Optimization, Design and Construction of an Experimental Biogas System in a Small Dairy in Colombia

by

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ABSTRACT

With the global population reaching approximately 9.7 billion by 2050, questions on how life's necessities - food, energy, water, and infrastructure - will be supplied are becoming more relevant. These necessities generate specific challenges and demand prompt and appropriate solutions. Energy, with its ability to power cities, industry, rural farms, and everyday households, poses a challenge to many regions of the world, especially to those populations located outside major metropolises. This is part of the reason why the development and implementation of alternative energies are being held in the forefront of affordable sustainability. Alternative energies have already played a critical role in today's world by providing on-site energy generation with the adoption of different technologies. For example, anaerobic digestion (AD) is a technology that is being employed by rural communities in emerging countries to improve the quality of life. This alternative technology offers several benefits that could address some of the energy and environmental needs that these communities have incurred. Among those benefits, AD provides clean fuel for cooking, heating, and electricity generation. It is also used to treat wastewater, capture greenhouse gases (GHGs), and produce as an excellent fertilizer for crops. These benefits are more evident in agricultural operations where biomass residues can be used to generate heating or electric energy while offsetting part or all of the operational costs. Biogas systems can be a practical and cost-effective solution to energy generation, allowing small, remote, urban, or rural communities to establish and take full

advantage of the benefits. Countries all over the world are promoting and incentivizing rural communities and farms to adopt and utilize this technology, substituting electricity, propane, butane, natural gas, and kerosene. Several countries in Central and South America are implementing AD on a smaller scale compared with eastern countries, normally encouraged by private and public initiatives. Colombia, as an example, is working on determining whether alternative energies should be heavily promoted and subsidized, and if programs encouraging and facilitating people to adopt renewable energies should be carried out. Several challenging factors of this technology need to be addressed to guarantee its success in the most demanding conditions. Currently, most of these solutions are neither cost-effective nor practical.

Biogas systems in Colombia have been adopted, mostly by small and medium agricultural operations to generate biogas. However, the extent of the technology implementation is not known. One of the objectives of the World Bank, World Health Organization and United Nations Environmental Programme is to reduce the reliance on fuel wood as a heating and cooking system. The use of indoor biomass as a fuel has been attributed to respiratory illness at an estimated loss in human productivity of 110 million disability-adjusted life years (Putti, Tsan, Mehta, and Kammila, 2015). Exposure of children to wood and other biomass burning fumes can result in long-term respiratory illness (WHO, 2012). Due to the rural demographics and availability of costly traditional alternative energy sources being limited, biogas offers a healthy and cost-effective alternative to the traditional wood fuel option. The purpose of this research was to design an optimized, rugged, cost-effective, weather-resistant, low-maintenance biogas system, capable of withstanding UV degradation, and be puncture-resistant while staying cost-effective and easy to use and maintain. The dairy sector was selected due to its location in rural distribution, high organic content load, and large amount of water use, making it a perfect candidate for anaerobic digestion. This research project was composed of three components: (1) an evaluation phase, to determine the best concentration of solids to water ratio, (2) an optimization phase, to determine how physical chemical parameters affect biogas generation, and (3) an implementation phase, where a biogas system was designed and assembled in a dairy operation located in a rural region of Colombia. This system was designed using high-density polyethylene (HDPE) of 40 mil thickness, which has demonstrated a high resistance to environmental factors and physical damage (Topliff, thesis in preparation). This demonstration was conducted to identify construction needs, resistance, biogas output, as well as local acceptance and interest. The biogas system has the secondary benefit of enhancing micro and macro farming operation (dairy and crops) by substituting costly chemical fertilizers with the biogas effluent, increasing farm resilience and reducing operational costs.

The research project was demonstrated at a field day to the local rural community of Victoria, Caldas, and also to several private and public institutions. The goal was to demonstrate the benefits of a biogas system and to address any misconceptions regarding the installation requirements, maintenance, and costs. Among the attendees were local political candidates, swine farmers, cattle ranchers, dairy/cheese producers, waste management companies, Servicio Nacional de Aprendizaje – SENA (Learning National Service), the University of Caldas, and other nearby communities interested in the project. The project proved to be a successful technical and social experience and is, at present, fully operational, generating $1m^3$ or three hours of continuous burning gas per day. Community members continue to visit the biogas system, to learn, and integrate biogas into their own operations. One valuable lesson was the need for a comprehensive program to involve the women in the project and to inform them of the health and environmental benefits of using clean and safe biogas.

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CHAPTER ONE

INTRODUCTION

The United Nations (2015) calculated that, by 2050, the world's population will reach 9.7 billion people, with more concentrated populations located in emerging countries. This raises questions on how demands for energy, food, clothing, water, and infrastructure will be met for this future population. Currently, energy poses the greatest challenge due to the dependency of its generation to power cities, industry, households, and rural farms. Fossil fuels, hydro, nuclear, and bioenergy power will continue to provide the majority of energy in the next century. Existing and planned hydroelectric, thermoelectric (fossil fuels), and nuclear power will continue to provide energy from centralized points to larger population settlements, i.e. cities. The generation and distribution of energy are shifting to integrate other energy sources like solar, wind, and other alternative forms of biomass into the energy grid. This shift is occurring based on public perception (nuclear energy), availability of resources (fossil fuels), public health (air pollution), and environmental degradation (air pollution, acidification of surface bodies of water, and climate change). Additionally, energy distribution is changing from centralized to regional and local distribution, managed by computerized systems that control energy supply, i.e. smart grids. Furthermore, microgrids are being developed for self-powered and more resilient buildings, housing, commercial, industrial, agricultural operations (U.S.DOE, 2016). Institutions and stakeholders in the private and public sectors are becoming more aware of these factors and are starting to demand "greener" energy sources. Nuclear power use is slowly increasing in countries located in Eastern Europe and the Middle East, and research efforts are being taken to develop improved, cleaner, and more efficient reactors (Gates, 2012). Coal powered plants are being regulated more strictly and new air pollution control systems are emerging to control not only conventional (Mercury, Lead, $PM_{2.5}$, CO_x, SO_x, and Ozone) pollutants but also carbon emissions through carbon capture systems (Deutch, 2013). Hydropower is becoming a main go-to energy source, where it is viewed as renewable. Environmental concerns over the impact of providing water to move the turbines and current trends in climate change make it difficult to decide whether hydroelectric will continue to provide a high percentage of the future energy worldwide (Madani and Lund, 2009). Even though these conventional sources can provide some energy to more isolated areas, most emerging countries do not possess the resources and/or infrastructure to reach these regions. While solar and wind energies are expected to continue to grow, the development and refinement of new alternative designs is not expected to provide an affordable dependable energy source for isolated and small farming and residential areas. Biomass will continue being a major source of energy worldwide. Alcohols, oils, and biogas from anaerobic digestion (AD) will supply some energy for the future, while minimizing the public health and environmental impacts. Most importantly, biogas has a great potential to provide a cost-effective, safe, and environmentally sustainable energy source for small and isolated farming and residential areas in developing and developed countries. It is estimated that the conversion from burning for cooking to biogas would result in the reduction of 4.3 million premature deaths worldwide and prevention of cancer, and chronic respiratory, and eye illnesses (Hivos, 2014)

The World Health Organization (WHO) and the World Bank are heavily promoting the implementation of clean combustion systems in rural communities of emerging countries in order to reduce of indoor air pollution from burning wood and fossil fuels (coal, kerosene, and gasoline). Indoor air pollution from burning these fuels is directly linked to women and children health issues in many emerging countries due to the traditional role of women in these communities. Activities like cooking and heating in poorly ventilated homes can cause inhalation of particulate matter in spaces such as kitchens or one-room houses. Most of the communities impacted are rural communities with limited access to cleaner fuel sources. The lack of resources and lack of technical and financial assistance from governments force these small rural domestic and agricultural operations to resort to using the dirtiest energy sources available within their budget.

From all the alternative energy technologies available, anaerobic digestion (AD) is ideal for agricultural operations and small rural communities where access to energy sources is limited or non-existent. AD is normally used to treat waste streams with high organic loads in anoxic environments. This technology has been successful in several countries, such as the United States, Germany, Sweden, Austria, and Vietnam. (IEA, 2014) This process generates two main outputs: biogas that can be used for cooking, heating, and generating electricity and a liquid effluent that retains most of the nutrients and minerals, making it an excellent fertilizer. AD is an alternative technology that can serve as a source of energy and provide clean and safe fuel for heating and cooking.

Furthermore, AD also provides the following benefits: wastewater treatment, carbon capture, use of digested animal manure as a high quality organic fertilizer, and the capture of odors and methane emissions.

For the implementation of AD in rural communities and agricultural operations, dairies are an ideal candidate for biogas due to the considerable amount of manure that is collected and wastewater from milking parlors and feeding lots (Weiland, 2000). AD provides an advantage to rural communities by taking proactive steps toward treating wastewater and reducing the amount of organic loads discharged into surface or ground waters. In the United States, less than one percent of operational dairies utilize biogas systems for treatment, reuse, and recovery of by-products from their waste streams. However, biogas systems are being implemented at a steadily increasing rate all over the world, especially in emerging countries. China is an excellent example, with 27 million biogas systems operating in remote rural communities all over the country in 2011 (Bond and Templeton, 2011). If manure is used, dairy wastewater has a higher gross methane potential compared to other biomass sources (Krich, 2005), mainly due to the presence of methanogens and the wastewater's high organic content. These characteristics provide a tremendous opportunity for biogas technology to be implemented in dairies, if biogas systems can overcome challenges such as cost-effectiveness, maintenance, resilience, and weather variables.

On a smaller scale, the Americas are also using AD technologies in rural communities. Central and South America AD systems are commonly built using polyvinyl chloride (PVC) or low-density polyethylene (LDPE) plastics in tubular form. These digesters have an average life span of 3 to 5 years depending on the management, and must work under pressures of approximately 14 cm of water. Due to the thickness, quality, and variety of the plastic, these digesters are vulnerable to rupture, UV degradation, and puncture. Therefore, roof and fences are normally used to protect the digester. Also, depending on the concentration of solids in the wastewater, these digesters must be cleaned or flushed every 1-3 years to reduce the buildup of deposited solids and to restore biogas generation to its normal state. These digesters also require protection from low temperatures, which result in reduced microorganism activity and biogas generation. For digesters located in areas where low temperatures are predominant or seasonal, the implementation of a greenhouse or thermal insulation becomes necessary.

Most farmers are looking for sturdy biogas systems that can be installed and are able to resist a wide array of environmental factors, such as solar radiation, strong winds, hail, wind-blown debris (such as branches), livestock and incidental encroachment form cows, hogs, goats and people, and resilient biogas systems lasting for extended periods of time (more than 20 years) that are also easily repaired if punctured and maintained, allowing removal of spent materials. There is a generalized perception that AD is time-consuming, complicated, and requires specialized training, disincentivizing the adoption and implementation of this technology. For example, system repairs must be reduced due to the difficulty in accessing all areas of the biodigester, and the repairs must be done with minimal equipment and materials. This study is important, because global rural communities demand cost-effective, robust systems capable of operating for substantial periods of time without incurring extra costs, extensive maintenance and reuse and repair or being hindered by low temperatures. Thus, research objectives were (1) to identify optimum dairy feed stock for AD, (2) to understand how physicochemical parameters affect biogas generation and how they can be optimized to improve biogas systems' overall performance, and (3) to improve the AD design to prevent temperature loss and maintain biogas generation. Addressing these objectives will help develop a reliable, rugged AD that will not incur further additional costs for the families and agricultural operations using these systems.

This research project was designed and implemented with the objective of constructing a cost-effective biogas system utilizing high quality dairy feed stock that could generate, improve and maintain biogas generation while reducing the risk of rupture, UV degradation, and puncture, while withstanding seasonable temperature fluctuations. This project also aimed to design a biogas system capable of flushing out suspended solids without risking the integrity of the digester, allowing multiple uses reducing the costs for the farmer.

CHAPTER TWO

LITERATURE REVIEW: THE FUTURE OF ENERGY SOURCES, USE, AND DEVELOPMENT

A much-needed systems approach is required to understand agricultural operations, and their current and future challenges. Agricultural sustainability is paramount to meet the needs of future populations. Initiatives of entities, such as the United Nations Commission on Sustainable Development (UN, 1993), the International Institute for Sustainable Development (IISD, 1990), and events like the 2002 World Summit on Sustainable Development have been discussing the social and economic growth associated with human development, and its impact on the environment. These initiatives have also proposed the need to minimize or prevent these adverse effects in local, regional, and global settings. In addition, the International Panel on Climate Control (IPCC) (IPCC, 2013; Mani, et al., 2008) has shown evidence of impacts to the global environment, and consequently, the direct impact on the social and economic development of communities, as well as industrial and agricultural development.

The concept of sustainability has become the centerpiece of discussions as an approach to address global environmental problems such as environmental degradation, overpopulation, and the depletion of natural resources that will, subsequently, affect future generations. The design of production processes to generate products and reduce waste should be reassessed, and changes must be made to restore or, in any case, conserve resources. Similarly, agricultural and industrial systems must find new ways to reduce and prevent pollution and remain competitive.

Agriculture is a keystone of human development with factors such as soil erosion, water availability, and nutrient content affecting the production and capacity of a farm to continue producing in the same region. Integrating production processes by reutilizing materials allows agriculture to restore soil nutrient content and reduce water pollution (University of Kentucky, 2012). These processes can also include educating agricultural communities on new/alternative technologies, improving production, and minimizing impacts on the environment.

Rural areas around the world require large amounts of resources to continue operations and guarantee the production of goods. These goods are normally shipped locally or internationally. In emerging countries, goods shipped to national markets generate smaller profits compared to international markets. This phenomenon leaves less investment capital that could be used to improve the operations. Also, there are limitations among developing countries, like access to clean potable water, access to (**clean**) energy, technology, technical assistance, money, and public infrastructure, making the growth of these emerging communities more complex while expecting an optimum lifestyle.

The global energy demand is constantly increasing to meet continued population growth and development of emerging economies. Energy use projections (Deutch, 2013; IEA, 2011) have shown that the energy demand will increase worldwide with China, India, and Pakistan consuming most of the energy to meet their economic growth and export demands. Smaller emerging economies, such as Colombia and similar-sized countries, will also continue expanding their energy demand and consumption of coal, crude, and hydro power. These energy sources are considered conventional due to their historic use and ability to generate large amounts of energy from centralized points for ultimate distribution to large numbers of customers. Colombia, for example, is focusing on developing its oil exploration capacity and maintaining it at one million barrels and coal production at 95 million tons, maintaining 4^{th} place as one of the major coal producers worldwide (Sistema de Informacion Minero Colombiano, 2016). Also, the country is expanding hydro and coal-powered infrastructure to meet the increasing energy demands of the country. Globally, the energy sector is responsible for two-thirds of global greenhouse gas (GHGs) emissions. This sector's emissions are rising rapidly and will potentially reach 20% of the global GHGs by 2035 (EIA, 2013). The increasing demand of energy and public pressure on generating electricity from "greener" sources are driving the energy sector to diversify sources and energy grids to meet public and private demands. Recent developments in smart technology and microgrids are revolutionizing the supply of energy in Canada, the U.S., China, and India (El-Hawary, 2014). Additionally, smaller capacity energy sources are currently being designed to decentralize the energy from a regional supply to a local supply, reducing transmission losses.

