,0%
Bobbin	Thousands head	2006	2610	1973	2659	2013	3,9%

Figure 3.7 and Figure 3.8 show the amount of crops harvested and livestock by department for the province of Santiago del Estero for the year 2020.

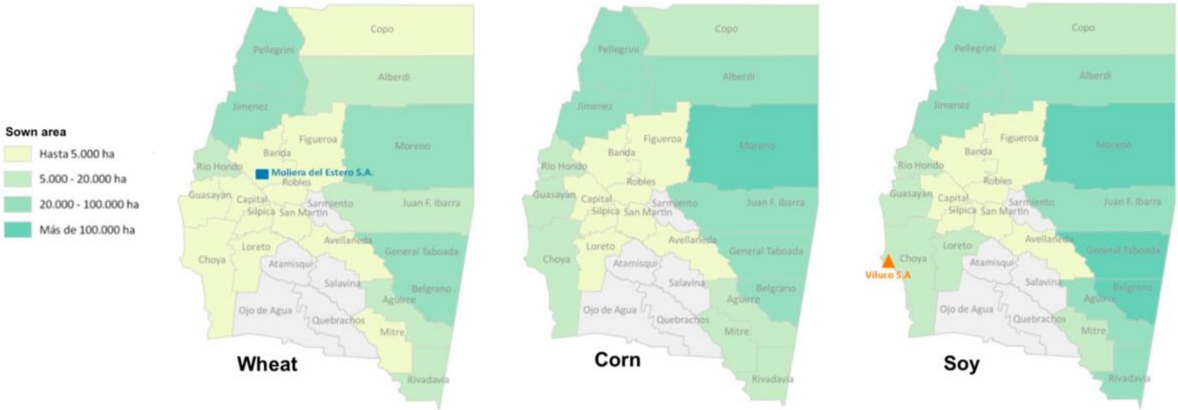

Figure 3.7. Sown area in Santiago del Estero [78].

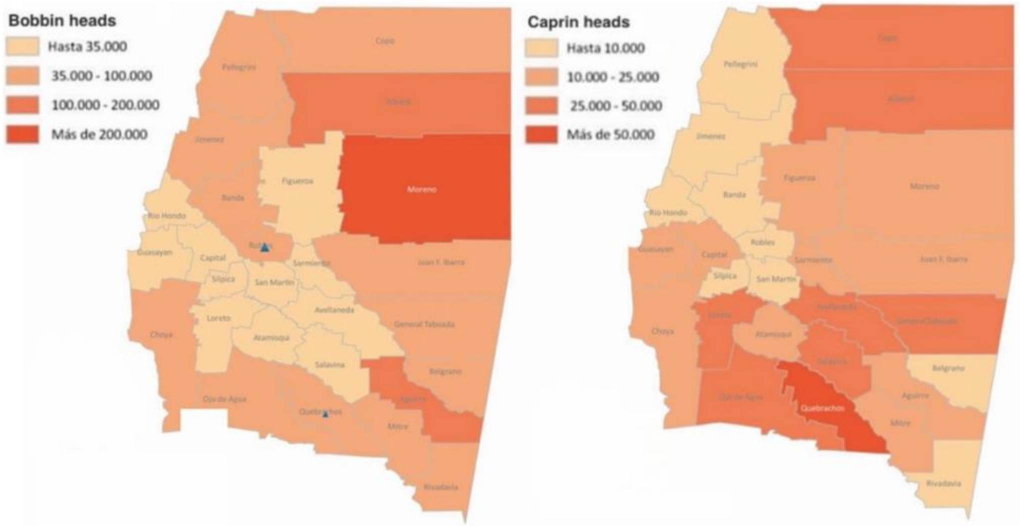

Figure 3.8. Bobbin and Caprine heads in Santiago del Estero [78].

On the other hand, *Figure 3.9* shows the amount of crops harvested and livestock by department for the province of Chaco for the year 2019.

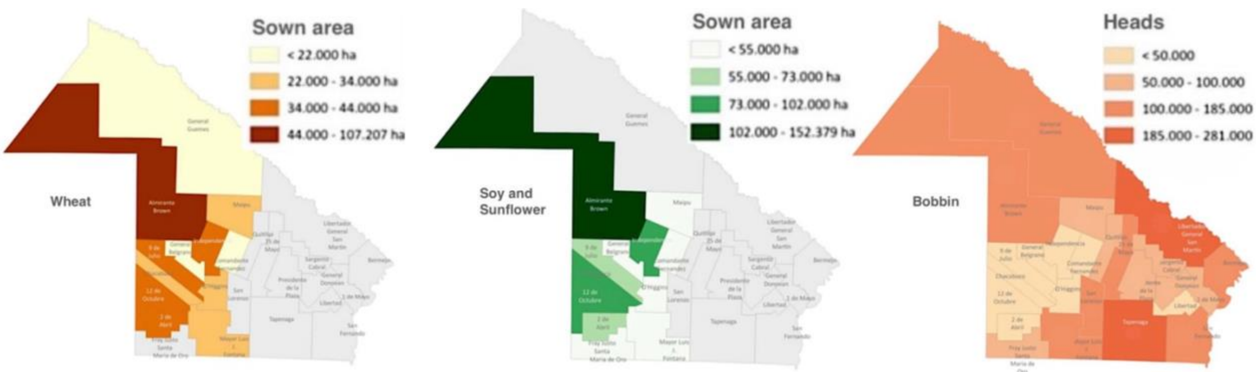

Figure 3.9. Activity development in Chaco [79].

3.1.3 Biomass characterization

The amount of biogas produced will depend mainly on how much of the material can be digested and converted into biogas by the bacteria in the digester. The amount of material (feedstock) that can be digested will depend mainly on two variables: the total solid content and the volatile solid content of the material added to the digester.

Table 3.2, shows for each of the materials that could be used as feedstock the %TS and %VS that will help later in this chapter to do the calculations to size and characterize the equipment needed in order to fulfill the objective of supplying a four members family with enough gas for their daily cooking needs.

Table 3.2. Santiago del Estero and Chaco's main substates characteristics [80–84].

Substrate	% TS	VS (% of TS)	% VS	Biogas yield m^3CH_4/Kg VS
Cattle manure	40%	79%	32%	0,42
Caprine manure	80%	80%	64%	0,37
Soy	85%	90%	77%	0,3
Corn	30%	90%	27%	0,35
Sorghum	80%	90%	72%	0,35-0,4
Dog manure	80%	45%	36%	0,15
Food waste from households	25%	85-94%	23%	0,32
Pig manure	35%	85%	30%	0,50
Fry fat/oil	90%	95-100%	88%	0,70
Horse manure	30%	80%	24%	0,17

To predict how much biogas will be produced with the available wastes in the region of interest, one needs to know the total solids content (%TS) and the volatile solids (%VS), that can be obtained from any organic material knowing the composition of each organic compound; fats; proteins and carbohydrates.

Besides the waste available from the main activities in the region, as can be seen in Table 3.2, to the classification of feedstock available in the region of interest made in section 3.1.2.3, a feedstock that normally exists in rural regions such as dog manure, food waste, pig manure, fry fat/oil, and horse manure were added to the list. Agricultural wastes and plants can be added to the reactor to increase biogas generation.

3.2 Design considerations

It has been proved that about 150/300 liters of biogas are needed to cook for one hour with a simple household stove under regular pressure conditions. It has also been shown that one person can regularly need 1 hour of cooking time considering lunch and dinner to fulfill their basic needs, therefore, based on the target definition and using a linear approximation, around 600-1200 liters of daily biogas supply will be needed to satisfy a four members family cooking needs [58].

Since it is not possible due to the lack of information and lack of structure that characterizes regions with high poverty rates to know how much organic waste is specifically generated per household, some assumptions will be made prior to addressing the mathematical model. Then the efficiency and performance of the different available stocks will be detailed to determine the necessary quantities and possible combinations in order to maximize the daily gas production.

The calculation will be based having as its main goal to maximize the amount of biogas that can be produced per day considering the available stock in each region. To achieve this goal a lineal mathematical model will be introduced in the following sections.

3.2.1 How to measure a family size biodigester production capacity

To measure a biodigester gas production oriented towards waste treatment, it is necessary to know the characteristics of the waste, mainly its physical composition (moisture, consistency, hardness), chemical composition (nutrients, organic matter, undesirable compounds for the bio digestion process, etc.) and the amount generated, preferably per day.

As mentioned in previous sections, the biodigester volume and operational volume can be sized through the hydraulic retention time HRT (average time interval over which the substrate is kept inside the digester) or through the loading rate. i.e., for the “Pampeana” region, located in middle Argentina, the ideal residence time is 40/35 days (minimum 30). The HRT is determined by the average working temperature in the region, the highest the temperatures, the highest the efficiency in organic decomposition, and the lowest the needed HRT.

Another option for sizing a biodigester is according to the amount of biofertilizer that a family farmer may need, although this one is the least required for small-scale digesters, instead of being an objective is a consequence for small biodigesters.

In this specific case, different assumptions will be made in order to simplify the calculations and finally obtain the estimated daily gas production.

On the first hand, the feedstock available is characterized considering its chemical composition as the percentage of carbohydrates, lipids, and proteins per one kilo of matter, then the %TS and %VS are obtained through a simple calculation that will not be covered in this thesis.

3.2.2 Sizing and calculation using Linear Programming

The problem of the production capacity knowing the feedstock daily availability for each region and the feedstock %TS and %VS was approached by implementing decision criteria using the concept of linear programming[2], the simplex method[3], and Excel’s solver as a tool to implement it.

The main objective is to maximize the daily amount of gas that can be obtained from the digester with a maximum digester volume of only 400 liters, a size more suitable for the design of a modular kitchen that could be inside homes. Finally obtaining that the maximum daily gas production for a low-efficiency digester working in the mentioned region would be no more than 0,583m^3.

3.2.2.1 Thinking process

All equations and variables presented in this section will be deeply explained in the mathematical model. This section intends to present to the reader the thinking process step by step.

---

2 Lineal Programming: method to achieve the best outcome in a mathematical model whose requirements are represented by linear relationships.

3 Simplex method: standard technique in linear programming for solving an optimization problem, typically one involving a function and several constraints expressed as inequalities.

Experimentally it has been shown that a load in semi-continuous digesters should not have more than 10% to 15% of total solids to ensure the good performance of the process [85]. To obtain an estimate of the total water to be added to the feedstock, the solids content (kg of TS) of the mixture must first be calculated:

$$kgTS = \frac{\sum_{i=1}^{n} kg_{feedstock_i} \cdot \%TS_{feedstock_i}}{kg_{total_{feedstock}}} \quad (eq. 17)$$

This equation can be used from two different perspectives, the first one is leaving the optimal selection of the amount of kg of each feedstock to be used in the input mixture as a variable, this equation permits to know and stablish the limit in the amount of TS regarding the criteria used for semi-continuous digesters.

The second perspective is for the specific case of application in a particular and defined place where the daily input is known with exactitude. In this case, from the kg of TS the user would be able to deduce how much water is needed in order to establish a %TS range between the 10-15%.