This change is demonstrated by current trends where, in 2006, 88% of the energy demand was met with fossil fuels (IEA, 2006) which slowly declined to 82% in 2013, and it is projected to decline to 75% by 2035 through global implementation of renewable sources. Global implementation of renewable sources like biogas systems in rural communities, solar plants and on-off shore wind energy has also resulted in a decline on fossil fuel dependency around the world. In the future, most of the population growth and development will be located in Southeast Asia, which will become the main consumer of energy by 2035 (EIA, 2013). Increasing populations in other population growth regions such as Africa, Eastern Europe, and Central and South America will continue increasing their development and energy supply challenges. These challenges offer great opportunities for the adoption of alternative energies and boost the sustainable development of the least privileged communities.

Bill Gates (2012) mentioned that sustainable energy can be achieved by tackling current energy issues and achieving at least one of the following five milestones:

1. Carbon capture improved: supposing that natural gas (CH_4) will be used widely across the world. Carbon capture must reach efficiencies of up to 95%
2. Nuclear power: increase nuclear power generation by implementing clean, safe, cost-effective generation
3. Biofuels: improved and integrated into the energy and transportation systems
4. Solar: technology improved and integrated into the energy system
5. Wind: technology improved and integrated into the energy system, energy storage improved allowing changes in energy supply

2.1 Trend and future development and adoption of conventional and alternative energy sources

The following sections discuss the current and future roles of the most common sources of energy: coal, hydro, nuclear, solar, wind, and biomass to meet the future energy demands and its environmental impacts.

2.1.1 Coal

Coal maintains an important role in the generation of energy worldwide. If operations continue as usual, coal reserves could last up to 112 years, with the major coal producers being the United States, Russia, and China (World Coal Association, 2013). For the U.S., natural gas will replace many coal-powered plants and by 2035, 35% of the energy in the United States will be generated with natural gas, while coal-derived energy will generate only 32%. Most of these changes are regulatory and technologically driven. The U.S. Federal Government is rapidly moving to control GHG emissions and other pollutants like mercury. Natural gas (99% methane) is currently considered the best alternative and the most cost-effective resource for generating electricity while meeting regulatory constraints.

Colombia is investing heavily in fossil fuel exploitation and incentivizing foreign investment in the country. The primary source of energy is currently hydropower, with coal as a backup. Colombia exported 87% (81.96 MMst) of its coal production in 2013, demonstrating that little of this mineral is used nationally. Natural gas usage has grown in Colombia after the last energy crisis in the 1990s (Comision de Regulacion de Energia y Gas, 2016).

At a worldwide scale, coal consumption will increase 44% by 2040 due to its economic relevance. China, India, and Russia have heavily invested in the coal industry, and to discontinue its use as a source of primary energy would require a greater amount of resources. Furthermore, these countries have social needs that outweigh the problems associated with coal production and use; these challenges make future reductions of carbon dioxide ($CO_{2\ eq}$) difficult. Thus, to reduce CO_2 emissions from coal-powered plants, economically feasible carbon capture systems (CSS) must be installed to collect, transport, and store the carbon emitted (Deutch, 2013). Currently, CSS are being studied in depth to determine potential opportunities to meet newly established and future regulatory standards.

2.1.2 Hydropower

Hydropower has become one of the primary sources of alternative energy worldwide. Hydropower and the associated environmental impacts are mainly produced during the developmental phase. These impacts are partly due to the modification of the landscape required for the construction of the dam, inundation of bottom land and alteration in stream flows (C2ES, 2014). Hydropower is expected to see an average of 0.1% growth, with generation averaging 0.5% growth by 2035. Overall, growth in hydropower will be reduced as a result of the implementation of other renewable energy sources (EIA, 2011). Additionally, hydropower alone will help reduce approximately 2% of the worldwide GHG emissions, adding to the 33.5% cut from other alternative energy sources by 2050 (EIA, 2010). However, in the future, environmental impacts and unavailability of proper sites to construct large-scale hydropower operations will make this alternative impractical (Kosnik, 2008). Hydropower generation systems are more susceptible to climate change because the alteration of rainfall and temperature regimes due to climate change can affect generation. To improve resilience, these generation systems must expand their storage and generation capacity which will make it economically and environmentally infeasible (Madani and Lund, 2009). Colombia, for example, obtains approximately 70% (EIA, 2015) of its energy from hydropower and is currently building another hydroelectric plant that will start functioning in 2018 to generate 2,400 MW located in Ituango-Pescadero (HidroItuango, 2015). However, hydroelectric power is highly dependent on water availability, and "…*climate change itself is threatening the viability of big hydro projects today and tomorrow. Shifting rainfall patterns and chronic droughts are shrinking river flows and draining lakes, leading to decreased power generation at hydroelectric facilities*" (Foreign Policy, 2015).

2.1.3 Nuclear energy

Advances in nuclear energy have suffered due to the Fukushima Daiichi incident in 2011. In order to meet the carbon concentrations needed to reduce the environmental impacts, nuclear power would be an ideal alternative to provide future energy demands and would potentially substitute for part of the fossil fuel-based power generation worldwide. The future concentration of energy consumption is moving toward the East, where countries like China, India, and Pakistan are becoming the main consumers (Jonter, 2012). The Gates Foundation is sponsoring a fourth generation nuclear power generator to produce 1GW operations. Normally, nuclear plants take 0.7% of plutonium to generate energy. A fourth generation nuclear power generator will utilize 100% of the material through burn and breed, extracting the 0.7% and converting the 99.3% to the burnable material. The Gates Foundation will have a demo power generator by 2022, and by 2028, a full-scale fourth generation nuclear power plant will be completed (Gates, B., 2012).

Currently, the only countries in Central and South America that are using nuclear power are Mexico, Brazil, and Argentina (IAEA, 2015). Colombia has no intentions, present or future, to construct or operate a nuclear plant in any of the energy development plans.

2.1.4 Solar, Wind, and Biomass Energy

Presently, solar, wind, and bioenergy technologies have the largest investment and the fastest growth worldwide from all renewable sources. Their applicability is dependent on solar radiation and wind strength and is typically not affected by changes in temperature, rainfall, or weather patterns. Bioenergy, on the other hand, is highly susceptible to these physical parameters; however, newly developed technologies are allowing industries to take advantage of more complex cellulose-based materials, expanding its use to areas where sugar producing vegetation does not yet exist (DOE, 2011).

At present, there are three future scenarios being considered by the International Energy Agency (IEA) for the solar, wind, and biomass energy sectors. The first scenario, or 6-degree scenario (6DS), focuses on implementing renewable technologies to limit carbon emissions and to prevent global temperatures from exceeding six degrees Celsius. This scenario seeks to expand renewable energy in order to supply up to 27% of the total global energy. The second scenario, or 2-degree scenario (2D), replaces fossil fuels with renewable and nuclear energies to prevent global temperatures from exceeding two degrees Celsius. The 2DS proposal seeks to utilize up to 65% of renewable energies to supply global electric energy. The third scenario, or High Renewables Scenario (Hi-Ren), considered by some as radical, proposes to replace all fossil fuel and nuclear energy sources with renewable energy sources (Hi-Ren). In this scenario, renewable energies will comprise up to 79% of the total energy sources utilized to meet global energy demands. Figure 1 shows how these three scenarios could comprise the global electricity generation in 2050.

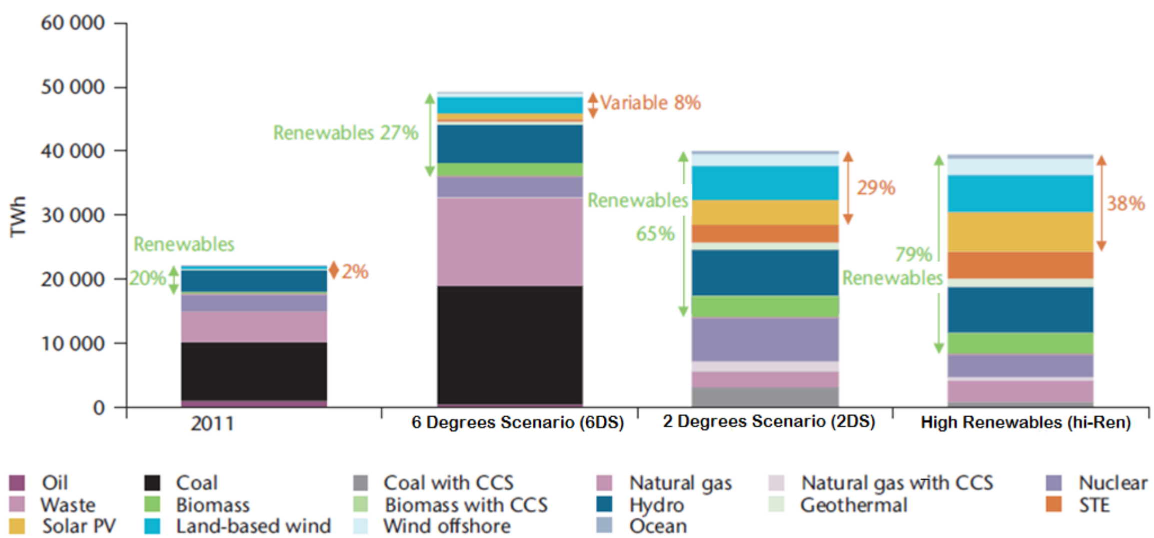


Figure 1. Global electricity sources in 2011 and future scenarios (Modified from IEA, 2014)

Solar Energy

Solar energy through Photovoltaic (PV) technology is presently one of the most relevant alternative energy sources. By 2010, the global community added new or had existing PV projects that surpassed anything done in the last four decades. In 2013, new PV systems were installed at a rate of 100 megawatts (MW) of capacity per day, with a total global capacity that passed 150 gigawatts (GW) in early 2014. Costs have been decreasing rapidly for solar panels and are expected to decrease from $240 USD/MW in 2010 to $45 USD/MW in 2050 (IEA, 2010). The U.S. energy information association (U.S. EIA) has developed extensive studies and metrics to compare energy cost per energy source (EIA, 2016).

Currently, the solar industry is working on reducing costs and increasing the efficiency of solar panels. For example, c-Si modules dominate 90% of the market, with an average efficiency of 16% in 2013. Companies are working towards increasing this factor up to 23% by 2015. Average efficiency is dependent on reducing degradation rates, increasing longevity (>25yr), and creating diversity for variable environments. If all these variables are improved, the increase in market share and accessibility for homes worldwide will increase, expanding its installation and usage (IEA, 2014).

Based on the international energy agency (IEA), China will play a critical role in the future by using14 GW/y in 2020, followed by the United States (5 GW/y), and Japan (3 to 4 GW/y). Currently, China has a fossil fuel-intensive power mix with health consequences that are forcing the country to change its energy policies and investments. If China decides to invest in a Hi-Ren scenario, it could eliminate 50% of global carbon emissions with the implementation of solar energy, as shown in Figure 2.

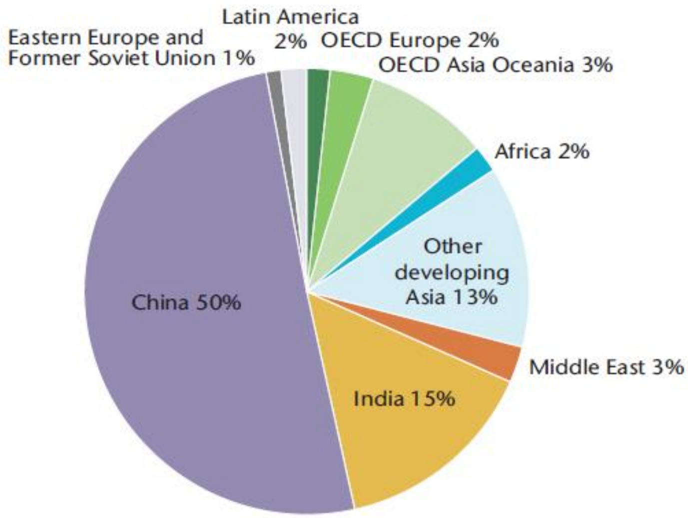


Figure 2. Carbon emissions reductions in 2050 due to PV implementation in a high renewable scenario (IEA, 2014)

Wind power

Wind power worldwide has doubled since 2008 and is approaching 300 GW of cumulative installed capacities. Figure 3 shows wind speed per region and capacity installed. This trend is led by China (75 GW), followed by the United States (60 GW), and Germany (31 GW). Currently, wind power provides approximately 2.5% of global electricity demand. The IEA expects that wind power will provide 15 to 18% of the global electricity by 2050, increasing its share by 12% (2009) (IEA, 2013). Wind power developments are predicted to have more relevance in places where stronger winds naturally occur. However, new research is being directed towards lower wind speed by increasing rotor height and blade size. The limiting factor of these new wind towers will be determined by weighing how costly and efficient they are against energy generated.

The IEA wind power roadmap estimates land-based wind power development to increase to 1,144 Terawatts/hour (TWh) in 2018. This projection includes exceeding 500 GW, with China being the largest cumulative capacity with a total of 185 GW, followed by the US (92 GW), Germany (44 GW), and India (34.4 GW). Also, countries that are part of the Organization for Economic Co-operation and Development (OECD) will produce over 44% of the global capacity. Offshore wind will continue to grow reaching approximately 28 GW by 2018 compared with 5.4 GW in 2012. In Europe, Germany and Denmark will continue driving much of the growth. The United Kingdom recently changed its energy policy by removing incentives and subsidies for alternative energy projects, for both rooftops solar and medium-scale onshore wind projects (BBC, 2015; Clean Technica, 2015; The Guardian, 2015). As wind power research generates new information, it will help to determine how this technology affects the environment of migratory and local bird species (Loss, et al., 2015).

Bioenergy

Currently, biomass is the largest source of bioenergy providing 10% of global energy supply. Bioenergy is a unique energy source that can be a solid, gas, or liquid. This energy source can then be used to generate electricity, as fuel for vehicles, heating and cooking, and industrial purposes. Biomass in the form of wood is mostly used in developing countries for cooking and heating. The burning of wood and other biomass sources for cooking and heating generates adverse health effects for the people involved, due to the inhalation of particulate matter and other organic compounds (EIA, 2012).

Bioenergy can also be defined as the energy made from living organisms or the waste that a living organism produces, such as energy crops, biomass residues, and manure. These can be divided into four categories (Cornell, 2014):

1st generation: biofuels made from sugars, starches, oils, animal fat, and waste.

2nd generation: biofuels made from high energy crops like switchgrass, willow, or wood chips.

3rd generation: biofuels made from algae and other fast-growing biomass sources.

4th generation: biofuels made from genetically engineered plants.

The IEA World Energy Outlook 2011 has made its goal to assist in the deployment of *"cookstoves and biogas systems to 320 million households in developing countries by 2030."* Furthermore, biomass could potentially produce 3,100 TWh by 2050, comprising 7.5% (Figure 3) of the total energy worldwide, and 22 Exajoules (EJ) or 15% of heating energy. To help reduce environmental impacts, such as emission of carbon dioxide into the atmosphere, it becomes necessary to reuse and reintegrate residues of on-site wastes. If accomplished, emissions will be considerably less than fossil fuel combustion.

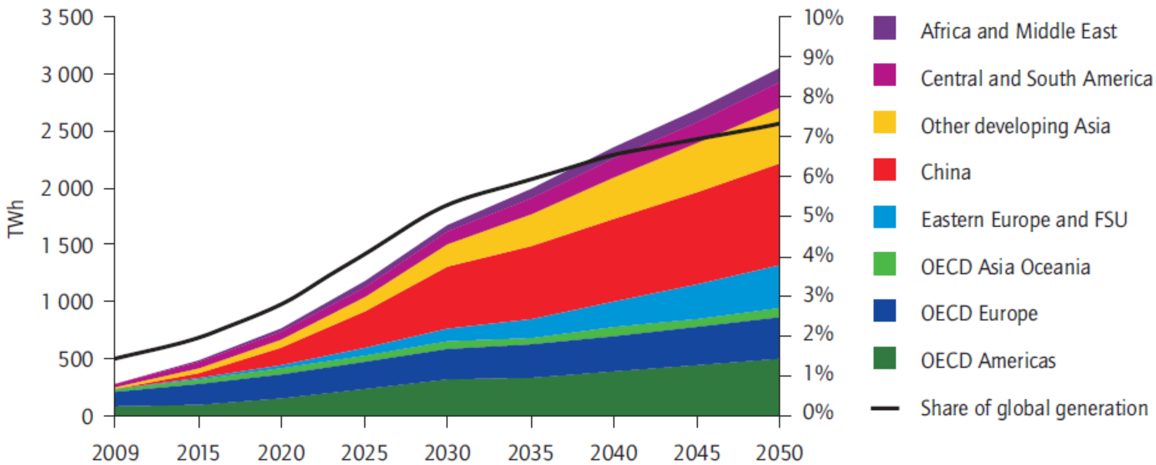


Figure 3. Global and regional average generation of bioenergy (IEA, 2012)

The National Biofuels Action Plan (2008) identified two main challenges that, if not surmounted, may threaten the continuous quantities of biomass for biofuels;

- "*the lack of biomass production capacity and*
- *the high relative costs of production, recovery, and transportation for feedstocks.*"

The impacts of biomass used to generate fuels are both positive and negative. The former allows farmers to increase crop production to meet market requirements, it incentivizes creation of industry, and creates a space to discuss the future of energy around the world. Also, it has created a wide array of unintended consequences at market and environmental levels (BRDI, 2008). These impacts and some examples are discussed below:

Food prices: food and fuel may conflict due to the increase use of food products to generate fuel, decreasing the quantity of corn, sugar cane, soy, and high energy crops available for other uses. For example, corn is a major cereal grain and primary feed for livestock, and increasing corn ethanol concentration in liquid fuels could lead to price inflation of consumer final goods—primarily food.

Livestock production: a portion of the corn used for ethanol (about one-third) is still available as a feed in the form of distillers' grains. Most of the corn-based ethanol is produced in the Corn Belt and potential animal feeding operations are distributed throughout the U.S., specifically in Texas, Nebraska, Kansas, California, and Oklahoma (NCBA, 2014; Cattlerange.com, 2014).

Greenhouse gases: besides reducing foreign oil dependency, the United States Department of Energy (2013) and Milbrandt (2005), among other public entities, portray biofuels as having zero GHG emissions. However, several studies performed by private and academic institutions have discovered that GHG emissions of biofuels occur throughout their life cycle. Such GHG emissions occur at: production of feedstocks (planting, fertilizing, spraying, etc.), transportation of feed stocks, changing land use to meet market demands, conversion of feedstocks, and use of biofuels (Adler, 2007; BRDI, 2008; Chouinard-Dussault et al., 2011; Davis et al., 2008).

Land use: a change in land use is anticipated as feedstock production is required to meet energy needs (BRDI, 2008; DOE, 2011; USDA, 2009). South America is expanding its sugar cane and African palm crops to meet its national biofuel goals, reducing land that could be used for crops destined for food (USDA, 2009; USDA-FAS, 2015)

Soil depletion: monocultures have direct impacts on soil quality. Production systems with no feedback require other systems (e.g. external inputs) to obtain what is needed to keep that system operational; this results in increased dependency on chemical fertilizers (Sundkvist et al., 2005).

Water Usage: an increase in crop area will require three main things - water, land, and energy (Stewart, 2014). Water will be used to increase production and maximize yield, aiming to generate the maximum revenue. the expansion of energy feedstocks to meet national goals could compromise availability and quality of water.

Carbon Markets: potential carbon markets can be developed based on the assumption that carbon emissions are being reduced (BRDI, 2008). Colombia is working with the United States Environmental Protection Agency (U.S. EPA) and the United States Department of Agriculture (USDA) to develop a baseline for a future national carbon market.

Pesticide-resistant strains of plagues: monocultures are susceptible to plagues that are unique to those species. The continued use of pest-specific pesticides can create pesticide-resistant plagues that could hinder crop productivity.

In South America, Colombia entered the biofuel market in the 1970s, following the steps of Brazil and its successful ethanol implementation program. Colombia's main sources of biofuel are derived from sugar cane (ethanol), and African palm and soy (biodiesel). After removing the sugars from the cane, the leftover biomass is used as a source of fuel for the processing and transformation to ethanol (Fedebiocombustibles, 2011). Biodiesel is becoming a major player on the energy market worldwide. African

Palm is highly promoted and subsidized in Colombia due to its outstanding capacity to produce biodiesel compared with soybean, sunflower, and rapeseed. African palm generates an average of 3.74 ton/ha/year and has a life expectancy of 20-25 years and bears 8-12 fruit brunches annually that weigh between 12 - 25kg. Soybeans, on the other hand, generate 0.38 ton/ha/year of oil with a life expectancy of 1 crop per year (Soyatech, 2016).

Colombia is slowly increasing the use of biomass by mostly substituting fossil fuels used in transportation as shown in Figure 8. It is also evident that coal-powered plants are increasing as a backup source of electricity to hydroelectric power. Some wind and solar projects are being implemented in high wind/high solar areas of the country. At the moment, Colombia does not have an updated record of energy generated with alternative energies. In particular, there is a lack of information regarding how many anaerobic digesters (AD) are being utilized to capture methane for cooking, heating, and electricity. This makes it difficult to identify current and future challenges of bioenergy technology and delays the development and implementation of programs designed to incentivize the adoption of these energy sources.

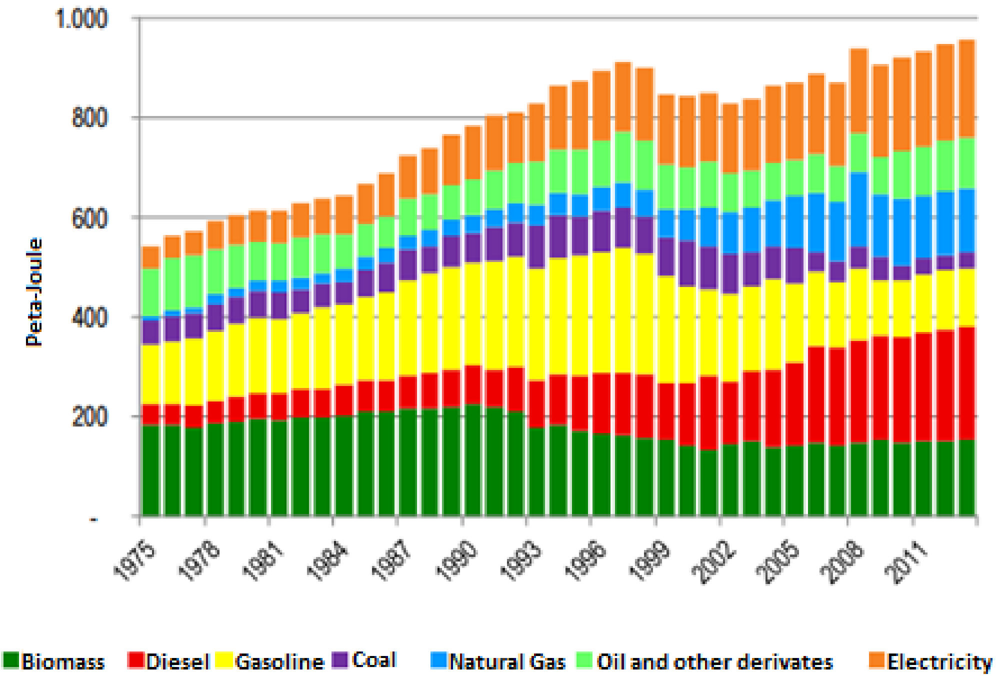


Figure 4. Colombia energy sources 1975-2011 (Modified UPME, 2014)

Colombia is increasing its electricity usage which forces the country to expand its hydropower and coal powered plants to obtain most of its energy for electricity. By expanding hydropower, Colombia's energy generation capacity is becoming susceptible to climatic changes, especially drought, a phenomenon that is currently affecting most of the country. In the early 1990s, Colombia experienced an extreme drought which led to nationwide energy and water shortages. This, in turn, affected national growth and industrial development. The future of energy in Colombia is highly dependent on where the government decides to focus its future energy policy.

2.2 Future Energy Management and Distribution

Armaroli and Balzani (2006) stated that, "*if externalities were included in energy accounting, some renewable technologies would be already competitive with traditional technologies on a purely economic basis.*" There is not a single solution, or a miraculous technology that will supply future energy demands. A practical approach would be a combination of different renewable energies to help supply energy demand, reduce the carbon footprint, and keep temperatures from rising. Implementing several energy sources can reduce the need to rely on fossil fuels to supply future global population needs. The state of Vermont is integrating several energy sources in the grid, such as wind, nuclear, coal, and biogas to increase energy availability and state resilience. Vermont has proved to be extremely successful at integrating all sources to generate electricity by creating state-funded programs, promoting the installation of biogas systems in dairy operations, and being able to guarantee their continued biogas operation. The Netherlands is currently in the process of designing an island that is fully energy sustainable, comprised of wind power and tidal power (IEA, 2012b).

Smart grids are computerized grids that allow an individual Conducting Laboratory Analysis to control their energy supply. These smart grids are becoming a standard to help manage available energy and to distribute it efficiently among industrial, agricultural, commercial, and domestic clients. Smart grids offer a real time dynamic network to manage electrical demand, supply, and control. Furthermore, energy generation is migrating from a centralized source to decentralized or local community-oriented generation with the capability of feeding excess energy back to the grid. This translates into many benefits, like the flexibility to use other energy sources and being able to manage generation peaks from sources like the wind or sun. Air emissions from coal and natural gas powered plants will be lowered while operating at a maximum capacity. Local generation, along with smart grids, would allow energy generation to become efficient and minimize further environmental impacts. The main disadvantage of alternative energy sources is availability and the capacity for meeting the demands when required.

Agriculture is not exempt in suffering from these changes; in fact, early adoption of new technology would allow food production to improve its efficiency while continuing to develop the processes. As with any other industry, agriculture has to deal with several factors that influence its performance, such as regulatory constraints, international standards, customer satisfaction, and competitive pressures. In addition, environmental impacts in areas such as resources (energy, raw materials, and land use), human health, and ecological effects (global warming/climate change and eutrophication), are critical considerations for any new project development. Current agricultural systems are often disconnected from ecological impacts, but if included, they could improve productivity and allow the re-use of biomass residues to generate energy and potentially substitute chemical fertilizers. This has been demonstrated by long-term studies carried out by Persson and Kirchman (1994) who demonstrated that manure application provided more nitrogen than applying a chemical fertilizer. Biomass residues can provide heating and electric energy, through decomposition of the organic matter and capture of the biogas. The biogas can provide energy independence and generate a fertilizer for agricultural operations. The use of the biogas effluent or bio-slurry could provide the necessary nutrients to substitute for most of the nutrient requirements for specific crops. If managed correctly, bio-slurry can serve as a good source of nitrogen, phosphorus, and carbon that could not only substitute for chemical fertilizers but boost crop production (FAO, 2013). The next section discusses anaerobic digestion in detail and the potential social, health, and environmental benefits of using biogas and the effluent.

CHAPTER THREE

ANAEROBIC DIGESTION

Anaerobic digestion (AD) is a first-generation biofuel technology that uses energy crops, animal excretes, and other organic wastes. This technology is gaining interest worldwide as a tool for the development of rural communities and small agricultural operations and reduces GHG emissions, treats high organic loads wastewaters, and odors, among other environmental and health impacts. It also promotes a sustainable source of energy.

This technology biologically treats organic waste streams and converts them into biogas and an effluent rich in nutrients and minerals. Biogas is defined as "the by-product of microorganisms' action on cellulosic materials and other organic residues" (DaSilva, 1980). Biogas is a mixture of gases that normally ranges from 55% to 70% methane (CH_4), 30% to 45% carbon dioxide (CO_2), and less than one percent hydrogen sulfide (H_2S). Traces of other gases are present in this mixture such as, oxygen, nitrogen, hydrogen, and carbon monoxide (Krich, 2005).

The generation of biogas provides an alternative to fossil fuels for both heat and electrical power for households, agricultural operations, and cities (Weiland, 2010). The production of food has become extremely energy-dependent, which makes it susceptible to any changes in energy availability. For example, seven liters of oil are needed to produce one kilogram of beef (Armaroli and Balzani, 2006). AD of biomass is probably one of the most promising forms to generate energy worldwide. For example, EPA (2011) identified 155 farms in Texas with potential for implementation of biogas systems with a methane production potential of 141 million m^3/yr or 429,000 megawatts per hour (MWh)/yr. This is sufficient to power approximately 38,000 homes based on average electricity consumption for a residential costumer (EIA, 2011).

AD has been used as part of treating wastewater as a secondary or biological treatment and has been widely studied by several agencies around the world. It was also explored extensively in the 1970s as an alternative source during the oil crisis. Nowadays, it is used as a tool in emerging countries, aiming at providing a reliable and clean source of heating/cooking fuel to substitute wood and manure burning. AD has slowly grown into a cost-effective alternative for rural areas around the world, especially for emerging countries. Six to eight million systems are installed around the world (PennState, 2015).

Biogas generation and its transformation to thermal or electric energy has been evaluated against fossil fuels and other biofuel sources, such as biodiesel from rapeseed, ethanol from wheat, and methanol from willow. It could provide more benefits towards powering agricultural operations while minimizing environmental impacts, especially GHG emissions (Börjesson and Mattiasson, 2008; De Vries et al., 2012; Mezzullo et al., 2013; Zah et al., 2007).

The biomass source can alter the digestion process due to the content of volatile solids (VS). For example, dairy manure generates 4.5kg VS per day. From this concentration, about 50%-70% will convert to biogas depending on digester design, temperature, pH, and retention time. In general terms, AD of VS is the first transformation into volatile organic acids, and later into methane, carbon dioxide, water, and other gases. Most of the nitrogen and phosphorus stays in the sludge, along with other carbon compounds (Schmidt, 2015).