By means of a simple mass balance, for both cases, the amount of water to add can be calculated how it is shown in Figure 3.10. The calculation is made to bring the waste (M1) with these characteristics to a total TS% no greater than 15% adding water (M2) and finally obtaining the mixture (M3):

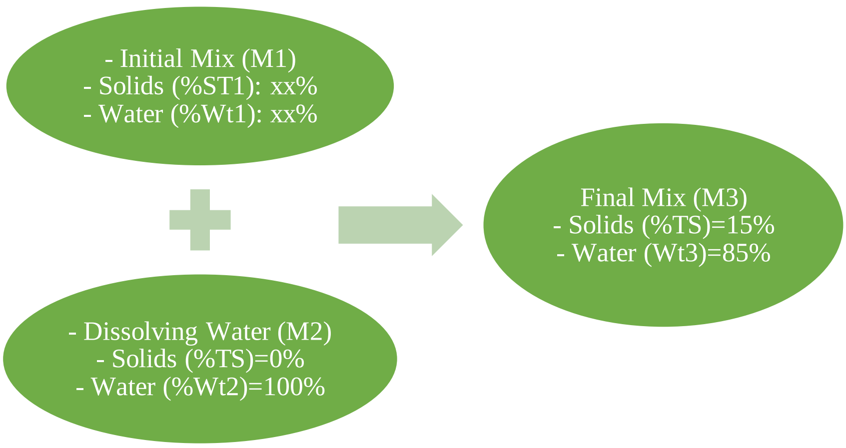

Figure 3.10. Mixture composition diagram. Own elaboration.

Balance and continuity equations that will be needed for the mathematical considering as unknown the final amount M3 are as follows:

- Final mixture:

$$M3 = M1 + M2 \quad (eq. 18)$$

- Dissolving water:

$$M2 = kgTS2 + kgWt2 \quad (eq. 19)$$

- Initial mix content:

$$M1 = kgTS1 + kgWt1 \quad (eq. 20)$$

From (eq.20) considering that %TS2 is equal to cero and stablishing the maximum amount of TS3 as 15% for M3 it can be obtained that the concentration of TS3 in M3 should be as follows:

$$15\% \geq \frac{kgTS3}{M3} \cdot 100\% \quad (eq.21)$$

By replacing (eq.19) and (eq.20) in (eq.18) and later inserting it in (eq.21), and considering %Wt2 as 100% and %Wt3 as 85%, can be obtained the minimum needed amount of water to add in the digestor in order to not the maximum permitted amount of TS in M3 as can be seen in ($eq.22$).

Now, from the masses balance it can be obtained that per each kg of waste, it is necessary to add M2 kg of water (or what is the same M2 liters). Depending on the amount of waste produced daily, the total amount of water per load will be:

$$Liters\ of\ water\ (M2) = \frac{kgTS1\ (0{,}85) - \ kgWt1\ (0{,}15)}{0{,}15} \quad (eq.22)$$

The total daily loading volume, considering the available feedstock as known and constant and the density of organic waste similar to the water density [86] would be as follows:

$$Total\ daily\ Volume\ (M3) = Litersof\ water\ (M2) + Loading\ waste\ Volume(M1)\ (eq.23)$$

Considering HRT of 35 days, as it was indicated for mesophilic working temperature, biodigester volume based on the known feedstock can be calculated as indicated in (eq.24). On the other hand, for the cases in which the total daily volume is a variable that could be obtained from different feedstocks following the objective criteria established by the user, the total daily volume would be instead of the daily charging volume that is a dependent of the variable Biodigester Volume.

$$Biodigester\ Volume = \ HRT\ \cdot Daily\ Charging\ Volume\ (M3)\ (eq.24)$$

Now, loading speed $\left[\frac{kgVS}{m^3 digestor}\right]$ rate can be calculated by knowing the digester volume and the feedstock properties as seen in (eq. 25).

$$Loading\ speed\ Rate = \frac{kgVS\ per\ day}{Biodigester\ Volume} \quad (eq.25)$$

It is important to know, as mentioned in previous sections, that the loading rate goes from 1 to 6 $kgVS$ per cubic meter of the digester and this value has limits that the user should consider in order to maintain a good microbial activity inside the containers.

The amount of organic dry matter or volatile solids could be calculated as:

$$kgVS\ per\ day = \sum_{i=1}^{n} [kg\ of\ waste_i \cdot \%VS\ of\ waste_i]\ (eq.26)$$

The calculation was made by including all waste listed previously in *Table 3.2*, where for each kind of feedstock (indicated with subindex "*i*") can be found the corresponding amount of %TS and %VS characteristic in each case.

3.2.2.2 Assumptions

Assumptions made and constant parameters:

⇒ Daily availability for each feedstock from each region is known and constant along the year.

⇒ Conversion rates are known and constants.

⇒ Working temperature is known and in the mesophilic range.

⇒ Digester volume will be stablished as 400L and useful volume (95%) – 380L since gas will be stored in an external storage.

⇒ Max %TS equals to 15% in digestion is known and constant.

⇒ Max amount of VS [kgVS/$m^3_{digester}$] depending on digester efficiency is known and constant.

⇒ HRT (hydraulic retention time) is known and constant.

⇒ Daily charging volume is known and estimated as Volume/HRT

⇒ Water density is assumed as 1:1, C/N ratio will not be considered into the equations and PH range is assumed in between 6,5 and 8.

3.2.2.3 Variables involved in the calculation

Variables and Parameters	Units	Description	Range
F_i	$\left[\frac{Kg}{day}\right]$	Optimal amount in kg of each feedstock	$\forall i \in [1\colon n]$
$\%VS_i$	$\left[\frac{KgVS}{Kg}\right]$	Volatile solid % of the selected feedstock	$\forall i \in [1\colon n]$
ε_i	$\left[\frac{m^3}{KgVS}\right]$	Biogas yield for each selected feedstock	$\forall i \in [1\colon n]$
A_i	$\left[\frac{Kg}{day}\right]$	Availability of each feedstock	$\forall i \in [1\colon n]$
M_1	$\left[\frac{Kg}{day}\right]$	Sum of total selected feedstock	–
M_2	$\left[\frac{Kg}{day}\right]$	Needed amount of water to add to M1	–
M_3	$\left[\frac{Kg}{day}\right]$	Mix resulting from the sum of total selected feedstock and water added	–
$\%TS_j$	$\left[\frac{KgTS}{Kg}\right]$	Total solids % for the mixes M1, M2 and M3	$\forall j \in [1\colon 3]$
$\%Wt_j$	$\left[\frac{KgWt}{Kg}\right]$	Water % for the mixes M1, M2 and M3	$\forall j \in [1\colon 3]$
HRT	$[days]$	Hydraulic retention time according to the working temperature	–
FGD	$\left[\frac{m^3}{day}\right]$	Family gas demand that could go from 0,6 to 1,2 m^3	–
OLR	$\left[\frac{KgVS}{m^3\ digester}\right]$	Maximum admitted amount of organic loading rate (VS) per m^3	–
$IDCV$	$\left[\frac{KgM3}{day}\right]$	Ideal daily charging volume depending on the digester volume and the HRT	–
RDV	$[m^3]$	Real digester volume that is available for the digestive process	–

Table 3.3. Variables and parameters involved in the mathematical model.

3.2.2.4 Maximizing gas production: Mathematical model

The solution was approached by settling as the main objective of the model the maximization of the gas produced per day, considering the volume as a fixed parameter equal to 400L or, what is the same, 0.4m^3. The objective function was defined as the sum and product of the optimal amount of feedstock to be selected, the %VS for each of these feedstocks and their respective gas yield, as can be seen in (eq. 27).

$$Max \sum_{i=1}^{n} F_i \cdot \%VS_i \cdot \varepsilon_i \quad (eq. 27)$$

When the volume of the digester is settled as a fixed parameter, some more variables are conditioned, making it necessary to introduce constraint equations that will allow to make an estimation as close as possible to what may happen in reality. Continuity equations remains the same as listed in the previous section for masses balance M1, M2 and M3.

Restrictions and conditions are stablished for calculating the optimal performance of the digester, such as not exceeding the maximum allowable OLR and that M3 not necessarily need to be equal to IDCV, meaning that it might be possible that the total amount of content in the digester could be lower than the RDV.

More restrictive equations were considered according to technical and theorical limitations presented in the model. Limitations like the maximum theorical amount of VS (eq. 28) and TS (eq. 29) that can be introduced in a digester in order to maintain a good microbial activity were considered in the model, together with limitations over the selected feedstock that cannot exceed the available feedstock in each region (eq. 30) and the restriction or condition over the real daily charging volume (M3) that cannot exceed the ideal charging volume (eq. 31) .

$$\frac{\sum_{i=1}^{n} F_i \cdot \%VS_i}{RDV\ m^3} \leq 2{,}5\ \frac{KgVS}{m^3} \quad (eq.28)$$

$$\sum_{i=1}^{n} F_i \cdot \%TS_i \ \leq \ M3 \cdot 15\% \quad (eq.29)$$

$$F_i \ \leq \ A_i \quad (eq.30)$$

$$M3 \leq IDCV = \frac{RDV}{HRT} \quad (eq.31)$$

3.2.2.5 Results

After defining the mathematical model, build and structure the needed data in Excel the model is implemented by using the “solver” tool obtaining that for the previously listed case, and under all the listed conditions, the maximum amount of gas that can be obtained is equal to 0,58 $\frac{m^3}{day}$ and the optimal combination of feedstock between the available listed amounts are pig manure 1,38kg and fry fat/oil 0,6kg as can be seen in Figure 3.11. From the figure can also be noted that fry fat/oil is the first compound to reach its limit.

By using a digester thank of 400L with an external gas storage deposit working under mesophilic conditions with a HRT equal to 35 days, a TS% content equal to 15%, an OLR considered for a low-medium efficiency digester equal to 2,5 $\frac{KgVS}{m^3 digester}$ can be noted that the results do not satisfy the basic daily gas demand of a typical family of four people, which was previously estimated at 0,6-1,2 $\frac{m^3}{day}$.

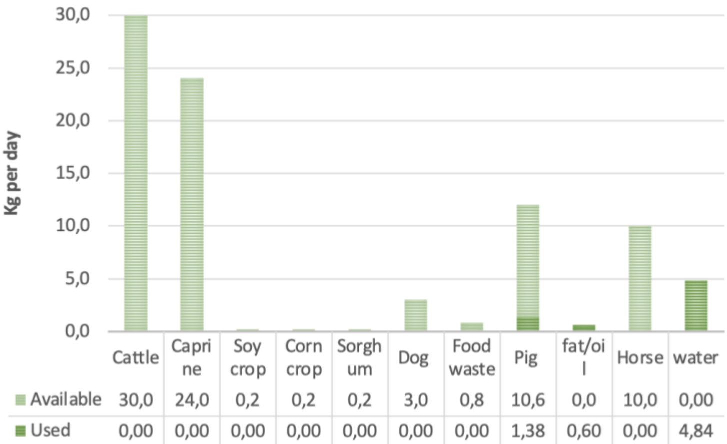

Figure 3.11. Feedstock optimal combination for a 400L digester.

With the objective of looking for different solutions and proposals that could satisfy the minimum daily demand, a sensitivity study was carried out on the results that will allow identifying which are the restrictions and parameters that are making it impossible to achieve greater efficiency in gas production.

In following sections the analysis will be performed to identify these parameters and evaluate the impact of increasing/decreasing the limiting resources, and to recognize the allowable increase/decrease if necessary. Along with this analysis, graphs will be introduced to evaluate the behavior of several parameters simultaneously when changing one constraint at a time, seeking to achieve the optimal design that will allow a family to meet its basic gas needs throughout the year.

3.2.2.6 Sensitivity analysis

The study of how a solutions of lineal programming is affected when parameters are changed is called sensitivity analysis and will be done over the limiting resources and constraints of the model, like the feedstock, the OLR and the DCV (daily charging volume).

As can be seen in the Table 3.4., those parameters that indicates cero in the slack column are limiting resources in the model, therefore, any variation on that amount will have a direct impact over the final solution. Note that the main parameters affecting the model are the admitted OLR, that is directly dependent of the digester volume (eq. 28), and the available amount of fry fat/oil available per family group. The DCV still have a slack of $4{,}04\ \frac{Lt}{day}$, meaning that for the optimal solution the tank does not need to be completely filled since the amount of TS in the feedstock satisfying the OLR should be diluted adding water until its %TS concentration reaches the 15% in M3.

The restriction over the %TS available in M3 could also be moved between 10-15% of TS in mixture in order to fill the tank completely by adding more water to dilute the kgTS existing in M1, but it would not be adding any extra value to the problem since it is a fixed working condition that is not affecting the final result.

Table 3.4. Variables slack.

Name	Value	Slack
Daily charging volume (DCV)	6,82	4,04
Organic loading rate (OLR)	0,95	0,00
Cattle manure Number of units Kg	0,00	30,00
Caprine manure Number of units Kg	0,00	24,00
Soy Number of units Kg	0,00	0,20
Corn Number of units Kg	0,00	0,20
Sorghum Number of units Kg	0,00	0,20
Dog manure Number of units Kg	0,00	3,00
Food waste from households Number of units Kg	0,00	0,80
Pig manure Number of units Kg	1,38	10,62
Fry fat/oil Number of units Kg	0,60	0,00
Horse manure Number of units Kg	0,00	10,00

In Table 3.5., can be seen for the constraints and the variables the sensitivity analysis. For the critical constraint OLR can be seen in the shadow price, how much the solution would increase if the OLR for the 380L could be increased by one unit. If the OLR would be 1,95 kgVS instead of the 0,95 kgVS allowed for this volume capacity, the obtained gas would increase in 0,5m^3. But since this is not the only constraint existent in the problem, it can only move between the allowable range, if the ORL constraint reaches the allowable increase limit of 0,515kgVS the new critical constraint will be the allowable DCV.

Table 3.5. Variables and Constraints sensitivity analysis.

Constraints

Name	Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
Daily charging volume (DCV)	6,816	0,000	10,857	1E+30	4,041
Organic loading rate (OLR)	0,950	0,500	0,950	0,515	0,410

Variables

Name	Final Value	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease
Cattle manure Number of units Kg	0,000	-0,025	0,133	0,025	1E+30
Caprine manure Number of units Kg	0,000	-0,083	0,237	0,083	1E+30
Soy Number of units Kg	0,000	-0,153	0,230	0,153	1E+30
Corn Number of units Kg	0,000	-0,041	0,095	0,041	1E+30
Sorghum Number of units Kg	0,000	-0,144	0,216	0,144	1E+30
Dog manure Number of units Kg	0,000	-0,126	0,054	0,126	1E+30
Food waste from households Number of units Kg	0,000	-0,041	0,072	0,041	1E+30
Pig manure Number of units Kg	1,378	0,000	0,149	0,060	0,024
Fry fat/oil Number of units Kg	0,600	0,180	0,630	1E+30	0,180
Horse manure Number of units Kg	0,000	-0,079	0,041	0,079	1E+30

From the analysis, can be deduced that since the temperature and the allowed %TS in M3 are fixed parameters the only two ways of obtaining different results is by either increasing the digester volume or increasing the efficiency of the digester in order to increase the OLR and admit more feedstock per daily charge.

The first thing to analyze is the critical constraint OLR. In Table 3.5., can be seen that for this digester volume the OLR can be increased by a maximum of 0,515kgVS without changing the critical constraint, meaning that the digester efficiency should increase from 2,5 $\frac{KgVS}{m^3 digester}$ to 3,85 $\frac{KgVS}{m^3 digester}$ in order to maximize the gas production and be able to obtain 0,85m^3 of daily gas. This goal is difficult to achieve working outside of a laboratory, but could be approached by doing different things like increasing the working temperature (adding an external heater) or by adding an external agitation device that could upgrade the digester admissible OLR to a value around 3-3,5 $\frac{KgVS}{m^3 digester}$.

With the aim of evaluating the influence of the OLR restriction over the model, the solver is executed for different OLR rates maintaining the digester volume constant and equal to 400lt, and thus be able to evaluate the possible impact of implementing some improvement in the digester design to increase the amount of volatile matter that can be daily digested. In Figure 3.12. can be seen that the relation between OLR and the digester production under the stablished working conditions is linear and can be estimated by the equation (eq. 32) with a R^2 equal to one, meaning that the linear approximation is very precise and accurate to what the model is describing.

$$F(OLR) = 0{,}019 \cdot OLR + 0{,}564 \quad \text{(eq. 32)}$$

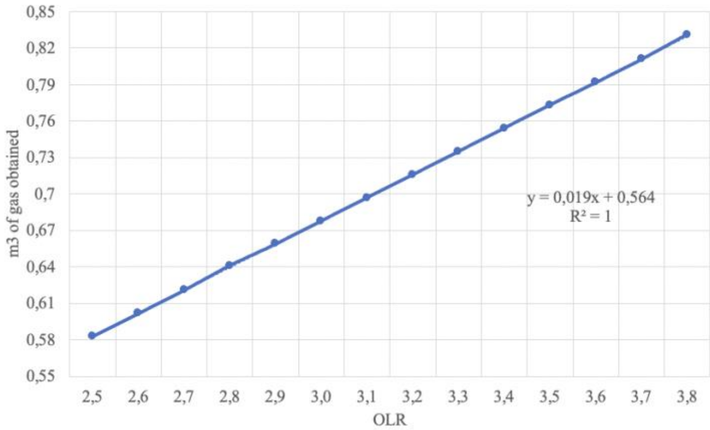

Figure 3.12. Daily gas obtained vs OLR for a 400L digester.

Another way of accomplishing the goal of increasing the daily gas production is by changing the digester volume by increasing it.

3.2.2.7 Volume variations

In order to make a more flexible solution and to be able to adapt the project to different regions depending on the local resources, the mathematical was also executed for different digester sizes. The original proposal was a digester of 400L that was easy to move and to locate inside the family house, having also the possibility to build a low cost modular kitchen cooking design.

In this case, and considering the same conditions and restrictions from the mathematical model, the focus will be in analyzing how variables and constraints change depending on the digester volume. It is interesting to see that the volume has a direct impact on the admissible amount of VS, meaning that by increasing the volume, at the same time the admissible amount of VS is increased, therefore, more gas can be obtained by daily introducing more feedstock inside the digester.

The model is executed mainly with two purposes :

- To see what are the optimal combinations of feedstock to use in kg for each biogas tank volume (Figure 3.13).
- To evaluate the daily gas production curve in function of the volume, for low-efficiency digester (Figure 3.14).

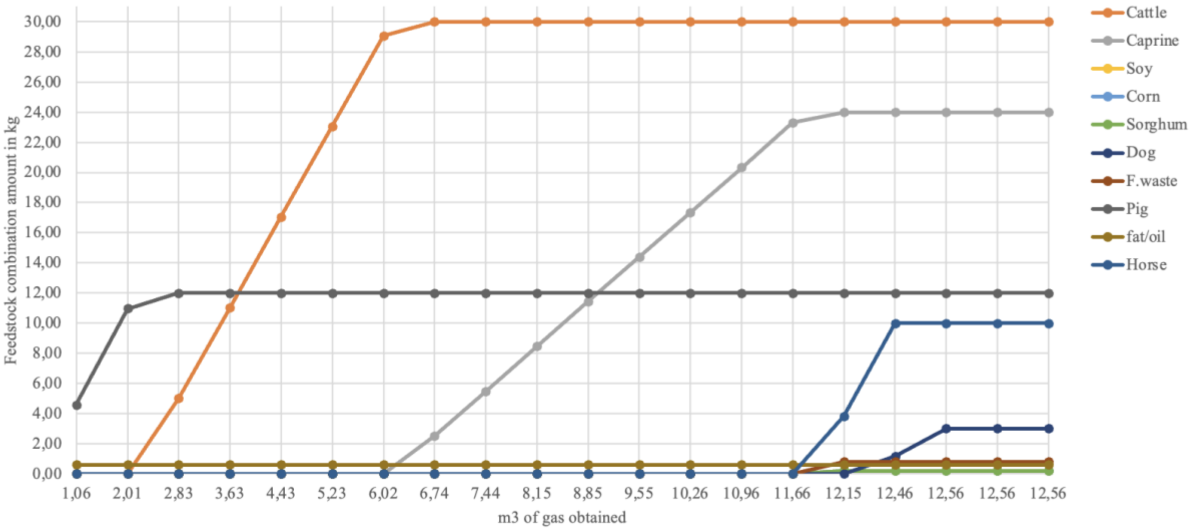

Figure 3.13. Optimal feedstock combinations for different gas daily demands.

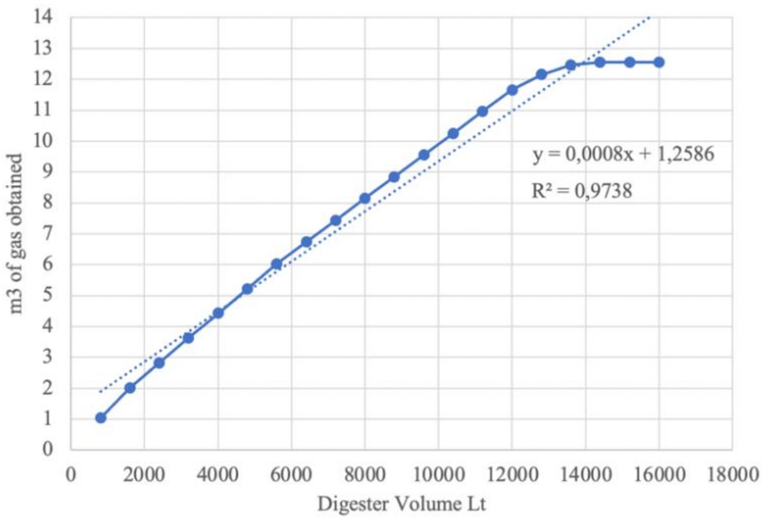

Figure 3.14. Daily gas obtained for different digester volumes.