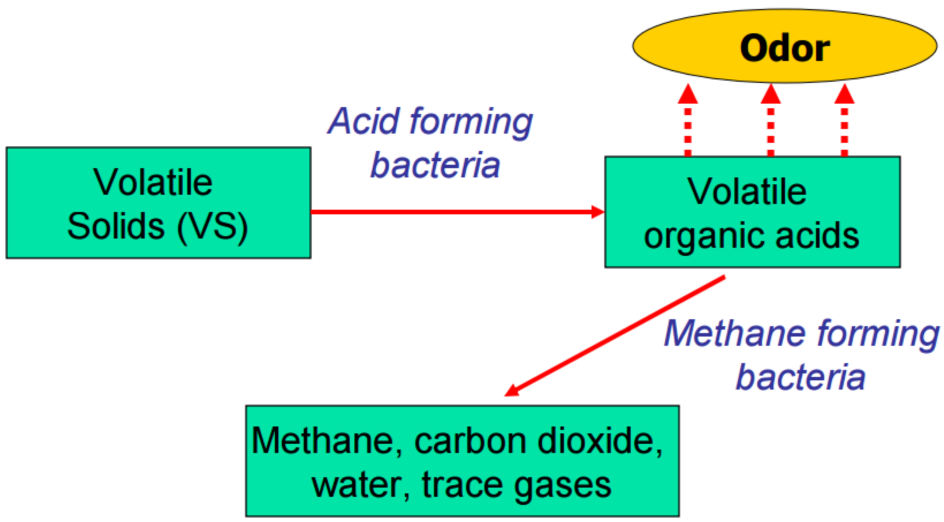


Figure 5. Anaerobic digestion process (Schmidt, 2015)

De Vries et al. (2012) studied mono-digestion and co-digestion of pig manure and other agricultural biomass products. This research showed that co-digestion generated less environmental impacts and increased biogas production up to 568%.

Biogas generation is affected by several variables: raw materials, the content of solids, amount of organic matter entering the digester, microorganism population, pH, temperature, nutrients, other compounds (compounds that could affect methanogenesis), mixing, and hydraulic and solids retention time (DaSilva, 1980; Krich, 2005). Table 1 shows how the primary variables affect methane generation.

Table 1. Variables and implications on biogas production

Variable	Explanation
Solids Content (Loading Rate)	Dilution of input materials with water affect biogas generation: • High dilution: Low biogas generation • Low dilution: Not enough fermentation and consequently low biogas generation It is recommended a 1:2 to 1:3 ratio for dairy wastewater.
pH	pH should range from 6-8. Most efficient production at 7
Temperature	The following temperatures are required for max. methane generation: • Mesophilic microorganisms: 30^0C-40^0C • Thermophilic microorganisms: 50^0C-60^0C Weather and seasonality may affect biogas production. If the biogas system is located with marked seasons, a heating system should be put in place.

Temperature changes inside the biogas system can control the production of biogas and its quality (Chayovan, 1988). Also, modifying temperatures and pH alters the microorganisms' population to other types of bacteria, impacting residence times and digester size (Biomass Energy, 2013). For an optimal generation of biogas, methanogens require a neutral to slightly alkaline environment. pH changes inside the biodigester could hinder methane production and increase generation of other gaseous compounds (Burke, 2001). Lastly, there is a direct relationship between organic load and temperature, where a high organic load can promote higher population growth increasing biogas generation and removal efficiency of compounds present in the wastewater, while low organic load hinders population growth, biogas quality and generation (Lamprecht, 2009; Gómez, 2011). Hydraulic Retention Time (HRT) is to allow a proper bacterial growth and transformation of biomass into biogas. Krich (2005) shows a direct relationship between time and transformation of volatile solids from dairy manure to biogas in Figure 11. If the biomass to be digested is cellulose, longer HRT will be needed to transform it into biogas.

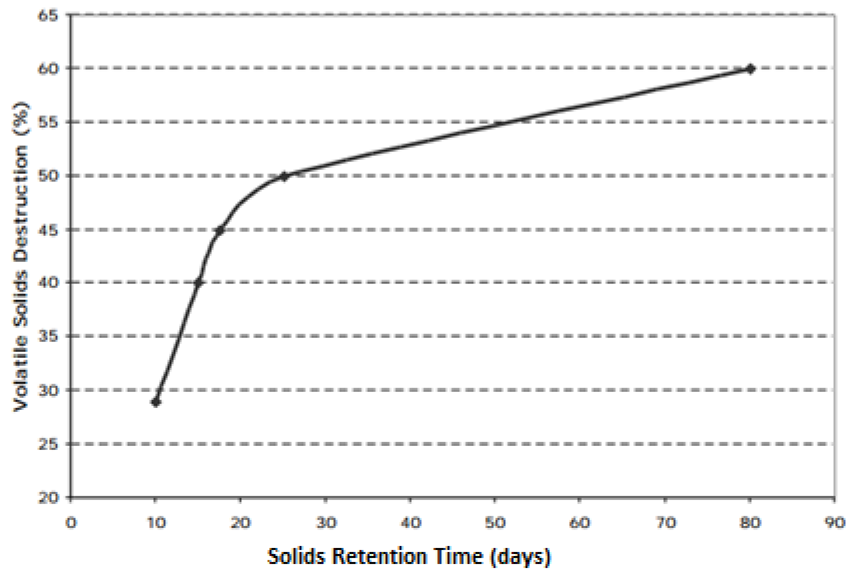


Figure 6. Volatile solid destruction per days of digestion (Krich, 2005)

3.1 Benefits of a biogas system

The benefits of implementing biogas systems integrated into their energy grid allow communities to improve their quality of life through a reliable source of energy and the enhancement of agricultural productive processes, directing it to a more sustainable development. It also promotes integrated production chains and use of alternative energy sources that create a better community while reducing health risks due to air and water quality deterioration.

Social benefits

The implementation of local projects that promote the development of alternative energies allows small communities to become independent and generate replication or further acceptance and use of the technology, resulting in a community with a sense of ownership. It also generates decentralization of knowledge. Finally, replication of knowledge and training replicators / implementer's future will be encouraged.

Health Benefits

The issue of health and environment is inherently related and this project clearly shows how fuel substitution can improve the health and quality of life of rural Colombia. The air quality in homes where solid fuel (wood or coal) is used can cause respiratory problems in vulnerable populations and ultimately lead to death. The World Health Organization (WHO) reported that the generation of smoke (i.e., particulate matter) produced by burning wood or coal is connected to the annual death of 1.6 million people worldwide. Additionally, particulate matter and volatile organic compounds reduce the defense mechanisms of exposed persons and increase the risk of respiratory infections, such as bronchitis and pneumonia. Emissions of these compounds can exceed 500 times the permissible exposure limits of $PM_{2.5}$ $10\mu g/m^3$ and PM_{10} $20\mu g/m^3$ annual mean where the main recipients are children and women (WHO, 2004; WHO, 2005).

Economic Benefits

This project generates direct benefits to communities and agricultural producers alike, allowing investing in other segments such as food or machinery. A biogas project generates direct benefits that reduce direct costs, indirect costs, and makes for a reliable source of energy.

Other Benefits

A biogas system becomes part of a systemic integration of the company's production chain and aids in mitigating global effects such as climate change due to emissions of GHGs (i.e., methane, carbon dioxide, and nitrous oxide).

Incentives and trade of carbon credits are still not clearly implemented and few countries have policies in place to promote the use of these tools. Most South American countries use these carbon credits, oriented towards the conservation and recovery of forest ecosystems. Given that agriculture is a key sector of the economy of these countries, it becomes necessary that policies and initiatives are developed to encourage the agricultural producer to make changes, improving their productive process.

Environmental Benefits

Biogas systems provide a wide array of environmental benefits. These benefits allow small rural communities and agricultural operations to reduce their environmental footprint as shown in Table 2.

Table 2. Benefits of a biogas system in production

Improving the use of natural resources	• The treatment of wastewater with high pollutant load enables the industry to reuse wastewater for irrigation of crops. • Results in a significant reduction of water consumption for irrigation of pastures designated for feeding cattle • Biogas production reduces the need for packaging gas. • Decreases consumption of forest for cooking.
Reduction in pollutant load	• System control and treatment reduce pollutant loading and unloading and achieve compliance with applicable local and national regulations.
Noise, noxious gasses, and odors	• The digester includes a treatment system that controls and reduces the emission of hydrogen sulfide (H_2S) and the generation of toxic gasses that may affect employees and the public. • Reduction of Greenhouse gasses emitted from the operation and carbon capture from high organic waste streams.
Solid waste management	• Reduce the volume of both the generation of hazardous and non-hazardous waste. • Features and reduces nutrients that may affect surface waters. • Reduce leachate that may affect surface water and groundwater.
Substitution of materials	• The use of waste as an energy source, eliminates dependence on bottled gas.

	• It is a renewable source. • Reduce deforestation and land use improvement.
Improved land use	• Reduces deforestation, improves land use and reduces erosion.
Other benefits	• The use of biogas to generate electricity and heat. • Increases crop production for dairy cattle due to the use of activated sludge result of the final product of the digester.

3.2 Anaerobic digestion and its adoption in the Americas

The digesters are within the technologies known as unconventional renewable energy, due to the use of biomass (manure, plants, algae, etc.) to generate biogas. These systems have been tested with high success around the world (Burdzy, 2012), especially in European countries, where systems are technologically and technically refined for maximum efficiency and methane production. In emerging countries, such as China, India, and Vietnam, which have a constantly expanding population, biogas systems have provided a great service, by reducing the need to invest in massive infrastructure to provide electrical, natural gas lines, and propane-bottled services to remote areas. Biogas could provide electrical independence, allowing people to increase their productivity, generate new revenue mechanisms, and improve their quality of life and economic and educational development (IFAD, 2008). To improve and implement this technology at a national or regional scale, programs that promote the widespread use of biogas as an alternative energy source for small farming communities becomes necessary. Most biodigesters found in developed countries have designs that can become expensive due to the materials used, methodology, and the desired efficiency. But, biogas generation can be simple enough to be reproduced with more accessible materials, which get similar results to other more complex systems. Bolivia, Costa Rica, Chile, and Colombia, have developed localized programs in some regions to implement biogas in low-income communities. To succeed in the implementation and guarantee the continuous use of biogas, it becomes necessary to work directly with the community and include their demands, adapting their needs and capabilities in the context of the offer, providing great flexibility, and focusing on concrete and tangible projects. Biogas has a moderate to high calorific value, with a high potential for use by small producers. Thus, this energy source is highly feasible for communities that do not have the electricity infrastructure or means to acquire natural gas and propane for cooking. Project implementation must provide financial, technical, and operational assistance to beneficiaries while working on issues related to knowledge management and strengthening networks of private actors and government.

These projects can be considered successful implementations of biodigesters in micro and small-medium enterprises and community households. For the purposes of this document, only those projects sponsored by governmental agencies or non-profit organizations are mentioned, due to the lack of information on private biogas initiatives; specifically, to demonstrate how this technology is used to improve the quality of life of communities and environmental treatment of organic waste streams.

3.3 Common materials used in biogas systems located in Central and South America

Traditionally, the construction of biogas systems in small rural areas has used low-density polyethylene (LDPE), Polyvinyl Chloride (PVC) sleeves, rubber strips and PVC pipes (Herrero, 2008). Small and medium agricultural operations use a tubular or sausage design from low-density polyethylene (LDPE) 8 mil. This plastic is easy to acquire, economical, is produced in different diameters (0.8m, 1.5m, 2.0m, 2.54m), flexible, and not space demanding if stored. However, thickness, plastic reuse, pressure from the biogas and deterioration due to weather and UV radiation demand frequent change. A digester made from this material requires protection from extreme weather, flying objects and animals that could potentially pierce it. If no external protection is provided, the digester life is reduced from about 10 years to 2-5 years depending on management and surrounding conditions (cattle, chickens, scavengers, and vermin). To increase the life expectancy of digesters made from LDPE, these are commonly double layered, increasing plastic thickness and resistance.

Medium and large scale digesters are made based on its type: complete mix, covered lagoon, plug flow, and combination reactor. The most common materials are concrete, fiber glass, stainless steel, and HDPE. These digesters are normally outside, with no external protection; therefore, the material should be able to withstand extreme climatic conditions, people, and animals such as cattle, chickens, scavengers, and vermin.

3.4 Central and South America: successful cases of biogas systems adoption

Anaerobic digester technology is expanding throughout the world and is becoming a reliable source of heat in emerging countries, where conventional energy sources are not readily available. This section discusses successful cases and programs in Central and South America for the installation and adoption of biogas.

3.4.1 Bolivia

Bolivia is one of the poorest countries in South America. About 49% of the population live in poverty (UNDP, 2013). This country has expanded electric energy service from 61% in 2005 to 81% in 2012, and continues expanding (Los Tiempos, 2014). Also, meals are still commonly cooked with wood, kerosene and Liquefied

Petroleum Gas (LPG). In rural areas, Bolivians use wood as their main heating source (Israel, 2002).

a. In Bolivia, a Cochabamba NGO introduced in 2002 biodigesters in Mizque, using similar systems to those used in other countries such as Cambodia, Vietnam, and Australia. In 2003, an experimental digester at 4100 m above sea level was installed. To prevent any heat loss, the NGO along with the community, installed a greenhouse to maintain a constant temperature. This experimental digester showed that there are limitations that may prevent this technology if not adopted properly. According to Herrero (2008), the main limitations for the construction and operation of the digester were: i) water availability, ii) number of cattle that the family owns (3 cows are sufficient), and iii) appropriation of technology by the family; cultural background.

b. Starting in 2005 and ending in 2012, and with technical assistance from the German Technical Cooperation organization - GTZ started the project of “households with Biogas” as a component of Access to Energy Services, which was part of the Sustainable Agricultural Development Programme (PROAGRO). This program had a duration of five years (October 2005-2010). The objective was to "increase the number of people who can access energy to meet basic energy and long-term sustainability needs, allowing a significant improvement in the quality of life and generating new economic activities." This project aimed to benefit more than 570 thousand people, allowing access to renewable technologies, such as biogas systems and the use of polyethylene sleeves. Herrero

(2007) studied the project success cases and its limitations, such as divulging the project and its benefits to other potential beneficiaries and access to funds to implement biogas systems.

c. The Organization for the Development of Netherlands (SNV) developed a National Plan for Biodigesters in Bolivia (2013). This program projected and quantified potential activities, actors, and budget required to carry out a program to install biodigesters in rural areas at a national level. The cost to implement this program was adapted from results of other programs developed in African and Asian countries. This budget and the amount needed to be invested for the implementation of this program is shown in Table 3.