In Figure 3.14., can be seen how the relation between the obtained gas and the digester volume (in liters) can be easily approximated to a linear equation (eq. 33) with a considerably high R^2 value, which means that working predictions by using the linear equations are accurate to the real results.

$$F(vol) = 0{,}0008 \cdot vol + 1{,}2586 \quad \text{(eq. 33)}$$

3.2.2.8 Improving digester performance

Research over similar projects has been made for this section to understand based on previous experiences the benefits and impact over the digestion efficiency of implementing a manual agitation device on a small-sized and low-efficiency digester.

The main objectives of implementing a vertical, manual (intermittent), linear agitation system is: removal of the metabolites produced by the methanogenic bacteria, mixing of the fresh substrate with the bacterial population methanogenic bacteria, mixing of the fresh substrate with the bacterial population, avoidance of the formation of crust formation inside the digester, uniformity of the bacterial density, and avoidance of "dead" spaces with no biological activity that would reduce the effective volume of the reactor.

It has been demonstrated in different experimental works that the simple fact of adding a mixer that allows mixing the contents inside the digester chamber, at least, before and after the daily charge, could have a significant effect on the effectiveness of the microbial activity in charge of digesting the VS content in the mixture [87].

It is not possible to calculate precisely the impact that would have the implementation of a mixer over this specific and theorical case, but approximations on the production level of the model can be established after considering different experimental results. Gas production efficiency assessment over digesters are usually done for both identical systems under identical working conditions, therefore, same digester volume, same amount of feedstock, same amount of VS in digestion, etc. Under those working conditions it was proved that digester efficiency could improve by a 7,56%, meaning that if the originally OLR of 2,5 $\frac{KgVS}{m^3 digester}$ is maintained, the daily gas production could raise from 583 $\frac{Lt}{day}$ to 627 $\frac{Lt}{day}$ [88].

For the mixer system selection, in this specific case, available low-cost and regional materials where considered. It should be taken into account that the anaerobic process involves a symbiotic equilibrium between various types of bacteria. The rupture of this equilibrium in which the metabolite of a specific group will serve as food for the next one will imply a decrease in biological activity and therefore a reduction in biogas production.

Agitation increases gas production and decreases HRT, basically for four reasons:

- Uniform distribution of temperature and substrate inside the biodigester.
- Uniform distribution of intermediate and final products.
- Greater contact between the substrate and the bacteria, avoiding the formation of clusters around the bacteria.
- Avoid the accumulation of sludge in the upper part of the digester, also called "cream" or "foam", which hinders the "foam" that hinders the biogas outflow.

3.2.3 Model design

Since the current work is focused on the feasibility analysis and implementation of small-scale digesters in regions that meet the conditions listed in previous sections, there will not be an extensive detail on the design of the digester together with all its parts, but instead, a preliminary design is made. The design intends to be a low-cost and easy to use model, that could be located inside homes and function as a modular kitchen as can be seen in Figure 3.15. Such a design can be easily covered by a low-cost structure made of phenolic material leaving openings for the entry and exit of material to the system.

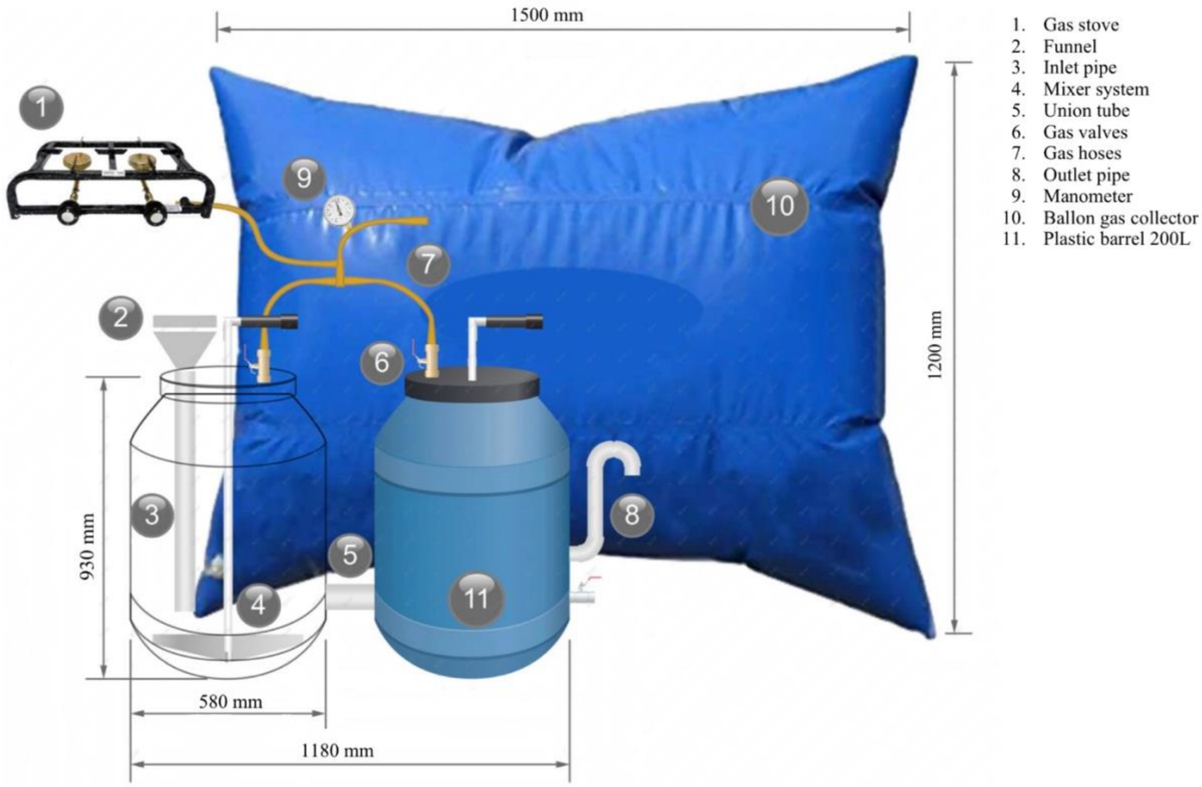

Figure 3.15. Model design scheme. Own elaboration.

In order to achieve a better understanding of the setup costs of a biodigester as shown in Figure 3.15, it was developed with materials that were considered costly. The list shown in Table 3.6. was made with regional and/or existing materials in Argentina.

Table 3.6. Basic list of needed materials for model design implementation.

Item	Description & Meassures	AR$ Unit Cost	AR$ Total Cost	U$S Cost
Removable inlet funnel	wide mouth funnel / old jerry can	ARS -	ARS -	USD -
PVC 90 degrees elbow	diameter 50mm	ARS 380,00	ARS 1.040,00	USD 8,67
Barrel 200lt	high: 980mm, diameter: 590mm	ARS 15.000,00	ARS 30.000,00	USD 250,00
PVC tubing	diameter: 50mm, length: 4000 mm	ARS 1.100,00	ARS 1.100,00	USD 9,17
PVC liquid valve	outlet, diameter: 50 mm	ARS 1.900,00	ARS 1.900,00	USD 15,83
Metal gas valve	female thread, diameter: 13mm	ARS 1.400,00	ARS 1.400,00	USD 11,67
Manguera para gas	diameter: 13mm, length: 500 mm	ARS 223,00	ARS 223,00	USD 1,86
Manguera para gas	diameter:13mm, length 1000 mm	ARS 305,00	ARS 305,00	USD 2,54
Balloon gas colecter	widht 1500mm, hight 1200 mm	ARS 6.000,00	ARS 6.000,00	USD 50,00
Manometer	screw-in, 10bar	ARS 1.000,00	ARS 1.000,00	USD 8,33
PVC adhesive welding	special PVC adhesive	ARS 400,00	ARS 400,00	USD 3,33
Stove	two burner adjustable stove	ARS 9.000,00	ARS 8.000,00	USD 66,67
Sealing silicone	mold resistant silicone to seal seams	ARS 640,00	ARS 1.280,00	USD 10,67
PVC tube cap	diameter 50mm	ARS 150,00	ARS 300,00	USD 2,50
	SubTotal #1		ARS 52.648,00	USD 441,23
Manual mixer system:				
Polypropylene outer tube	high: 1200mm, diameter: 1"	ARS 600,00	ARS 600,00	USD 5,00
Roller thrust bearing	COD SKF 51106	ARS 300,00	ARS 300,00	USD 2,50
Epoxy 90 degrees elbow	dual female thread1/2"	ARS 210,00	ARS 420,00	USD 3,50
Galvanized inner pipe	dual male thread 1/2"	ARS 780,00	ARS 780,00	USD 6,50
Epoxy "T" union	female thread 1/2"	ARS 250,00	ARS 250,00	USD 2,08
	SubToal#2		ARS 2.350,00	USD 19,58
	Total		ARS 54.998,00	USD 460,82

4 Technical aspects

The following chapter aims to introduce necessary considerations to be taken into account when using the equipment. For this purpose, two sections will be developed; the first section will address the value chain analysis of the project; the second section will address the necessary working conditions to achieve the maximum performance of the biodigester under the conditions indicated in the previous chapter, for which standard operating procedures for the user will be developed.

4.1 Daily working considerations

Working step-by-step scheme procedure is introduced, as can be seen in Figure 4.1, and later explained to instruct the user on how to make use the digester on a daily basis and at the same time to avoid possible errors that may affect the correct operation of the equipment.

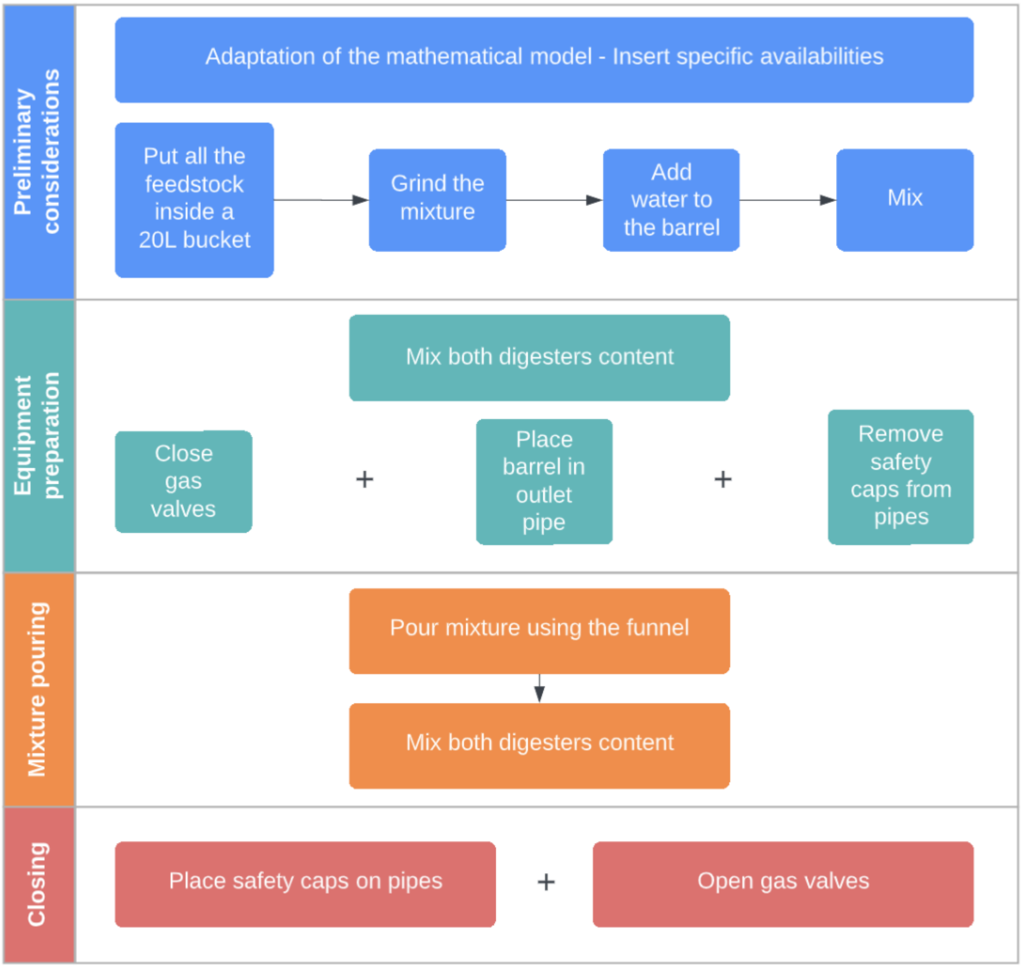

Figure 4.1. Step-by-step daily working scheme. Own elaboration.