Table 3. Potential costs of implementing a national biogas program in Bolivia based on Netherland (SNV, 2013)

Annual costs of the program in USD						
Year	**2013**	**2014**	**2015**	**2016**	**2017**	**Total**
Number of Regions	3	3	3	3	3	3
Biodigesters per year	150	400	1,200	2,000	2,750	6,500
Costs of the program	844,220	787,360	897,465	931,758	886,565	4,347,368
Costs of feasibility studies	26,825	74,013	247,449	438,145	561,313	1,347,745
Total financing[1]	**871,045**	**861,373**	**1,144,914**	**1,369,902**	**1,447,879**	**5,695,113**
Contribution from privates	**78,295**	**215,979**	**711,012**	**1,244,936**	**1,599,119**	**3,849,341**
Total cost of the program	**949,340**	**1,077,353**	**1,855,926**	**2,614,838**	**3,046,997**	**9,544,454**
[1] Corresponds to the costs of the program + the investment on subsidies						

The feasibility study for the implementation of this Bolivian biogas program concluded that the country has the capability to build and run 175,000 biodigesters with favorable results.

Results of these programs

- NGOs Cochabamba: technology was installed and showed favorable results in high altitude (approx. 4100 m) parts of the country.
- Bolivia-Germany cooperation: the minimum number of cattle required to generate a continuous source of biogas was identified to implement biodigesters in rural communities.
- Bolivia-Germany cooperation: will potentially benefit 570,000 people.
- Bolivia-Germany cooperation: the cost of a digester system using polyethylene sleeves can range from $ 110 to $ 170, depending on the location of the system (the tropical highlands).

Family involvement throughout the installation of biodigesters is critical for its appropriation and understanding of technology. There have been cases in which the family has disassembled and reassembled a digester to consider other, more suitable ones, or to repair location (Herrero, 2007).

3.4.2 Costa Rica

Costa Rica has maintained a steady economic growth through modifying their industry towards tourism. About 22% of the population lives in poverty (Instituto Nacional de Estadistica y Censos – INEC, 2014). The country has expanded the electrical service to 99.43% by 2014 (Instituto Costarricense de Electricidad, 2014). Costa Rica's population uses Liquid Petroleum Gas (LPG) and kerosene to cook. Poor and extreme poor sectors of Costa Rica still use wood for cooking (World Health Organization, 2010).

a. Through the Ministry of Agriculture, a group of rural women from the region Santa Fe have been developing biodigester projects since 2006. This program was developed in several stages; the group received training through the National Institute of Learning (2006) and The Ministry of Agriculture to build and maintain biodigesters. The funds for this project were donated by the Group of Women of the United Nations in Vienna, Austria and the Ministry of Agriculture and Livestock (MAG) of Costa Rica. This program has installed sixteen biodigesters using cattle manure. The program scope includes and aims at resolving issues of environmental welfare, family health, and accounting. Additionally, the program included awareness and training sessions related to wetland conservation and reforestation of the Santa Fe region.

b. EARTH University has been working for over 15 years to implement digesters in rural areas of Costa Rica. Part of this project is to build a database to determine the coverage of this technology. It was determined that over 2,000 households and about 100 industrial units have installed a biogas system. Also, EARTH University has focused on identifying organizations implementing these systems in Costa Rica (BBC News, 2009).

c. Other initiatives of biodigesters in Costa Rica developed by organizations and institutions such as Municipality of Heredia, INBIO parque, POCOTSI Project Neotrópica foundation, Dos Pinos Cooperative, Social Pastoral of Limón, and Biosinergia Alternative (BBC News, 2009).

Results of these programs

- Women of Santa Fe: 16 digesters were built in 2006.
- Women of Santa Fe: biodigesters were associated with wetland conservation area.
- Women of Santa Fe: other mechanisms such as income and rural tourism were linked to AD.
- EARTH University: established the digester cost is about $200 and a capital recovery in 6 months (Botero and Preston, 1987).
- EARTH University: current costs are about $950 for a biogas system, with a return on investment in six months.

The introduction of biodigesters means that a family no longer requires a daily search for firewood for cooking, a task usually performed by women and children. By reducing the workload, women and children will have more time for other productive uses, school, training, and social participation (Women of Santa Fe, 2006).

3.4.3 Chile

Chile has one of the best economies in South America, with strong financial institutions and sound policies. Chile's primary energy supply comes mainly from oil (54%), coal (13%), combustible renewables and waste (17%), natural gas (8%), and hydro (8%). Chile is committed to reducing their oil dependency and carbon emissions by promoting renewable energies. Additionally, Chile is looking to increase its resilience to shortages of fuel due to earthquakes, droughts and political differences with neighbors (IEA, 2012).

a. In June 2013, in the Casablanca Santa Elena commune, the first large-scale biogas plant receiving 200 tons of dairy manure was opened. This initiative was sponsored by the Ministry of Agriculture within its program of Non-Conventional Renewable Energies (NCRE) and the Foundation for Agrarian Innovation - FIA. This project was exemplary because it allowed the dairy to have hot water for washing udders and other uses in milk production (Casablancahoy, 2013).

b. UTEC Corporation (GmbH) and the Evangelical Development Service (SEPADE) installed a pilot digester in 2007-2008 to generate electricity and power the Agri-Food Education Center (CEA). This center is located in the commune Negrete. The project and its infrastructure were funded by the German Ministry of Economic Cooperation and Development (BMZ). The main biomass source for this digester is residues from a dairy farm. In addition to generating electricity, it has also used the sludge generated by the digester to fertilize the crops used to feed dairy cattle (SEPADE, 2008).

c. The Foundation for Agrarian Innovation (FIA) and the Ministry of Agriculture are co-financing a pilot demonstration plant project for small and medium-scale biogas systems in the livestock sector. Based on studies by the Chilean Ministry, the livestock sector has the capacity to generate 258 MW, where two-thirds would come from organic waste. The first pilot plant was launched in March 2013, according to the article published in portalfruticola.com/FAO (2012).

d. Kaiser Energy will be carrying out a project installing and launching six demonstration pilots biogas plants that use organic waste to replace fossil fuels. Kaiser Energy remarks that biogas projects at the industrial level could generate up to 40% of the energy into electrical and 45% into thermal energy.

3.4.4 Colombia

Colombia has been working towards reducing their convoluted political climate with the purpose of reducing social and income inequality and improving access to basic services. About 30.6% of the population lives in poverty, especially communities located farther from the capital. Colombian researchers and enthusiasts created the RedBioCol, a non-profit organization with the objective of promoting non-conventional energy sources in the country. Colombia has a wide array of experiences using biodigesters to generate biogas. However, these experiences have not been recorded, and most of them are communicated through conferences and informal conversations. There are many systems sponsored by the local or national government. Similarly, there are experiences that have been supported by associations and non-profit organizations in disadvantaged rural communities.

a. The Colombian Association of Pig Farmers has promoted the use of digesters through its members. The Association produced videos and educational material to demonstrate that the installation of biodigesters is possible and that it is a competitive advantage for the company and, at the same time, serves as a stage in the treatment of effluents. Pork producers have implemented biodigesters in 19 of their production establishments in order to heat the piglets using gas lamps.

b. The Square Central Wholesale Market of Antioquia in cooperation with the dairy Zarzal built a biodigester to digest ruminal content and whey (NCPC, 2009). In addition to treating the effluents of these activities, the digester serves as a demonstration project for educational institutions located in the region.

c. The palm oil processing company, Palmar Santa Elena, has installed a system of biodigesters in order to treat effluents from the extraction of oil. The sludge is used as fertilizer for crops, and biogas is used to generate electricity for the operation of the plant. This digester generates 800 m^3 of biogas daily. The plant has a conditioned mixture diesel engine with biogas to generate electricity for the company.

Results of these programs

- Colombian Association of Pork Farmers: farms with biodigesters. These farms use biogas as a source of heating for their piglets and power generation for the production area.
- Wholesale Market Square of Antioquia: serves as a demonstration project. This shows that effluents with different sources can be mixed to generate biogas.
- Palmar St. Helena: digestion of process effluents to generate electricity. Such projects also have the added value of selling carbon credits.

3.4.5 Argentina

Argentina presents a highly complex political and economic system. Uncertainty and the manipulation of inflation numbers by the government have not been provided accurate information regarding poverty and other development indicators. The country began addressing some of these issues in 2014, but no realistic information has been published. Argentina had a great opportunity to begin implementing renewable energy projects throughout the whole country with the Argentina Industrial Sustainable Development; however, political instability forced the project to shut down.

1. La Granja del Sol is a closed loop cycle pig farm located in the Province of Buenos Aires, Argentina. The current process manages 850 sows, with a maximum capacity of 1,050 sows, producing about 19,000 piglets per year. This plant has 3 digesters that are independently loaded at a rate of 8 m^3/hr. Company calculations determined that the farm's biogas system is capable of producing about 105 m^3/hr of methane, and eventually generate about 225 kWh, providing electricity for the whole farm.

2. In 2012, PFI Energy & Ecology S.A. and Hernando's Cooperative developed a project to generate electricity using the effluent from La Lay, a swine farm. This energy is used not only by the producer but by the nearby community, stating that the electricity is more stable and constant. Currently, the swine company has the capacity to generate electricity to power 10 other companies of the same size (PFI, 2012).

3.4.6 Uruguay

Panamerican Energy, an Argentinean company, is currently developing near the city of Durazno a mega project to host a dairy operation of 8,800 cows to produce milk powder, a grain storage plant, and a plant for soybean oil for a biodiesel plant. The wastewater treatment system will include an anaerobic digester. The biogas will be used to generate heat and electricity for the operation and the surrounding community.

3.4.7 Peru

In March 2013, the Hivos, SNV, and Practical Solutions organizations proposed the "National Program of biodigesters for Peru". This plan is designed to be developed in five years with six phases; i) promotion and awareness, ii) business initiatives, iii) design and implementation, iv) research and development, v) technical assistance vi) monitoring and evaluation. It also proposes to install digesters in three regions of Peru for a total of 10,000 biogas systems across the country. The funding system proposed is based on subsidizing 60% with funds from public sources, donations or local contributions and international organizations interested in participating. The remaining 40% must be financed by the beneficiary (producer or family) that is participating. The approximate cost for biogas system for this project is around $1,800/digester. The total amount calculated for the execution of this project is $18.063.432, where 60% or $10,725,776 is funded by other entities and 40% or $7,337,655 dollars represents the contribution of the beneficiary farmers with the program.

CHAPTER FOUR

DAIRY WASTE AD EVALUATION

The agricultural industry has a great potential to implement anaerobic digesters (AD) in their daily operations due to the large generation of organic waste. Dairies accumulate a considerable amount of manure and wastewater that could be utilized in the production of biogas and compensate for energy used in their operations. Understanding how physical and chemical parameters affect biogas generation is paramount for reliable and high-quality energy. Additional benefits are the treatment of wastewaters, odor reductions and overall waste reduction. A properly functioning biogas system can generate nutrient-rich, odorless, almost sterile effluent, and biogas capable of generating energy (Bond and Templeton, 2011; House, 2006; Krich, 2005; Sanders, Roberts, Ernst, and Thraen, 2010). Evaluating the waste stream properties is critical to AD system design. The most common parameters needed for AD design are (1) water content; (2) total, volatile, and fixed solids, (3) pH, and (4) the daily average temperature of the area. Total, volatile, and fixed solids provide an idea of how much biogas can potentially be generated from the wastewater. Volatile solids are mostly composed of organic compounds, and, under the right conditions, 50-70% will be converted into biogas. Volatile solids transformation is primarily dependent on the pH and temperature inside the digester. Fixed Solids are primarily inorganic compounds or compounds not decomposed by the anaerobic process that will precipitate, becoming part of the sludge or effluent. For example, a high fixed solid substrate will have more sediment accumulate, which in turn will reduce the life of the digester.

In order to obtain a determination for the optimum dairy feed stock for an AD system, wastewater samples were collected at a local dairy in Hereford, TX, with samples collected from the free stalls, pre-settling basin, and the post-settling basin. The samples collected were then submitted to a series of treatments to identify the best wastewater type for maximum biogas output.

Panhandle dairy site background

Samples were collected from a dairy which had the following characteristics:

- Operation: 11 years
- Current operation size: 4,200 cows
- Desired operation: 10,000 cows
- Average # of births: 21 calves/day
- Cows are milked three times, or twice a day based on productivity.
- Manure from a free stall is scraped and dumped into the main channel named “Main Street”, where it is washed and directed toward the settling basin and later to the retention ponds.
- High yield cows are located in the free stalls (20% of the total livestock)
- Medium yield cows are located in the open lots (80% of the total livestock)
- Water source: three wells provide water for the operation. Average production per well is 125 gal/min
- Total water consumption: 500,000 gal/day (high estimate) or approximately 110 gal/cow-d

- Free stalls are scraped once a day, when cows are taken to the dairy parlor.

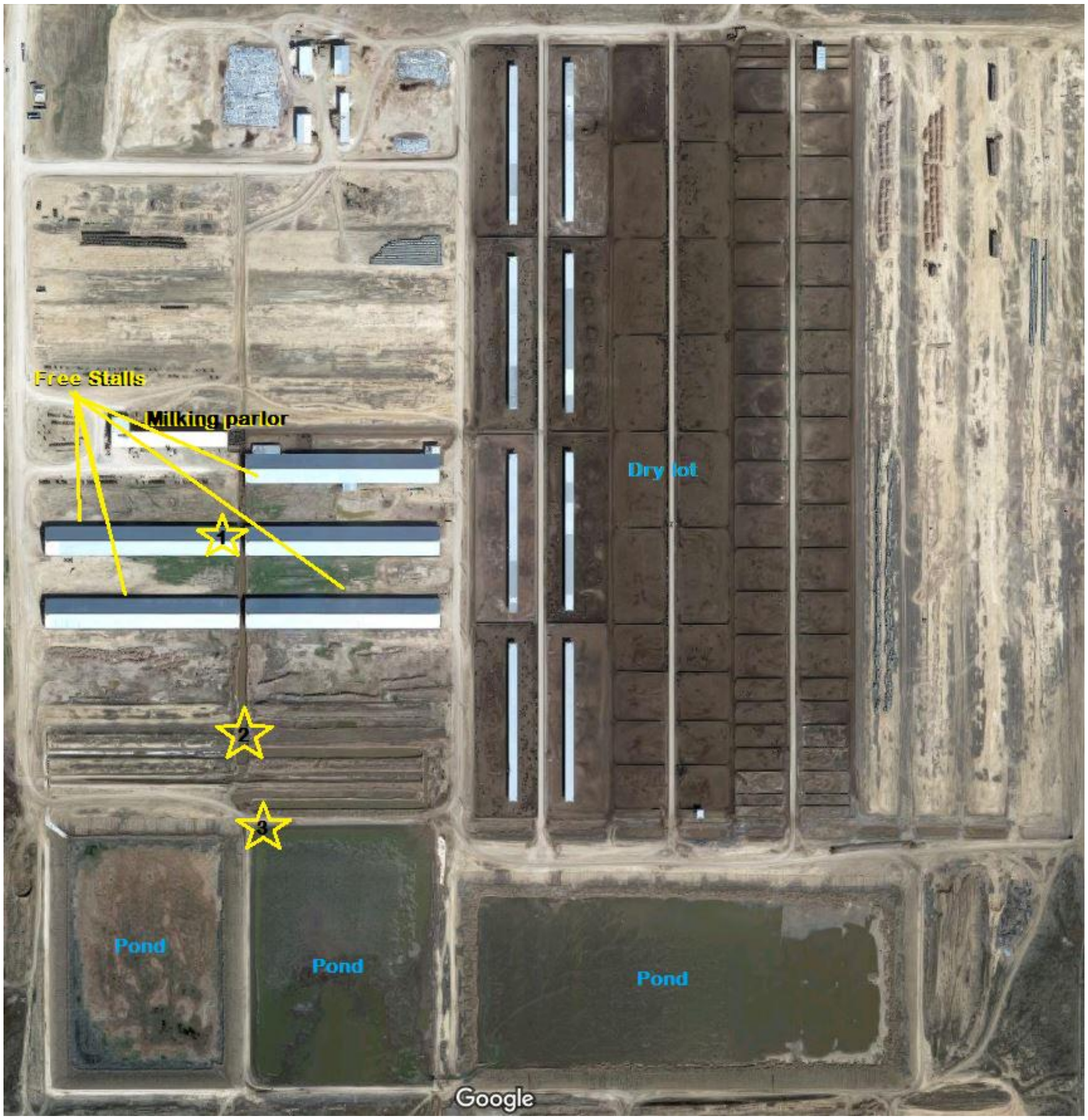


Figure 7. Hereford dairy infrastructure and sampling points

4.1 Methodology

Samples were collected in March of 2014 on the sampling points as shown in Figure 7. These samples were maintained at ≈ 4 °C for 24 hours throughout transportation to the Agricultural and Natural Science building at West Texas A&M University. Sub-samples were taken from these samples to determine moisture content, total solids, fixed solids, and volatile solids. To determine how much solids were present in the samples, the EPA method 160.2 was followed. A drying oven was used at a temperature of ≈ 104 °C for a period of 24 hours. Samples were weighed prior to and after the drying period. After drying the samples, these were taken to a furnace oven, and heated to a temperature of 550 °C (1022 °F) for a period of 6 hours, as established in EPA method 160.4.

Water Content: Water is mainly used as a transport medium. Theoretically, water content affects biogas production, where water reduces pipe and pump clogging and facilitates mixing in the digester. However, increasing water volume reduces effective volume of the AD (Homan, E., 2016). High concentration of solids requires mechanical stirring to promote an even decomposition of the substrate into biogas and digested slurry or effluent (House, 2006). The water content for each sample was calculated by weighting the sample before and after placing it in the drying oven for a period of 24 hours at 104 °C. The percentage of water content was calculated by subtracting the percentage of total dissolved solids and multiplying by 100.

Total Dissolved Solids: Total solids are the concentration of solids (organic and inorganic) present in a substrate. Total dissolved solids were analyzed utilizing EPA method 160.2. The samples were placed in a Cole-Parmer StableTemp drying oven, as shown in Picture 1, for a period of 24 hours at a temperature of 104 °C (219.2 °F). Each sample was weighed prior to and after drying. The results were averaged to obtain an overall amount of dissolved solids in each sample, as presented in in Table 4, the results of this section.

Picture 1. Hereford dairy free stalls, pre-settling, and post-settling samples in oven prior to drying at 104 °C

The percentage of total solids was calculated using the following formula:

$$\textbf{Calculations}$$

$$Total\ Solids, \% = \frac{(A - B)}{(D - B)} \times 100$$

$$\textbf{Where},$$

$$A = weight\ of\ dish + dry\ sample\ (in\ grams)$$

$$B = weight\ of\ dish\ (in\ grams)$$

$$D = weight\ of\ dish + wet\ sample\ (in\ grams)$$

<u>Volatile Solids</u>: After drying the samples at 104 °C, the samples were processed using EPA method 160.4 to determine fixed and volatile solids. Samples were placed in triplicate in a furnace oven for a period of 6 hours and a temperature of 550 °C (1022

°F). The samples were placed in the furnace and marked, as shown in Picture 2. The samples were weighed prior to and after volatilizing. The results were averaged to obtain an overall amount of solids in each sample, as presented in Table 4.

Picture 2. Hereford dairy samples in crucibles, before burning and ashing at 550 °C

The percentage of volatile solids was calculated using the following formula:

$$\boldsymbol{Calculations}$$

$$Volatile\ Solids, \% = \frac{(C - B)}{(A - B)} \times 100$$

$$\boldsymbol{Where},$$

$$A = weight\ of\ dish + dry\ sample\ (in\ grams)$$

$$B = weight\ of\ dish\ (in\ grams)$$

$$C = weight\ of\ dish + sample\ after\ ashing\ or\ ingnition\ (in\ grams)$$

<u>Fixed Solids</u>: Fixed solids are composed of inorganic material that would not volatilize after being submitted to high temperatures. The percentage of fixed solids was calculated by subtracting the percentage of volatile solids from the total dissolved solids weight.

Theoretically, it is assumed that all organic matter is potentially a source of biogas. Based on this assumption, the theoretical amount of biogas can be calculated using the results obtained from the total solids and volatile solids analyses. These values serve as a reference point for the experimental phase, as well as the results with literature values.

4.2 Results

Water content: Post-settling (98%) showed to have the largest water content from all the samples, followed by pre-settling (94.3%), and last free stalls (65%). These results are acting accordingly with the process, where free stalls have a higher concentration of total dissolved solids, then mixed with wastewater from the milking parlor before the settling basin, where pre-settling sample was taken, and last after the settling basin, where most solids were deposited and only suspended solids remained.

Total solids: Free stall (scrape lot) has the major amount of total dissolved solids with an average of 35% followed by pre-settling basin with an average of 5.7%, and lastly post-settling basin with an average of 2%.

Fixed and volatile solids: The free stall was found to have the largest amount of fixed solids and volatile solids or inorganic compounds (27%), pre-settling basin yielded (3.7%), and the post-settling basin (1%). Table 4 shows the results for the solids analysis; total, volatile and fixed solids. The values shown in this table are given as a percentage of Total Solids. The calculations and data are presented in Appendix 1.

Table 4. Results of total, fixed, and volatile solids analyses from each sample

Samples	Average Total Solids (%)	Average Fixed Solids (%)	Average Volatile solids (%)

Free stall samples	35%	27%	8%
Pre-settling basin samples	5.70%	3.7%	2%
Post-settling basin samples	2%	1%	1%

The decline in the concentration of volatile and fixed solids for pre-settling and post-settling samples can be attributed to the dilution factor. When manure is scraped and pushed to the main channel, it is mixed with the wastewater from the milking parlor. It also showed that free stall substrate has considerably more fixed solids than the other two substrates. This high amount of fixed solids will pose a problem for managing the biogas system because of increased flushing, which will be required, reducing the AD energy supply reliability.

Using the values for a 500kg dairy cow obtained from the University of Minnesota (2015), potential biogas generation based on the results shown in Table 5, indicated that post-settling has the greatest biogas generation potential with 2.08 m^3/day-kg VS, followed by pre-settling samples with 1.89 m^3/ day-kg VS, and lastly, free stalls with 1.15 m^3/ day-kg VS (see Appendix 2 for calculations). . To improve volatile solids digestion and increase biogas generation, dairy wastewater could be optimized by stabilizing the pH and temperature to appropriate levels, where methanogens can thrive and maximize their degradation process (House, 2006; Krich, 2005).

CHAPTER FIVE

BIOGAS OPTIMIZATION OF PREFERRED DAIRY WASTE

Biogas generation is mainly dependent on the substrate, concentration of volatile solids, pH, and temperature of the waste stream. The evaluation above provided the concentration of volatile solids for free stall, pre-settling, and post-settling basin, indicating that theoretically, post-settling wastewater would generate the largest amount of biogas per day. However, depending on the feed stock, not all volatile solids will be converted to biogas and some carbon molecules like lignin may volatilize but will not easily decompose. Thus, a small or laboratory scale biogas generation system is useful to accurately determine the biogas generation from a substrate (House, 2006). This experiment utilized wastewater samples from the points previously sampled (free stall, pre-settling basin, and post-settling basin) from the same local dairy in Hereford, Texas, to test how pH and temperature changes affect biogas generation. This testing was performed using an ANKOM® RF Gas Production System composed of five gas production modules, five 500 ml jars, a remote zero, a base coordinator, and a system software. These modules are fitted with wireless automatic pressure release valves and sensors. The sensors sent radio frequency signals to a receiver and the data was tabulated and recorded in the ANKOM® system's software. The data can be exported to an excel sheet file, where further analyses can be performed.

5.1 Methodology

The samples included grab samples of wastewater from the free stalls before the settling and after the settling basin. Sample collection and measurement of pH, conductivity, and temperature was performed prior to placing them in the cooler. Samples were maintained at ≈ 4 °C (39.2 °F) for a holding time of 24 hours prior to and throughout transport to the Palo Duro Research Laboratory at West Texas A&M University. These samples were maintained at this temperature to reduce microbial activity and further decomposition of organic material. Each sample was split into sub-sample triplicates for each treatment, and then placed in the ANKOM® jars. Initially, the system had 25 500 ml jars and it was expanded to 30 500 ml jars to meets the experimental design of this experiment. However, three sensors went out of service, reducing the number of jars available to 27 jars. The samples were placed in the 27 jars of the ANKOM® system, as shown in Table 5. This experiment was composed of one control and two treatments, pH and temperature, which were constantly monitored during a period of time of 63 days. Solids (Control) was used to compare the different rates of biogas generation from the pH and temperature treatments. The ANKOM® system jars transmitted temperature in degrees Celsius (°C), absolute and cumulative pressure in pounds per square inch (psi), and battery life every five minutes. The experiment was designed in the following manner:

Table 5. Laboratory Experiment treatments

Samples / **Treatment**	**pH**	**Temperature**	**Solids (Control)**	**TOTAL**
Free stall	0	3	3	**6**
Pre-settling basin	3	3	3	**9**
Post-settling basing	3	3	3	**9**
Water	3			**3**
TOTAL				**27**

After placing the free stall samples in the jars for the pH treatment, the sensors started to malfunction and stopped working a few weeks after the experiment started. Therefore, no data for free stall were recorded for the pH treatment. The control, temperature, and pH data recorded by the system's software was exported to an excel file, transformed to volume rates per sample, and modified to daily biogas generation, as presented in Appendix 3. The volume of biogas generated per bottle was later calculated using the equations provided in the ANKOM system manual, as shown in Appendix 4. The AD laboratory setup for the temperature, pH, and solids (Control) experiment is shown in Pictures 3 and 4.

Picture 3. Room temperature set up for pH, Solids, and Controls

Picture 4. Temperature treatment for samples

The treatments were prepared in the following manner:

Solids (Control): the sub-samples were placed in the ANKOM jars and then exposed to the laboratory temperature (approximately 25 °C). The concentrations of total solids were determined in the evaluation of the substrates in the dairy waste evaluation section. These control jars were used to compare the effects of low pH and low temperature. Also, these sub-samples were used to determine which sample would generate the most biogas and compare generation with the results from the previous section.

pH: concentrated sulfuric and hydrochloric acids were used to lower the pH of each sample. Acids were diluted from a 100% concentrate to a 25% solution. This solution was mixed with the samples until the pH was equal to or below 6. It was expected that the acids would promote the generation of methane or any other compound, utilizing the organic matter present in the samples. Sulfuric acid is known to stabilize digested manure products to extend the life cycle and reduce ammonia releases (Rotz, 2004).

Hydrochloric acid is commonly found in gastric acid and in fertilizers, along with other products.

Temperature: it has been vastly documented that maximum production of biogas is reached at mesophilic temperatures (20-45 °C). To determine how low temperature boosted or diminished biogas production, three samples of free stalls, pre-settling, and post-settling for a total of 9 samples, were placed in a small refrigerator at approximately four degrees Celsius (≈ 4 °C). These samples were compared with the samples exposed to the laboratory temperature (≈ 25 °C) at the Palo Duro Research Facility Laboratory.

5.2 Results of the Hereford Dairy Laboratory Experiment

This experiment section presented great challenges that ended up compromising part of the results of this experiment. The data were collected and analyzed in the best manner possible to establish and answer the questions that triggered this research initiative and it was possible to identify patterns and potential biogas generation volumes from the results obtained. All the procedures were followed as described in the literature and standards.

Data were collected for a period of sixty-one and twelve days. Over 19,000 data points for each variable were recorded by the ANKOM system to assess biogas production within each treatment. The data were modified to show biogas generation per day, instead of every 5 minutes. The cumulative pressure in psi was utilized as stated by the ANKOM manual and transformed into milliliters using the equations shown in Appendix 4.

Solids (Control)

At laboratory temperatures, the controls started generating from 3 – 5 days after sub-samples were placed in the ANKOM jars. Pre-settling basin started to generate biogas at 5 days and had a sinusoidal behavior for 24 days with peaks of almost 10,000ml/day and valleys of no generation. Post-settling basin presented a similar behavior, generating similar amounts. Free stall started generating at 3.5 days and reduced biogas generation, decreasing to about 5,295ml/day. This decline in production was possibly caused by a high solids content and lack of agitation, as discussed in the dairy waste AD evaluation. The no generation gap of almost 12 days could have been attributed to equipment malfunction. The RF antenna filaments detached and was not receiving any information from the jars. This issue was resolved and biogas generation was peaking for pre-settling and post-settling samples with an average of 22,790ml/day and 17,296ml/day, respectively. At 30 days the pre-settling and post-settling samples increased production significantly, reaching a maximum production of 107,646ml/day and 174,327ml/day. Literature mentions that longer HRT (30-50 days) increases biogas production supporting the trends showed by pre-settling and post-settling. Biogas generations per sample and trend lines per waste are shown in Figure 8.