4.1.1 Preliminary considerations

Since the model has been made by introducing an estimation over the daily available feedstock for a generic, not specific, four member family located in northern Argentina, probably that in some occasions these amount will not follow exactly all families availabilities restrictions, therefore, it is advisable before starting to use the equipment, to adjust the availability restrictions to the reality of each specific family, and thus facilitate each family group which would be the optimal combination and quantities of feedstock to use in each case.

4.1.2 Feedstock pre-treatment

After running the model for each specific group member, the feedstock should be placed in the indicated amounts by the model inside a 20 liters plastic bucket. The organic matter must be shredded as much as possible, achieving fragments that would allow the free flow of fluid through the digester system. Then, introduce water in quantities indicated by the model and stir the mixture until a unified solution of water and organic matter is obtained.

4.1.3 Equipment preparation

Once the mix is ready, close all gas valves in order to isolate the gas container and avoid possible gas leaks from the system during loading and unloading.

Place another 20 liter barrel under the outlet pipe of the digester that will receive the organic matter already digested and ready to be used as fertilizer in the plantations. It is expected, if the functioning of the digester is correct and the outlet pipe was placed at the correct height, that the amount of material leaving the digester daily will be equivalent to the amount of material entering the digester. remove the plastic caps from the feed pipe and the outlet pipe of the biodigesters. Once the feed pipe and outlet pipe covers have been removed, place the funnel in the feed pipe. That is to say, if 6,28 liters are loaded, the same volume should leave the system in order to maintain ideal working conditions.

4.1.4 Mixture pouring

Make sure that the above steps have been followed rigorously. Pour the mixture little by little using the funnel. Make sure that there are no obstructions in the inlet tube. If it is observed that the material does not flow, stop loading and use the manual agitator to move the mixture inside the barrel. If the tube is still clogged, use something such as an old broomstick or a thick brunch to push the mixture into the digester and remove any bulky fragments that may be obstructing the passage.

At each feeding, a volume of the liquid contained in the biodigester equal to that which has entered will overflow through the discharge outlet.

Figure 4.2. Liquid flow under stationary working conditions [89].

The liquid that emerges (digestate) should be collected in a plastic bucket to be disposed of as fertilizer in the desired location to be disposed of as fertilizer in the desired location after leaving it in contact with the air for at least half a day to oxygenate.

4.2 Technical considerations

4.2.1 Installation

After finishing the assembly and installation of the gasometer (gas bag) and the biodigester, quality tests are carried out to ensure correct operation.

4.2.1.1 Hydraulic test

This test consists of verifying that there are no liquid leaks in the biodigester. It is advisable to perform this test once the construction and assembly of the parts are finished, to check if the sealing of the parts was effective.

The reactor should be loaded with water up to the level of the outlet pipe. First perform a visual inspection on the sealing of the two flanges, the joint between the two barrels, the fertilizer outlet, and the manure outlet (outlet pipe).

The inspection should be repeated 24 hours after the tanks have been filled. In the case of finding a minimal leak, empty the biodigester and perform the sealing again where the problem was detected.

4.2.1.2 Pneumatic test

The pneumatic test consists of verifying that there will be no future biogas losses. In this case, with the biodigester filled with liquid up to the discharge level (discharge pipe), all the devices are connected together and the air is injected into the system through a compressor until the gas bag is completely filled.

There are two ways to perform the evaluation. The first is using a sponge and detergent, placing foam in each of the joints, and performing a visual inspection, observing if bubbles are formed. If there is minimal leakage, bubble formation will be found when detergent is passed.

Another way is after loading the gas bag with air to the limit, wait for 48 hours and verify that the gas level has not dropped. Note that there may be a fluctuation in volume due to changes in ambient temperature.

If a leak is found, reseal the joints and repeat this test until the system is airtight.

4.2.2 Start-up

Once the biodigester has been installed and its installation has been verified, the biological process is started up. First, the initial load (inoculum) is added to the biodigester starting the acclimatation phase that will work under “batch” mode and not under continuous conditions. The possible alternatives are:

a) Load the total volume of the biodigester with effluent in working proportional amount.

b) Load the biodigester with inoculum from another biodigester.

Since it is not expected that many biodigesters could be found in the region, option b) is not feasible.

Since there are considerable number of plantations and animal farms in the region with effluents suitable for use as inoculum, options a) is considered more suitable for this case.

As was mentioned in the previous section, the amount of volume that can be occupied by the available feedstock is limited by the OLR (2,5 kgVs/day) and therefore is lower than the available volume of 380lt. The result from the model indicated that the maximum loading total capacity is equivalent to the DCV (6,816 L/day) times the HRT (35 day), obtaining as its result a total volume of 238,56L. Having said this, families should accumulate a considerable amount of feedstock that could make possible this first load until the digester starts to operate in stationary mode.

For this first load and considering the complications that might have for a low-income rural family to have the optimal combination amount of feedstock available to put inside the digester, a simplification is considered to facilitate the initial loading procedure. Therefore, it is established as sufficient for the acclimatization phase, to fill the equipment by introducing the equivalent of 1/4 of matter or fresh manure of the available volume of the digester, and the rest of the water, leaving the mixture to work for 30-35 days under “batch” conditions, venting the gas produced every one or two days.

Once the degradation residence time of organic matter is accomplished, the biodigester can start to be fed on a “continuous” basis. The equipment will not work under ideal conditions for the first 45-60 days until it reaches the stationary mode and the acclimatization phase ends.

4.2.3 Operation

The biodigester, like any biological system, needs daily attention. It must be fed on a daily basis for optimum performance.

When solid waste is used for loading, the feeding is done by assembling the M3 mixture that arises from combining the M1 feedstock with the appropriate amount of water M2 indicated by the model result, so as to generate sludge and then place the mixture in the biodigester inlet. In case of finding residues on it, the volume of effluent extracted from the outlet can be added.

In case the digester is not used for a period of time that exceeds 35 days, when resuming the activity it will be necessary to start with a new acclimatization phase, as it is done during the start-up.

It is recommended for these reactors to have continuous and slow agitation throughout the day. However, to achieve this, a mechanical agitator should be available, and generally, for small and medium-scale digesters, manual ones are used. In these systems, it is recommended to agitate at least two or five times a day for at least two minutes. It is essential to stir before and after feeding, otherwise, a crust could form on the upper part of the biodigester (at the liquid-gas interface) similar to those formed in septic chambers.

When burning the biogas, the color of the flame should be observed. A blue flame indicates that the process is stable. A red flame, or a flame coming out of the burner, indicates that there is a problem. In this case, the gas bag should be emptied and the flame test should be performed again.

It is important to check that there are no gas leaks in the fixed and mobile installations of the biogas piping, from the biodigester to the burner. To do this, at least once a week, with a mixture of water and detergent, the connections should be cleaned with a brush and sponge. If there is a leak, the formation of a bubble can be observed.

4.2.4 Outlet effluent

In the case of the effluent, it can be applied in the compost bin or vermicompost, where there may be other types of waste that do not degrade in the biodigester (i.e.: leaves during the autumn that are generated in excess). This favors the decomposition and forms a product

stable product.

It can also be applied directly on the soil of the orchard or plantation that is not cultivated. In this case, after application, it is recommended to cover it with grass or dry leaves. This improves soil conditions, mainly: texture, structure, salt fixation, microbial development.

The effluent can also be used as "fertile-irrigation", for which, in order to preserve the food safety of the garden products, extreme precautions should be taken with leafy vegetables and fruits. In all cases, the use of personal protective equipment is recommended: latex or nitrile gloves and safety goggles.

4.2.5 Maintenance

Consistent, active and permanent operational maintenance is the key to maximizing the biogas system. A poorly running equipment can cause process upsets, undesired fluctuations, pipe or valve clogging, and even digester shutdowns due to erratic swings in the process conditions.

4.2.5.1 Weekly to monthly monitoring

For biogas to be used as cooking fuel, the biogas stoves need to be cleaned regularly in order to avoid clogging of the air intake holes that could occur because of dust or food particles.

Gas pipes, joints and stove need to be checked to ensure they are still gastight when valves are closed. This can be easily detected either by smell, as biogas contains small amounts of hydrogen sulphide which smells like rotten eggs, or by smearing some liquid detergent onto the place where leakages could be expected. If leaks are present, bubbles will be observed at those locations. Leakages need to be repaired immediately to avoid hazards to the kitchen staff. Condensed water in the pipes should be removed on a weekly to monthly basis to ensure that the biogas can pass through the gas pipe easily.

The appearance and odour of the digested slurry needs to be checked on a regular basis. If well digested, the effluent should not have an acidic odour (this would be an indication of overload or imbalanced microorganism population). Checking the pH of the digested slurry by means of litmus paper or a pH-meter can help to examine biological activity. A decision making diagram was elaborated for maintaining the adequate pH level as shown in Figure 4.3. If pH is lower than 6,5 or greater than 8, a buffer should be added and the content should be mixed until reaching the desired pH interval.

The gas pipes above ground, valves, fittings, appliances and gas storage balloons need to be checked for leaks. The section on ‘Annual monitoring activities’ provides methods on how to examine gas tightness.

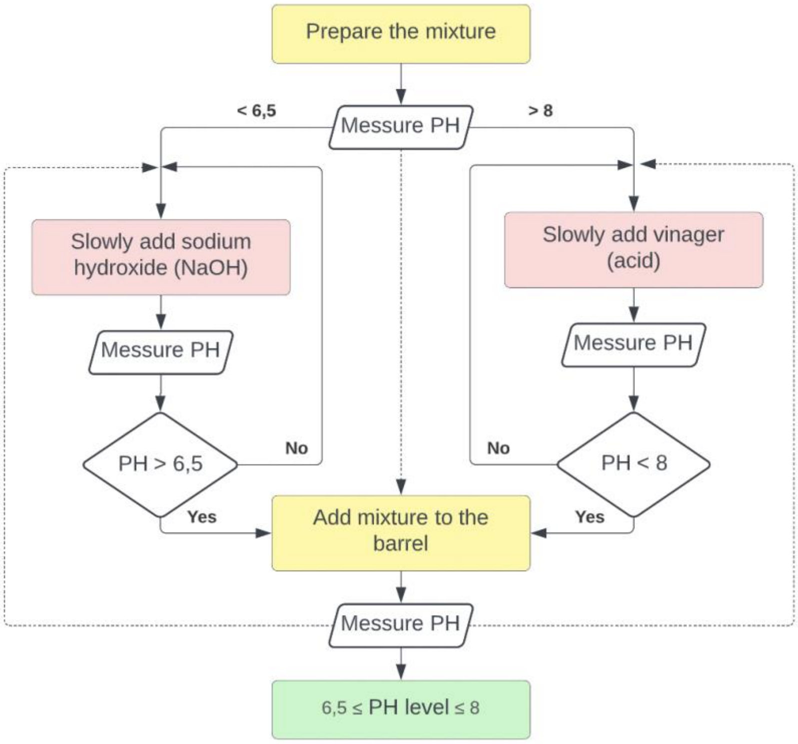

Figure 4.3. pH level decision making diagram. Own elaboration.

4.2.5.2 Annual monitoring

A list of methods on how to examine digester activity and tasks to perform when the biogas quantity that is currently reaching the gas stove is unstable or substantially decreasing is introduced in this section. Ideally, if no complications are found, these procedures should be done at least once a year.

- Control the biogas stove:

  The shape and form of the flame that is generated in the gas stove can provide valuable information about gas pressure and slurry conditions.

  - Elongated yellowish flame indicates incomplete combustion, therefore oxygen intake must be regulated.
  - Flame lifting off or too big, indicates excessive pressure (vent some gas and check diameter of injector not to be too big).
  - Flame extinguish or small flame can be motive of little gas flow or low gas pressure. Little gas flow may result from lack of pressure in the gas reservoir or a corroded or blocked injector which must be repaired.

- Control gas leakages

  Leaks can be detected by applying soap water on the dome, if accessible, and then repaired.

- Eliminate sludge accumulated at the bottom of the digester:

  If all the above measures have been performed but the gas production is still very low, it may be that over the years the active reactor volume has decreased because of accumulated sludge on the bottom of the digester. In this case, the sludge needs to be manually removed from the bottom of the digester. The frequency of desludging depends on many parameters but typically, if properly designed and operated, sludge emptying should only be necessary every 5–10 years. When removing the digester slurry and sludge through the compensation chamber, it is important to ensure that the health and safety of the labourers is not compromised. Prior to entering the digester, open all the gas valves and flush out the gas holder with exhaust gas from an engine. Ensure good ventilation before entering the digester and be aware of the risk of explosion.

5 Results and Discussion

5.1 Development considerations

Since the estimated minimum cost of implementing a digester system, such as the one proposed in the current work, is far beyond the purchasing power of low-income families in northern Argentina, it is necessary to count on the assistance and support of governmental agencies or non-profit organizations that could develop and accompany a progressive and comprehensive process of both capital and educational investment in these regions.

This work was made, from the beginning, with the main purpose of solving problems and basic needs of low-income communities in rural areas and in developing countries, where basic recourses like gas/energy are not provided by the government. Therefore, this work does not seek to monetize or generate profit from gas production using biodigesters, on the contrary, it seeks to provide a basic service to people in need and to solve health and environmental issues.

However, the Argentinian government is currently subsidizing gas bottles throughout the whole country area, under the "Hogares" program in a percentage corresponding to 80%, therefore, the implementation of biodigesters could not only help the family economy avoid the dependence on having to buy three bottles per month but also, in the long term, would benefit the Argentine state [90].

5.2 Energetic and economic analysis

Considering that a regular family of four people is demanding between 600-1200L of gas per day, for the current economic analysis, the lower end of the demand range is considered, since the purpose of this work is to provide basic cooking gas daily needs.

Different sources show that currently, four people families in northern Argentina are currently regularly consuming one liquified petroleum gas bottle (LNG) every 10 days, that means, a total of three bottles per month [91].

In terms of the cost of bottled gas in the regions covered by this study, it is subsidized by the state, as it was mentioned before, by an 80% under the “Hogares” program, and the cost for the people of the area is much lower than the regular cost of a home in any other place. It is estimated that the cost of a subsidized cylinder of gas in the region covered by the project is approximately AR$496 (U$S4,13)[4] per cylinder of 10kg or 13L.

Taking 600L/day as a reference value for biogas production, considering the ideal operation of the digester equipment, it is possible to cover in a the minimum daily gas demand which is equivalent to 150 L/day per person.

Note that the value used to estimate the daily demand was the minimum within the daily range of consumption that goes from 150L/day to 300L/day per person. If both ranges are considered, the daily demand coverage range is between 100% and 50% for each household.

4 Using as reference the actual rate provided by the Argentinian Republic Central Bank (BCRA) for the 18th of May of the 2022, 1 USD = 127,25 AR$.

These values support the importance of deepening efforts in the use of easy-to-implement alternative energies such as small-scale anaerobic digesters, in the energy efficiency of this equipment, and in discussing what plan should be carried out to cover this existing problem in low-income communities of northern Argentina.

The cost of materials for the construction of the biodigester, excluding labor, was estimated using regional products, giving a total of AR$54998 (U$S469). Estimating the durability of the biodigester of 10 years, its annual amortization could be calculated considering as a reference the equivalent cost of LNG currently consumed by the families, giving a total of 5499AR$/year (U$S46,9), equivalent to 458AR$/month (U$S3,9) and 15AR$/day (U$S0,13). The 600L/day, of biogas produced is equivalent to a cost in the cylinder of 49AR$/day (U$S0,42), considering that a regular family of four people in northern Argentina is using three LNG bottles per month and each of them cost AR$496 (U$S4,23).

Considering that the average monthly household income for low-income families is AR$37.830 (U$S322) [73], the current analysis indicates that the implementation of a project that allows the development of technology as simple as a biodigester could have an impact of 4% on the monthly economy of the families, without mentioning that in most cases it is necessary for people, in order to get one bottle, to get up early, make long trips and stand in long lines outside the gas distributors.

From the government point of view, considering that actually is subsidizing the real LNG bottle price of AR$2480 by an 80%, therefore, paying a total of AR$1948 for each bottle for a total of 2,84 million homes [90] that are using on average three gas bottles per month, the impact would be direct in its energy matrix expenses, saving a monthly total equivalent to AR$16903,68 millions (U$S132,84 millions) if ideally all families that are actually using LNG bottles could be provided with biodigester equipment. Hypothetically speaking, and considering the digester regional materials cost, the amount of houses under the poverty level and the monthly amount of money that the government is currently spending on gas bottles subsidizing, the government “payback” or “stop loss” period after investing the necessary amount of money to provide each of these families with a digestive equipment, would be no more than ten months as can be seen in Table 4.1 and Figure 4.4.

- Subsidized gas bottle price GLP per unit: AR$1.948 and U$S15,6 (80% of AR$2480)
- Gas bottles demand per family group: 3 u/month
- Government monthly saving: U$S132,84 millions (supposing that 100% of the total gas demand is supplied by the digester)
- Inversión: U$S 1.308,729 millions

Since the current work purpose is not to generate profit from building biodigesters, the payback time is defined as the minimum period of time theoretically necessary to recover the original investment in the form of project cash flows.

In the present project the payback time is obtained by comparing the initial investment and the institution's monthly savings. These savings are added monthly and deducted from the total investment. In the month in which a positive sum is achieved, that is to say that the savings of all the months is greater than the investment, this indicates that in that month the total of the investment made was recovered.

Table 4.1. Government initial investment and monthly savings in U$S.

Month	Investment	Savings	Difference
0	$ 1.308.728.800	$ -	$ (1.308.728.800)
1		$ 132.838.350	$ (1.175.890.450)
2		$ 132.838.350	$ (1.043.052.101)
3		$ 132.838.350	$ (910.213.751)
4		$ 132.838.350	$ (777.375.401)
5		$ 132.838.350	$ (644.537.051)
6		$ 132.838.350	$ (511.698.702)
7		$ 132.838.350	$ (378.860.352)
8		$ 132.838.350	$ (246.022.002)
9		$ 132.838.350	$ (113.183.653)
10		$ 132.838.350	$ 19.654.697
11		$ 132.838.350	$ 152.493.047
12		$ 132.838.350	$ 285.331.396
13		$ 132.838.350	$ 418.169.746
14		$ 132.838.350	$ 551.008.096
15		$ 132.838.350	$ 683.846.446

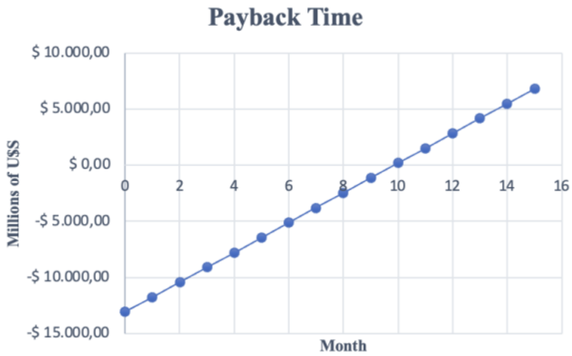

Figure 4.4. Government payback time in months.

When talking about cost, the digester system is a very strong and recommended alternative to the actual situation in the area. It is believed, that the main reason why this technology has not been developed in the area are the initial investment required to purchase the equipment, the logistics, the assembly, the instruction and training of the users, and the set-up of the equipment. The results obtained show the feasibility of developing a sustainable energy program considering only materials costs.

5.3 Social and environmental analysis

From the environmental point of view, i.e. the circular economy that is achieved from waste recovery to fertilizer production, it is convenient to implement an anaerobic digestion system, since the process has as its main objective the production of biogas (which will be transformed into caloric energy) and its by-product, secondary objective, can be used as fertilizer, thinking of the biodigester as an integrated technology in a system that is diversified in its production.

Particularly in the region studied in the present work, kitchen, vegetable garden, and farm wastes do not present a relevant problem, due to their low volume and distribution in the space they have. However, the existence of technologies that allow obtaining a valuable resource from something that is to give proper disposal to them, in order to avoid certain negative impacts that can cause bad management. In this case, the biodigester is a treatment alternative.

Socially, one of the main advantages of implementing new technologies in regions where there is great need is the education that can be provided to the people and the possibility of being self-sufficient and producing a valuable resource from waste that used to be discarded.

6 Conclusion

6.1 Achievements

This thesis presents the effective implementation model of family-size small biogas digesters in low-income rural areas in northern Argentina. Small Biogas digesters represent a tool to achieve rural areas sustainable development, giving access to a clean and free renewable energy source. The use of biodigesters in low-income rural areas serves as an environmentally friendly way to reduce health diseases due to charcoal burning, reduce biomass disposal, and improve family economies.

The digestive system proposed for families living in rural areas is simple and substantially for domestic uses and can even be installed inside homes. The maximum biogas yield can be obtained by following all instructions provided in the current work, and by adding extra tools to the system such as a heating system by using the power of the sun with solar panels.