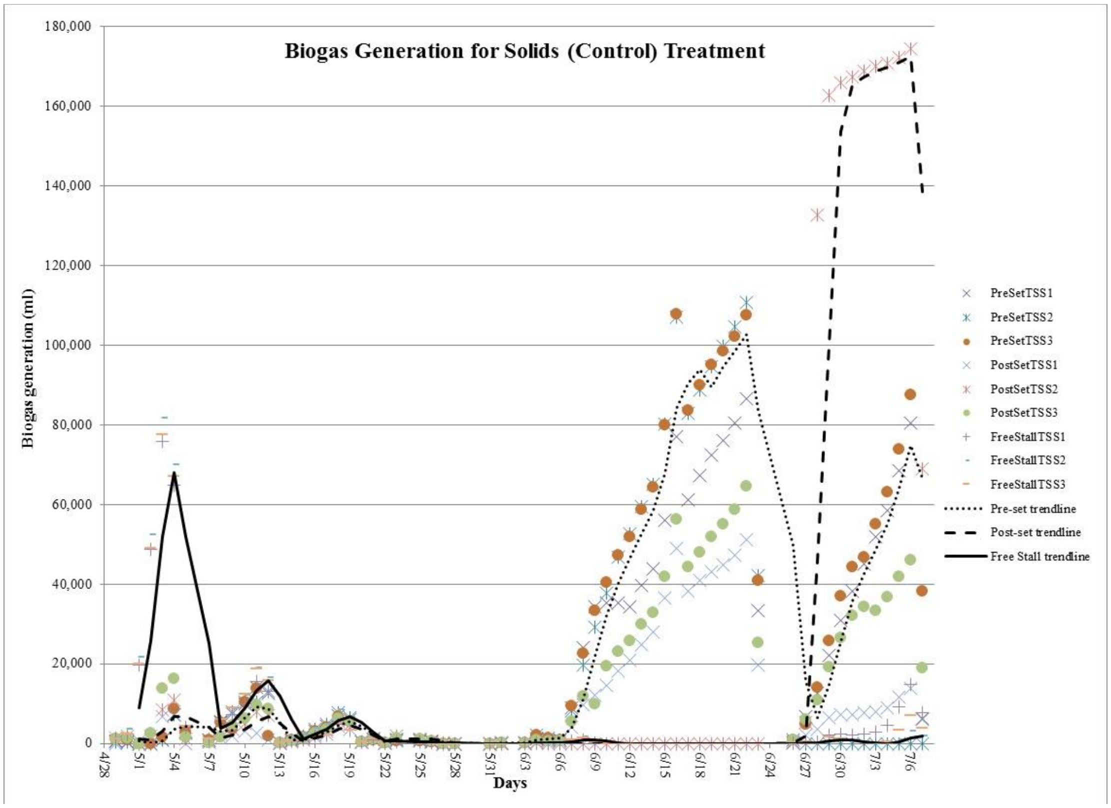


Figure 8. Biogas production from Hereford dairy samples for solids (control) treatment

<u>Temperature treatment</u>

The purpose of this treatment was to determine how biogas generation is affected by temperature. Waste samples and pH-treated samples were exposed to laboratory temperature. Laboratory temperature oscillated from 22 °C to 30 °C. The temperature changes in the laboratory showed mesophilic bacteria (includes methanogens) having a direct response to these fluctuations. For example, the pre-settling basin samples accelerated production at higher temperatures and slowed production at lower temperatures, as shown in Figure 9. The other samples presented a similar pattern.

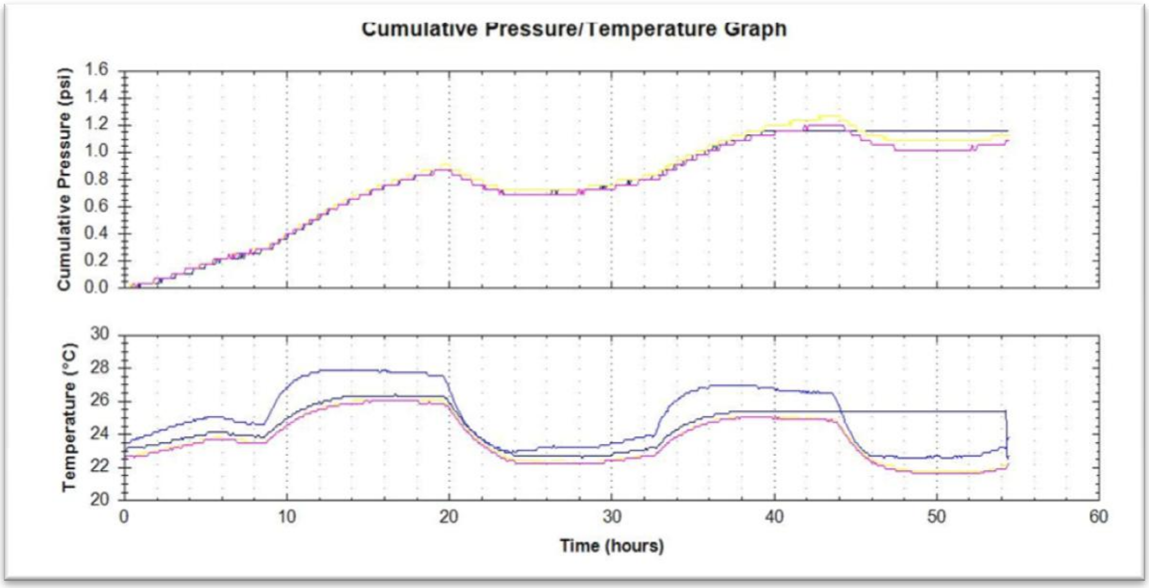


Figure 9. Pre-settling basin samples cumulative pressure and temperature changes based on temperature fluctuations in the laboratory

The 3 samples of each location (pre-settling, post-settling and scrape) were placed in a small refrigerator to simulate low temperatures and determine how these affected the generation of biogas. These low temperatures oscillated between 2 °C to 8 °C. The samples that were exposed to low temperatures of ≈ <5 °C showed a slower but steady increase in biogas production. The refrigeration unit used for this experiment did not have a homogeneous distribution of temperature, creating different temperature exposures. Rotation throughout the refrigeration unit was performed daily and at the moment of changing batteries, with the objective of evenly exposing the samples to the different temperatures. The free stall started producing biogas at 8 days of AD and had the largest amount of biogas produced at an average of 961 ml/day, reaching its peak at 33 days of production; subsequently, its production capacity started to decline. The pre-settling basin slowly started generating biogas at 8 days, and had a steady average production of 742 ml/day throughout the whole experiment. Lastly, post-settling generated an average of

316 ml/day of biogas throughout the period of the experiment. Biogas generation per sample is shown in Figure 10.

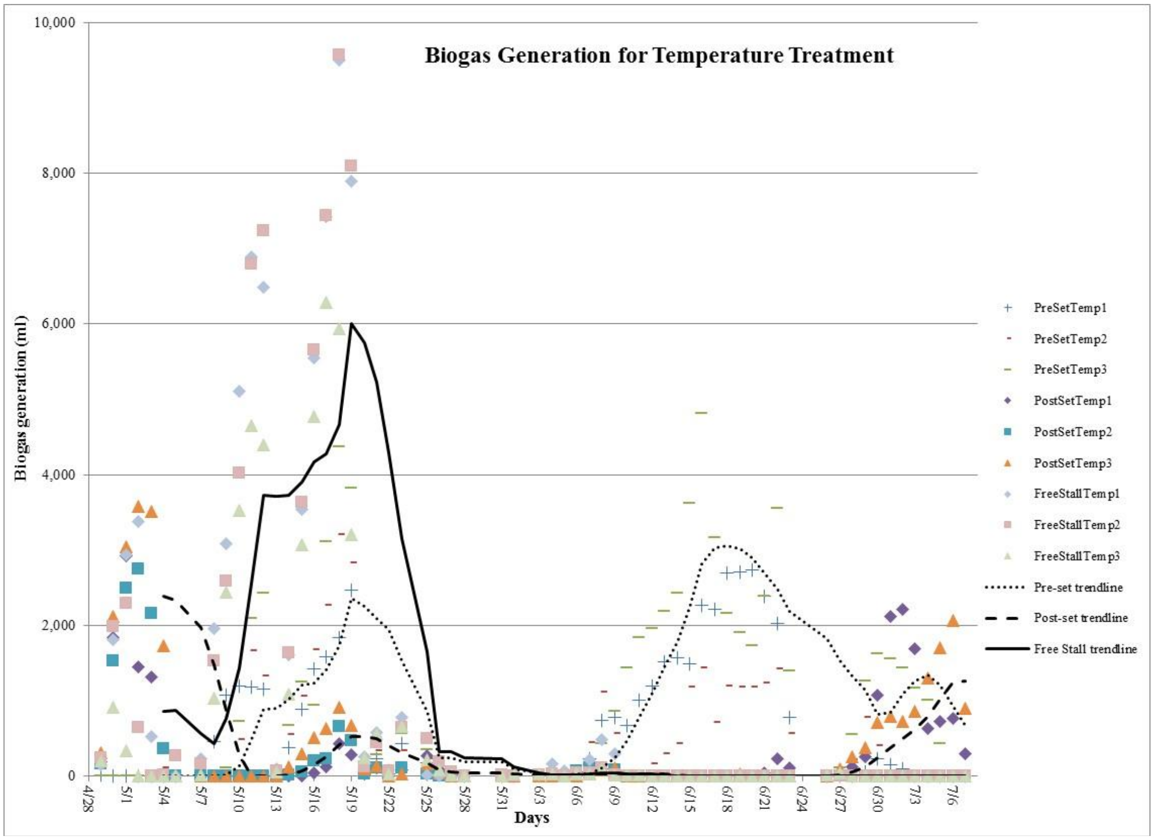


Figure 10. Biogas production from Hereford dairy samples at temperatures between 2 °C – 8 °C

The temperature treatment showed a reduction in biogas generation for post-settling of 98%, followed by pre-settling of 97%, and free stall of 82% compared to total solids.

pH treatment

The purpose of this treatment was to determine if and by how much pH levels affected biogas generation. Methanogens require a pH range of 6.8-7.4 to function properly and be able to transform volatile solids to biogas (Schmidt, 2015). Hydrochloric and sulfuric acids were utilized to lower the pH below 6. Both acids were diluted and mixed with both pre-settling and post-settling samples. Based on research performed on low pH and biogas generation, it was expected that biogas generation would be significantly reduced compared to solids (control). Biogas generation per sample is shown in Figure 11.

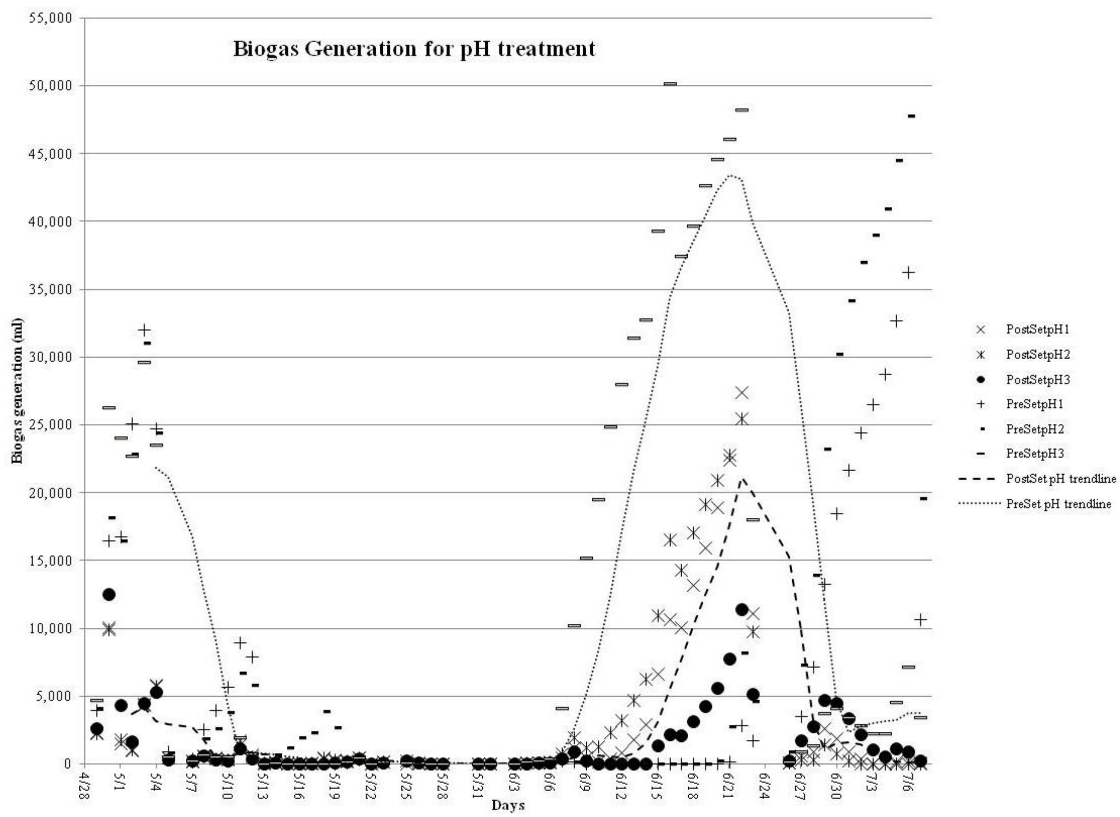


Figure 11. Biogas generation for pH treatment

Pre-settling samples had an initial response and started generating biogas at an average of 8,447 ml/day, followed by post-settling samples with an average of 2,665 ml/day. This showed that low pH affects the methanogens’ activity, resulting in diminished biogas generation. Furthermore, biogas generation peaked at the beginning of the second month following the pattern of the solids (control) reaching a maximum generation of 50,224 ml/day for pre-settling and 27,406 ml/day for post-settling. This experiment demonstrated the relevance of maintaining a pH range between 6.5-7.5, and how sensitive methanogens are to changes in pH levels. By lowering the pH from 7 to less than 6, we had an average reduction of 63% for pre-settling samples and 85% for post-settling of gas production.

CHAPTER SIX

NANCE RANCH BIOGAS EXPERIMENT

Methanogens work best in mesophilic conditions, and any abrupt changes can reduce the microorganisms' performance. These changes can occur while loading wastewater into the appropriate containers which can result in a rapid temperature drop, or if changes in the climatic conditions are not appropriate to maintain the internal temperatures in the digester; this could potentially diminish the generation of biogas (DOE, 2013). However, research with low temperatures (<10°C) using organic wastewater from swine and dairy operations, found that moderate amounts of biogas can be generated by extending the HRT of the digester to 100-300 days. As temperature rises more than 10°C, biogas generation increases linearly and then exponentially, as it reaches 35°C (Safley and Westerman, 1990; Stevens and Schulte, 1979, Sutter and Wellinger, 1985). Cover layers and infrastructure aimed at reducing the impact of low temperatures on biogas generation have been utilized in digesters located in regions with colder climates (seasonal, location, or altitude). For countries like Germany and Sweden, ADs are thermally insulated with plastic layers, fiber glass, and other highly efficient insulating materials. Other insulation attempts have been made with successful results in Bolivia and Peru using greenhouse plastic, adobe, wood, polystyrene foam, and straw (Perrigault, et al., 2012). The latest technique is highly practical for emerging countries where income and access to technology are not available. These greenhouses are normally built with substantial space from the digester to decrease thermal loss. This experiment's objective was to prevent temperature loss from low temperatures that occurred during the winter of 2014-2015 in the Texas Panhandle for an HRT of 60-90 days. To prevent low temperatures and wind from reducing biogas generation, covered layers were installed to recreate a greenhouse effect and maintain and stabilize internal temperatures. These covered layers were located at approximately 0.2 m from the digesters. The pre-settling wastewater was utilized for this experiment since it generated the largest amount of biogas than the other samples based on the results of the biogas optimization of the preferred dairy waste.

6.1 Methodology for the Nance Ranch experiment

Based on the results obtained at the laboratory, it was found that pre-settling sample generated the most biogas compared to free-stall and post-settling sample at ambient temperatures of 22-30°C. Also, the laboratory phase showed that low temperatures affected the methanogens' capacity to generate biogas for up to 97%. Nine 55-gallon open-top drums were used as biodigesters, and black LDPE 8 mil was used as a top cover. Since this experiment was aimed at maintaining internal temperatures, black LDPE 8 mil proved to be satisfactory to serve as a cover for this experiment. A trench was excavated for the drums to be placed and buried, leaving only the lid above soil. The bottom of the trench was compacted and leveled to guarantee an even surface for the drums to sit. A pressure gauge meter (0-100 pounds per square inch-psi) was installed on each drum to measure the internal gas pressure of the digester. Later, three manometers were installed to determine any internal pressure changes by liquid displacement. The experiment design is shown in Table 6.