Starting from the spatial analysis deep investigation of the country's current situation is done and segmented into two groups, the macroanalysis, and the microanalysis. In the macroanalysis is found how the poverty and the population are distributed in the country, together with the availability of the basic services, obtaining as result that a potential area of interest is northcentral Argentina, due to its poverty that reaches the 52%, low urban density, and lack of basic services like conventional gas. In the microanalysis, deeper investigation help to obtain the relevant data and characteristics for the mentioned area, obtaining that the average working temperature, after analyzing the SMN data from the different meteorological central stations of the country, is within the mesophilic range, that the public objective is a family of four people, and that the main economic activities are related to agriculture and animal husbandry, thus facilitating the existence of organic matter rich in VS content to feed the digesters. Finally, the biomass characterization shows the %TS, %VS, and biogas yield, which will later be the input data for defining the optimal feedstock combination to maximize the gas production.

The mathematical model proposed and developed in the design considerations section shows all the thinking processes to finally make the considerations and assumptions and, design a model that maximizes the daily amount of gas from the available daily feedstock per family group in the mentioned area. It is obtained from the model that the maximum amount that can be obtained per day is equivalent to 583L of gas. The obtained result may be lower than families' daily demand, but reaches 97% of the objective. The possibility of introducing a mixer that would make it possible to achieve the daily gas production goal is also introduced and analyzed, obtaining that a maximum amount of 627L of gas per day could be obtained, which means, an increase in the system performance of 7,56%, without changing the OLR rate.

The energetic and economic discussion demonstrates the potential of the implementation of this technology in the mentioned area, showing by numbers the impact that it would have in families and the savings for the government in the long term.

Overall, the results of the several stages in this work resulted in a general portrayal of the biodigester potential to produce the minimal basic cooking needs for families in northern Argentina, just by using the daily disposal from their activities and domestic animals, and of their crops, as well as some environmental, energetic and economic impact over the different actors involved.

6.2 Future work

For future work, it would be interesting to develop real trials of the proposed model, following the instructions provided in the current work, to obtain real information and evaluate the possibility to design a more complex, more efficient, and easy to use the equipment by, for example, adding solar heating and a pH regulator, that would allow obtaining greater amounts of gas per day by lowering the HRT and increasing the daily load amount and therefore, the OLR. In terms of humanitarian matters, the development of an elaborated, extensive and exhaustive project, that would help people in need to be auto sufficient in energy matters, and a support program to accompany and train people in the use of this type of energy and the potential that it has could be explored. Finally, based on the positive impact that developing a solution like this may have not only on the user's life and economy but also on the government's economy, a deeper financial and economic study based on a long term investment would be interesting to perform to know how much money could be saved over a ten-year period if an idea such as the one proposed here were implemented.

References

[1] Rohit Khanna, Radha Muthiah. The state of the global clean and improved cooking. ESMAP-Energy Sector Management Assistance Programme 2015.

[2] Masera OR, Bailis R, Drigo R, Ghilardi A, Ruiz-Mercado I. Environmental Burden of Traditional Bioenergy Use. Annual Review of Environment and Resources 2015;40:121–50. https://doi.org/10.1146/annurev-environ-102014-021318.

[3] Cohen AJ, Brauer M, Burnett R, Anderson HR, Frostad J, Estep K, et al. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. The Lancet 2017;389:1907–18. https://doi.org/10.1016/S0140-6736(17)30505-6.

[4] Ojo OM, Babatola JO. Evaluation of Biogas Production from the Digestion and Co-Digestion of Animal Waste, Food Waste and Fruit Waste. 2015.

[5] Jesus RHG de, Souza JT de, Puglieri FN, Piekarski CM, Francisco AC de. Biodigester location problems, its economic–environmental–social aspects and techniques: Areas yet to be explored. Energy Reports 2021;7:3998–4008. https://doi.org/10.1016/j.egyr.2021.06.090.

[6] Martínez Lozano M. Biogas potentiality production using pig manure in Guanajuato state. Revista Electrónica Nova Scientia 2015;3.

[7] Zafar S, Zafar Ilyas S. A Case Study to Bottle the Biogas in Cylinders as Source of Power for Rural Industries Development in Pakistan. World Applied Sciences Journal 2006;1:127–30.

[8] Kapdi SS, Vijay VK, Rajesh SK, Prasad R. Biogas scrubbing, compression and storage: Perspective and prospectus in Indian context. Renewable Energy 2005;30:1195–202. https://doi.org/10.1016/j.renene.2004.09.012.

[9] Coker Craig. Aerobic Composting And Anaerobic Digestion. Biocycle 2014.

[10] Hajji A, Rhachi M. The influence of particle size on the performance of anaerobic digestion of municipal solid waste. Energy Procedia, vol. 36, Elsevier Ltd; 2013, p. 515–20. https://doi.org/10.1016/j.egypro.2013.07.059.

[11] ISO/IWA. Guidelines for evaluating cookstove performance 2012. https://www.iso.org/obp/ui/#iso:std:iso:iwa:11:ed-1:v1:en (accessed March 8, 2022).

[12] WBA - World Bioenergy Association. Clean and efficient Cookstoves n.d.

[13] WHO - World Health Organization. World Health Organization Regional Offi ce for Europe SELECTED POLLUTANTS. n.d.

[14] Kushkevych I, Vítězová M, Vítěz T, Bartoš M. Production of biogas: Relationship between methanogenic and sulfate-reducing microorganisms. Open Life Sciences 2017;12:82–91. https://doi.org/10.1515/biol-2017-0009.

[15] Conrad R. Contribution of hydrogen to methane production and control of hydrogen concentrations in methanogenic soils and sediments. FEMS Microbiology Ecology 2006;28:193–202. https://doi.org/10.1111/j.1574-6941.1999.tb00575.x.

[16] Barton L, Hamilton WA (William A. Sulphate-reducing bacteria : environmental and engineered systems. Cambridge University Press; 2007.

[17] Burgess Clifford Caroline. Alternative Fuels from Biomass Sources - Anaerobic Digestion. Pennsylvania State University - Energy Institute 2017. https://www.e-education.psu.edu/egee439/node/727 (accessed December 3, 2021).

[18] Singh S, Kaushik KS. Factors affecting anaerobic digestion of organic waste. Warangal: 2018.

[19] Kumar BS, Subrahmanyam B, Akhil P, Prashanth B. Biogas: a renewable energy for future. International Journal of Mechanical Engineering Research and Development (IJMERD) 2018.

[20] Gumel SM, Yaro. Effects of Concentration and Catalyst on the Kinetics of Biogas Production from Cattle Dung at Thermophilic Temperature. Chemistry and Materials Research 1996.

[21] S Mtui GY. Trends in industrial and environmental biotechnology research in Tanzania. African Journal of Biotechnology 2007;6:2860–7.

[22] J. B. Van Lier, S. Rebac, G. Lettinga. High-rate anaerobic wastewater treatment under psychrophilic and thermophilic conditions. Water Science and Technology 1997;35. https://doi.org/10.1016/S0273-1223(97)00202-3.

[23] Lou XF, Nair J, Ho G. Field performance of small scale anaerobic digesters treating food waste. Energy for Sustainable Development 2012;16:509–14. https://doi.org/10.1016/j.esd.2012.06.004.

[24] Castano J, Martin J, Ciotola R. Performance of a Small-Scale, Variable Temperature Fixed Dome Digester in a Temperate Climate. Energies (Basel) 2014;7:5701–16. https://doi.org/10.3390/en7095701.

[25] Nayak SK, Pattanaik BP. Experimental investigation on performance and emission characteristics of a diesel engine fuelled with mahua biodiesel using additive. Energy Procedia, vol. 54, Elsevier Ltd; 2014, p. 569–79. https://doi.org/10.1016/j.egypro.2014.07.298.

[26] Oginni OT, Rominiyi OL, Adaramola BA, Babalola SA. Effect of Media Material on Biogas Production. World Journal of Engineering and Technology 2017;05:540–9. https://doi.org/10.4236/wjet.2017.53046.

[27] Bishir M, Atta H. Quantitative and qualitative analysis of biogas produces from three organic wastes. International Journal of Renewable Energy Research 2016;6.

[28] Hilkiah Igoni A, Sepiribo Kingnana Harry I. Design Models for Anaerobic Batch Digesters Producing Biogas from Municipal Solid Waste. Energy and Environmental Engineering 2017;5:37–53. https://doi.org/10.13189/eee.2017.050202.

[29] Ward AJ, Hobbs PJ, Holliman PJ, Jones DL. Optimisation of the anaerobic digestion of agricultural resources. Bioresource Technology 2008;99:7928–40. https://doi.org/10.1016/j.biortech.2008.02.044.

[30] Khalid A, Arshad M, Anjum M, Mahmood T, Dawson L. The anaerobic digestion of solid organic waste. Waste Management 2011;31:1737–44. https://doi.org/10.1016/j.wasman.2011.03.021.

[31] Kang AJ, Yuan Q. Enhanced Anaerobic Digestion of Organic Waste. Solid Waste Management in Rural Areas, InTech; 2017. https://doi.org/10.5772/intechopen.70148.

[32] Heo NH, Park SC, Kang H. Effects of mixture ratio and hydraulic retention time on single-stage anaerobic co-digestion of food waste and waste activated sludge. J Environ Sci Health A Tox Hazard Subst Environ Eng 2004;39:1739–56. https://doi.org/10.1081/ese-120037874.

[33] Zhang C, Xiao G, Peng L, Su H, Tan T. The anaerobic co-digestion of food waste and cattle manure. Bioresour Technol 2013;129:170–6. https://doi.org/10.1016/j.biortech.2012.10.138.

[34] Fricke K, Santen H, Wallmann R, Hüttner A, Dichtl N. Operating problems in anaerobic digestion plants resulting from nitrogen in MSW. Waste Manag 2007;27:30–43. https://doi.org/10.1016/j.wasman.2006.03.003.

[35] Motte J-C, Trably E, Escudié R, Hamelin J, Steyer J-P, Bernet N, et al. Total solids content: a key parameter of metabolic pathways in dry anaerobic digestion. 2013.

[36] Brown D, Shi J, Li Y. Comparison of solid-state to liquid anaerobic digestion of lignocellulosic feedstocks for biogas production. Bioresour Technol 2012;124:379–86. https://doi.org/10.1016/j.biortech.2012.08.051.

[37] Roman P. Taller-Biodigestores y Biogas. Paraguay: 2012.

[38] Sebastián F, Royo N-J, Circe HF. CICLO ENERGÍAS RENOVABLES JORNADAS DE BIOMASA GENERALIDADES. 2002.

[39] Dr Jain Sarika, Newman David, Nizhou Ange, le Feuvre Pharoah, Richter Hannah, Gobe Frederic, et al. global potentialof BG. World Biogas Association 2019.

[40] Vandevivere PC, Roberto Bianchi, Willy Verstraete. Treatment and reuse of wastewater from the textile wet-processing industry: Review of emerging technologies. Journal of Chemical Technology & Biotechnology: International Research in Process, Environmental AND Clean Technology 1998.

[41] J. B. Van Lier, S. Rebac, G. Lettinga. High-rate anaerobic wastewater treatment under psychrophilic and thermophilic conditions. Water Science and Technology 1997;35. https://doi.org/10.1016/S0273-1223(97)00202-3.

[42] Náthia-Neves G, Berni M, Dragone G, Mussatto SI, Forster-Carneiro T. Anaerobic digestion process: technological aspects and recent developments. International Journal of Environmental Science and Technology 2018;15:2033–46. https://doi.org/10.1007/s13762-018-1682-2.

[43] Carlsson M, Ab A, Schnürer A. Handbok metanpotential Rapport SGC 237 2011.

[44] Schnürer A. Microbiology of the biogas process Exploration of novel Syntrophs in state-of-the-art enrichment chemostat View project Energy Crops and manure in co-digestion, for improved farm scale biogas production View project. 2018.

[45] Ammenberg J, Bohn I, Feiz R. Systematic assessment of feedstock for an expanded biogas production-A multi-criteria approach. 2017.

[46] Rajendran K, Aslanzadeh S, Taherzadeh MJ. Household biogas digesters-A review. Energies (Basel) 2012;5:2911–42. https://doi.org/10.3390/en5082911.

[47] Gemechu FK. Evaluating the Potential of Domestic Animal Manure for Biogas Production in Ethiopia. Journal of Energy 2020;2020:1–4. https://doi.org/10.1155/2020/8815484.

[48] Borges Neto MR, Carvalho PCM, Carioca JOB, Canafístula FJF. Biogas/photovoltaic hybrid power system for decentralized energy supply of rural areas. Energy Policy 2010;38:4497–506. https://doi.org/10.1016/j.enpol.2010.04.004.

[49] Food and agriculture organization from the United Nations. Biogas characteristics FAO n.d.

[50] Mir MA, Hussain A, Verma C. Design considerations and operational performance of anaerobic digester: A review. Cogent Engineering 2016;3:1181696. https://doi.org/10.1080/23311916.2016.1181696.

[51] Takman J, Andersson-Sköld Y. A framework for barriers, opportunities, and potential solutions for renewable energy diffusion: Exemplified by liquefied biogas for heavy trucks. Transport Policy 2021;110:150–60. https://doi.org/10.1016/j.tranpol.2021.05.021.

[52] Chowdhury T, Chowdhury H, Hossain N, Ahmed A, Hossen MS, Chowdhury P, et al. Latest advancements on livestock waste management and biogas production: Bangladesh’s perspective. Journal of Cleaner Production 2020;272:122818. https://doi.org/10.1016/j.jclepro.2020.122818.

[53] Abdeshahian P, Lim JS, Ho WS, Hashim H, Lee CT. Potential of biogas production from farm animal waste in Malaysia. Renewable and Sustainable Energy Reviews 2016;60:714–23. https://doi.org/10.1016/j.rser.2016.01.117.

[54] Rupf G v., Bahri PA, de Boer K, McHenry MP. Barriers and opportunities of biogas dissemination in Sub-Saharan Africa and lessons learned from Rwanda, Tanzania, China, India, and Nepal. Renewable and Sustainable Energy Reviews 2015;52:468–76. https://doi.org/10.1016/j.rser.2015.07.107.

[55] Parawira W. Biogas technology in sub-Saharan Africa: Status, prospects and constraints. Reviews in Environmental Science and Biotechnology 2009;8:187–200. https://doi.org/10.1007/s11157-009-9148-0.

[56] Calise F, Cappiello FL, Cimmino L, D’accadia MD, Vicidomini M. A review of the state of the art of biomethane production: Recent advancements and integration of renewable energies. Energies (Basel) 2021;14. https://doi.org/10.3390/en14164895.

[57] Werner U, Stöhr U, Hees N. Biogas plants in animal husbandry. n.d.

[58] Voegeli Yvonne. Anaerobic digestion of biowaste in developing countries : practical information and case studies. Eawag-Sandec; 2014.

[59] Kandpal TC, Joshi B, Sinha CS. Economics of family sized biogas plants in India. Energy Conversion and Management 1991;32:101–13. https://doi.org/10.1016/0196-8904(91)90150-H.

[60] Deng L, Liu Y, Zheng D, Wang L, Pu X, Song L, et al. Application and development of biogas technology for the treatment of waste in China. Renewable and Sustainable Energy Reviews 2017;70:845–51. https://doi.org/10.1016/j.rser.2016.11.265.

[61] Singh KJ, Sooch SS. Comparative study of economics of different models of family size biogas plants for state of Punjab, India. Energy Conversion and Management 2004;45:1329–41. https://doi.org/10.1016/j.enconman.2003.09.018.

[62] Walekhwa PN, Mugisha J, Drake L. Biogas energy from family-sized digesters in Uganda: Critical factors and policy implications. Energy Policy 2009;37:2754–62. https://doi.org/10.1016/j.enpol.2009.03.018.

[63] Tigabu AD, Berkhout F, van Beukering P. Technology innovation systems and technology diffusion: Adoption of bio-digestion in an emerging innovation system in Rwanda. Technological Forecasting and Social Change 2015;90:318–30. https://doi.org/10.1016/j.techfore.2013.10.011.

[64] Ioannou-Ttofa L, Foteinis S, Seifelnasr Moustafa A, Abdelsalam E, Samer M, Fatta-Kassinos D. Life cycle assessment of household biogas production in Egypt: Influence of digester volume, biogas leakages, and digestate valorization as biofertilizer. Journal of Cleaner Production 2021;286:125468. https://doi.org/10.1016/j.jclepro.2020.125468.

[65] Ferrer-Martí L, Ferrer I, Sánchez E, Garfí M. A multi-criteria decision support tool for the assessment of household biogas digester programmes in rural areas. A case study in Peru. Renewable and Sustainable Energy Reviews 2018;95:74–83. https://doi.org/10.1016/j.rser.2018.06.064.

[66] Luis Gustavo Contigiani. Agriculture Department of Argentina . Https://WwwArgentinaGobAr/Agricultura/Alimentos-y-Bioeconomia n.d.

[67] Huerga IAI, Butti IAM, Venturelli IAL. Biodigestores de Pequeña Escala Un análisis práctico sobre su factibilidad Autores. INTA; 2014.

[68] Amb Ignacio Huerga Ing Agr Leonardo Venturelli I. Energías Renovables. Su implementación en la Agricultura Familiar de la República Argentina. 2011.

[69] QGIS. A Free and Open Source Geographic Information System n.d. https://qgis.org/en/site/ (accessed February 22, 2022).

[70] Banco Mundial. Argentina: panorama general 2021. https://www.bancomundial.org/es/country/argentina/overview#1 (accessed January 30, 2022).

[71] Central bank of the Argentinian Republic BCRA. US dollar - Argentinian peso rate. Http://EstudiodelamoCom/Cotizacion-Historica-Dolar-Peso-Argentina/ 2022. http://estudiodelamo.com/cotizacion-historica-dolar-peso-argentina/ (accessed February 22, 2022).

[72] IGN - Instituto Geografico Nacional de Argentina. GIS layers 2020. https://www.ign.gob.ar/NuestrasActividades/InformacionGeoespacial/CapasSIG (accessed February 22, 2022).

[73] Argentina R. Incidencia de la pobreza y la indigencia en 31 aglomerados urbanos. Primer semestre de 2021. Informes Técnicos 2021;5:182.

[74] Argentina R. Indicadores de condiciones de vida de los hogares en 31 aglomerados urbanos. Segundo semestre de 2020. Informes Técnicos 2020;5:83.

[75] ENERGAS. Provincial gas network Atlas 2020. https://www.enargas.gob.ar/secciones/informacion-geografica/atlas-provincial-del-gas.php (accessed February 22, 2022).

[76] SMN. Servicio Meteorologico Nacional 2021. https://www.smn.gob.ar/ (accessed March 9, 2022).

[77] Direccion general de estadisticas y censos - GCBA. INFORME DE RESULTADOS. 2010.

[78] Argentine Gobernment M of E. Provincial economy reports 2020. https://www.argentina.gob.ar/economia/politicaeconomica/informes-provinciales (accessed March 11, 2022).

[79] Maximiliano Guzmán M, Morra F, Storti AUTORIDADES Coordinación Yamila Méndez L, Cardin Rosa Gorzycki R, Busellini L, Sacco E, et al. Chaco productive report. 2021.

[80] Miranda AP, de Lucas Junior J, Thomaz MC, Pereira GT, Fukayama EH. ANAEROBIC BIODIGESTION OF PIGS FECES IN THE INITIAL, GROWING AND FINISHING STAGES FED WITH DIETS FORMULATED WITH CORN OR SORGHUM BIODIGESTÃO ANAERÓBIA DE DEJETOS DE SUÍNOS NAS DIFERENTES FASES ALIMENTADOS COM DIETAS FORMULADAS COM MILHO OU SORGO. 2011.

[81] Energy Partnership Programme between Mexico and Denmark. feedstock database for Biogas in Mexico 2020.

[82] Murphy J, Braun R, Weiland P, Wellinger A. Biogas from Crop Digestion Task 37-Energy from Biogas. n.d.

[83] National university of the northeast - Faculty of Engineering. Biogas made from dog manure. Https://ArgentinainvestigaEduAr/NoticiaPhp?Titulo=biogas_a_base_de_heces_caninas&id=992#:~:Text=Como%20resultado%20de%20la%20prueba,Gratuito"%2C%20resaltó%20el%20investigador 2011.

[84] Einarsson R, Persson UM. Analyzing key constraints to biogas production from crop residues and manure in the EU - A spatially explicit model. PLoS ONE 2017;12. https://doi.org/10.1371/JOURNAL.PONE.0171001.

[85] Cesaro A, Cieri V, Belgiorno V. Press-extrusion pretreatment of the organic fraction of municipal solid waste for enhanced methane production. Journal of Material Cycles and Waste Management 2021;23:130–8. https://doi.org/10.1007/s10163-020-01105-3.

[86] Tchobanoglous G, Angelakis AN. Technologies for wastewater treatment appropriate for reuse: potential for applications in Greece. Water Science and Technology 1996;33:15–24. https://doi.org/10.2166/wst.1996.0657.

[87] Singh B, Szamosi Z, Siménfalvi Z, An Z, Enfalvi S. Critical Reviews in Biotechnology Impact of mixing intensity and duration on biogas production in an anaerobic digester: a review Impact of mixing intensity and duration on biogas production in an anaerobic digester: a review 2020. https://doi.org/10.1080/07388551.2020.1731413.

[88] Keanoi. EFFECT OF WITH/WITHOUT AGITATIONOF AGRICULTURAL WASTE ON BIOGAS PRODUCTION FROM ANAEROBIC CO-DIGESTION-A SMALL SCALE. American Journal of Environmental Sciences 2014;10:74–85. https://doi.org/10.3844/ajessp.2014.74.85.

[89] Manual de uso del biodigestor. n.d.

[90] ANSES. Home Programme . Https://WwwAnsesGobAr/Programa-Hogar 2022.

[91] InformateSalta. Duration of a 10kg gas bottle 2010. https://informatesalta.com.ar/contenido/72087/cuanto-le-dura-una-garrafa-de-10-kg-a-una-familia-tipo (accessed May 17, 2022).