Table 6. Nance ranch biogas experiment treatments

Treatment / Sample	Black lid*	Black lid+ Transparent	Black lid + Semi-transp.	TOTAL
Sample 1	3	0	0	**3**
Sample 2	0	3	0	**3**
Sample 3	0	0	3	**3**
TOTAL				**9**

*The black lids for each drum were made of LDPE 8mil

Three drums were utilized as controls for the experiment and only contained the LDPE 8 mil as a cover, while another three drums were given an additional transparent sheet of LDPE 6 mil cover, and the last three drums were given an additional semi-transparent LDPE 6 mil cover. The extra cover aimed at creating a greenhouse effect to maintain a constant temperature and to prevent heat loss from weather changes. This experiment was scheduled to run from November 2014 - February 2015, with a maximum theorized production of 20 days.

Sampling and construction of 55-gallon drum digesters

A second sampling trip was carried out on November 17th, 2014 to the Hereford dairy to collect 0.9 m^3 of wastewater in order to perform the experiment. For this experiment, a sludge pump was acquired to pump the effluent from the dairy's main channel to the 0.95 m^3 tank, as shown in Picture 5.

Picture 5. Hereford dairy second sampling trip for the Nance Ranch Experiment

The sample was transported to the Nance Ranch at WTAMU and left in the 0.95 m^3 tank to begin the breakdown of organic matter and anaerobic processes. After a period of 22 days, the wastewater was divided and placed in the nine 55-gallon drums, with approximately 0.075 m^3 in each drum, as shown in Picture 6. The soil was moved to cover most of the drum, aiming to reduce temperature loss. Before samples were placed, the nine 55-gallon drums were modified to have a coupling attached with a pressure gauge meter (0-100 psi) and a bleeding valve.

The drums were installed in a single row with the three control drums left uncovered. To build the greenhouse, it was crucial to leave the lid uncovered and make sure it was free from anything that could potentially block the sun from reaching the digester. A 0.025 m x 1.2 m x 2.4 m board frame was built to place the semi-transparent and transparent plastic. These were laid and then stapled to the wood frame to prevent the wind from tearing the plastics. After placing the plastic covers over the drums, a trench of approximately 0.1 m by 0.25 m was dug around the wood frame to anchor the plastic with dirt to prevent any heat loss from winds leaking inside the "greenhouse". The Nance Ranch experiment is shown in Picture 6.

Picture 6. Wastewater being pumped to the 55-gallon tank

The transparent and semitransparent layers were put in at a height of approximately 0.2 m from the drums. Later, it was noticed that the pressure obtained from the gas generation was too insufficient to be noticeable with the pressure gauge, so a manometer was built with a 12.7 mm vinyl hose and antifreeze cooling fluid to record the differences of pressure by liquid displacement, as shown in Picture 7 and 8.

Picture 7. Drums On-site with semitransparent and transparent layers

Picture 8. Pressure gauge and manometer

The experiment was monitored daily to identify changes in gas pressure, to check that outer layers were in optimum condition, and to prevent any animals, domestic and wild, from threatening the integrity of the experiment.

6.2 Nance Ranch Experiment Results

The Nance Ranch experiment provided valuable information regarding the implementation of AD in low temperatures. A qualitative approach was carried out recording bulging of the drum's lid and liquid displacement in the manometers. Based on the observations performed, the transparent outer layer had the best effect on maintaining the temperature for the digesters. Even though the experiment design considered the nature of the Texas Panhandle, the high winds, snow precipitation, and low temperatures, these became a challenge that showed real-life outdoor conditions and potential impacts on biogas generation. The drums and their integrity were revised daily and, in cases of bad weather, twice a day. High winds carrying branches and other materials frequently damaged the piping and the outer layers.

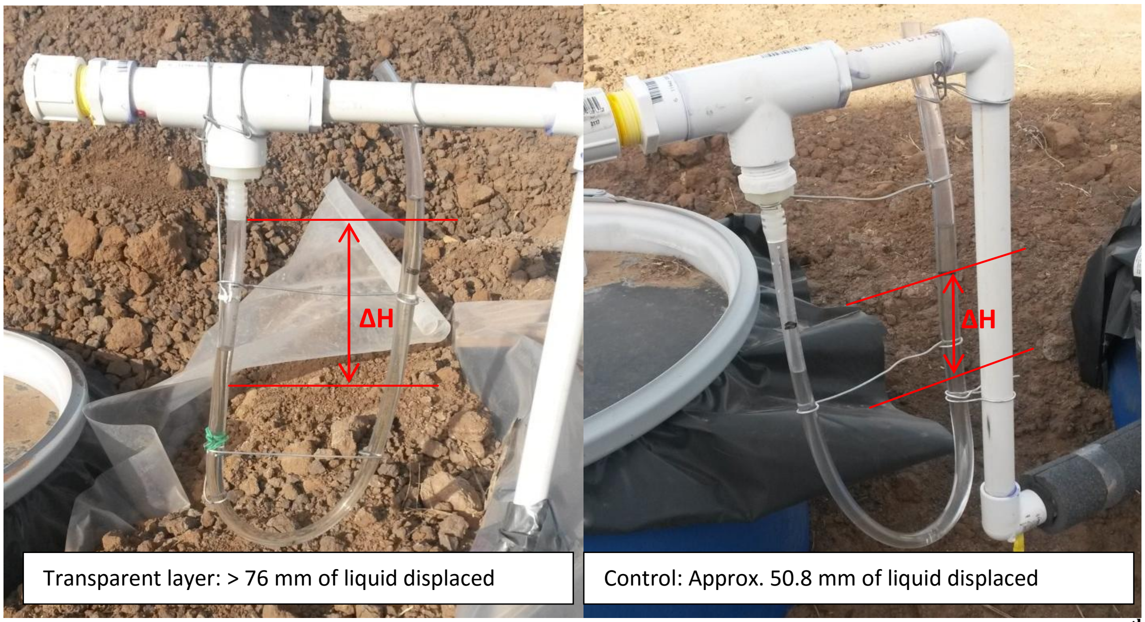
Two drums developed leaks in unknown places. One of the drums was a control and the other drum was located under the semi-transparent layer. These drums did not bulge even in high temperatures. The leaks were not located due to low biogas production. In addition, one other drum was punctured by a branch carried by high winds, allowing the effluent to freeze and have contact with oxygen, losing its ideal conditions to generate biogas. This drum presented a delayed response of several days, from which it never truly recovered.

The manometers were located in the corners of the drums for each one of the experiments. These manometers began showing a change of pressure starting approximately around 9:00 AM for the transparent cover and 12:00 PM for the semitransparent cover layer and controls. It was found that most of the changes in pressure were the biogas expanding and contracting due to the changes of temperature.

The bleeding valve was opened in the drums with manometers and the gas was drained. It took three to four days to generate a similar amount extracted previously. As mentioned previously, observation of manometers and the drum lids allowed inspection of the biogas generation, as shown in Picture 9.

Picture 9. Transparent cover with a control drum

Even though manometers are meant for liquids, they proved to be a highly useful tool to determine the dynamics of the biogas in the drums as shown in Picture 10. These readings showed a qualitative change of pressure since quantification was not possible with the materials used for this experiment.



Picture 10. Manometer reading of the changes of pressure inside the drum on February 20th of 2015

Based on the readings from the manometers and lids, February had the highest biogas generation due to its high temperatures, displacing the liquid between one to more than 76.2 mm in the tubes. Gas was drained when pressure was at its highest, to release pressure and see if liquid displacement or the lids rising were caused by the gas expanding or by the generation of new biogas. The transparent layer showed better results than the semi-transparent layer or the control.

CHAPTER SEVEN

COLOMBIA BIOGAS SYSTEM EXPERIMENT AND SETUP

Small, medium and large dairies employ confined, semi-confined, and free range management practices worldwide. Each practice has specific challenges: cattle management, health of the cattle, feed, milking, space utilized, and infrastructure. In the United States (U.S.), the dairy sector is transitioning towards large dairy farms (>2,000 cows) to meet market demands and profitability. Small U.S. farms (<200 cows) are struggling to stay in business because profit margins for dairies are narrow (USDA, 2007). In emerging countries, dairy operations and markets are mostly composed of micro, small, and medium producers. In Colombia, for example, small dairies (less than 50 cows) compose 82% of total producers of the country (FEDEGAN, 2004).

The signing of the free trade agreement between Colombia and the European Union (E.U.) for the commercialization of milk and milk-based products has resulted in the dairy sector expressing its concerns regarding over-supply and dropping milk prices. The E.U. is one of the leading dairy producers worldwide, and these trade agreements could be affecting dairies nationwide; especially micro and small dairies that will not be able to compete in terms of price and production. Other challenges faced by the dairy sector are:

- Inefficient use of water, energy and other inputs, and impact on production costs and market competitiveness.
- Ratio costs, product life cycle, and competitiveness in the local and/or national market.
- Newly established regulatory requirements.
- New requirements issued by international organizations, NGOs and the public, creating financial risk.
- Promotion of locally produced products and services in local, regional and national markets. Also, reduction of local product barriers to trade, creating opportunities for expanding sustainable trade.
- Lack of liquid capital to improve milking parlor technology.
- Continued increase in energy costs.
- Deforestation due to wood use for water heating.

Currently, dairies are struggling to stay afloat. The price of 1 liter of milk went from $900 Colombian pesos (COP) ($0.35 USD) to $700 COP ($0.25 USD) per liter due to free trade with Europe. To overcome these challenges, many dairies have decided to diversify their portfolio with new products, finished products and improved efficiency by converting from free range to semi-confined or confined management systems, and to invest in alternate high-priced crops, such as cocoa.

Colombia project background and project description

Among the small and medium-size dairymen, it is commonly known that biodigesters are capable of producing biogas that could potentially meet their energy needs. However, they have not been able to find a reliable system capable to withstand long periods of time without the need of constant oversight and maintenance. Furthermore, the lack of technical support in the most remote locations of the country makes AD inaccessible for a majority of rural families. Other plastics utilized in the construction of AD systems proved to be expensive or too thin for agricultural operations. HDPE 40 mil material has been evaluated and used effectively in the US and is considered the minimum weight for landfills, hazardous materials landfills, and lagoon type ADs. The purpose of this project was to determine whether HDPE 40 mil can substitute LDPE 8 mil and it is an appropriate material for the construction of AD systems in Colombia. This plastic will have to prove that needs minimal supervision, maintenance and ease of solids removal and reuse. This material has been found to be durable, puncture-resistant, and able to withstand UV exposure with minimal degradation. To successfully implement this project, key players and potential partnerships were identified by means of email and telephone calls. Several universities and the Ministry of Agriculture in Colombia were contacted without any success. Several private parties showed interest in the project and were willing to accept a full-scale biodigester on their property, if part of the cost was offset. GD Montajes, a private company, also participated in the project providing most of the capital to acquire the materials for the construction of the channel from the pen to the digester, entry and exit boxes, and biogas and wastewater pipelines. For the implementation, a set of small dairy farms were identified, of which one, Flandes, was selected to set up the biogas system.

Weather and climatic conditions

Weather is extremely important for AD. Its functioning depends on water and organic load. Both are influenced by the weather. At the time of the study, Colombia was being affected by the climatic phenomenon called “El Niño”. This phenomenon is characterized by its strong dry patterns. This presented additional challenges for the farm to maintain water for the cattle, crops, and ultimately the digester. The farm increased their water storage capacity by improving their ponds and holding capacity. Also, two more ponds are projected to be built; one for crops, and another for household and cattle consumption. The drought continued and affected the AD’s feeding frequency, changing from daily to once every two days. The initial objective of the implementation of this system was to collect fresh manure from the milking parlor prior to final cleaning the milking and dissolve it with parlor wash, as a first wash, water to meet the solid to water ratio.

Brief description of the farm and agricultural activity

Flandes is a family estate, owned by Enriqueta Molina and Clemente Donato but now managed by their 6 children. Flandes is located in the rural area of Victoria, province of Caldas, Colombia, South America. The farm has 40 hectares (ha) of land, of which eight ha are dedicated to crops (cocoa, corn, plantain, avocado, lemon, and other fruits) and 32 ha are dedicated to grazing dairy cattle. Dairy cattle are gathered every morning, milked manually once a day and then taken back to the fields. The cattle are rotated through 30 small plots in order to maintain an optimum amount of grass. Newborn calves are left in the pen to prevent the attack of birds of prey such as vultures and other predators. Year-old weaned calves are sent to a separate field. The remaining 6- to 12-month calves go to pasture with the mature dairy cattle.

Climate variability, with more extreme weather fluctuations and reduced pasture productivity and seasonality, poses a dairy management challenge. Dairymen are seeking new and cost-effective alternative sources of feed for livestock. Dairy management strives to increase production and to use land more efficiently, while diversifying its portfolio by changing the production model from a grazing to semi-confined model.

The Flandes dairy farm, and most like it, use wood and propane as sources of energy for cooking and heating water for the milking process. Wood is the main energy source used for heating and cooking, with propane used as a backup. The wood is procured on the farm and the propane is delivered to the farm for an extra fee. Normally, a 40lb propane bottle costs $42,000 COP or $17 USD. Wood is collected every week and the propane bottle is replaced every month. Electricity has proven to be too costly ($100,000 COP or $40 USD a month) so, in most cases, electric stoves are not an option for low-income families. Most of the cooking is performed by the farm keeper's wife or his young ten-year-old daughter, starting around 5 AM and closing kitchen around 10 PM. Also, the farm keeper's wife cooks with their four-year-old son at her side, since she has no one to take care of him while she performs her household duties. The kitchen has an open concept, but chronic exposure from wood burning particulate matter and volatile organic compounds (VOCs) is highly likely due to the poor design of the stove stack. The lack of doors on the firebox let live charcoals fall onto the floor, increasing the risk of burns, especially for small children.

The farm gets its water from the Purnio River, which is transported through a 25.4 mm pipe to a storage tank. To increase water availability for crops and cattle, the farm made a $5,000 USD investment to build a water reservoir to supply water in times of drought; however, the reservoir rarely provides enough water to meet the needs of the farm.

After meeting with the management and discussing the farm short-, medium-, and long-term goals, they presented the following:

- Install clean fuel sources for heating and cooking to reduce exposure to particulate matter and VOCs from cooking with wood and other biomass sources.
- Comply with the environmental regulations applicable to the sector and region.
- Generate opportunities to enhance the industry and its processes.
- Increase dairy herd from 25 to 60 head.
- Change the feeding system from a free-grazing operation to a semi-confined space feeding operation.
- Design a zero-discharge system to reduce wastewater discharges to creeks, soils, and other vulnerable areas, reduce water consumption in the milking parlor, and reuse water in irrigation processes.
- Increase crop production of cocoa, corn, plantain, and sugar cane and using treated wastewater for crop irrigation.
- Increase sugarcane feed production from 1,000 kg to 10,000 kg/ha.
- Develop a cocoa-drying system using biogas as a heat source.

The holding pens, milking parlor, and proposed biogas system location are shown in Figure 12.

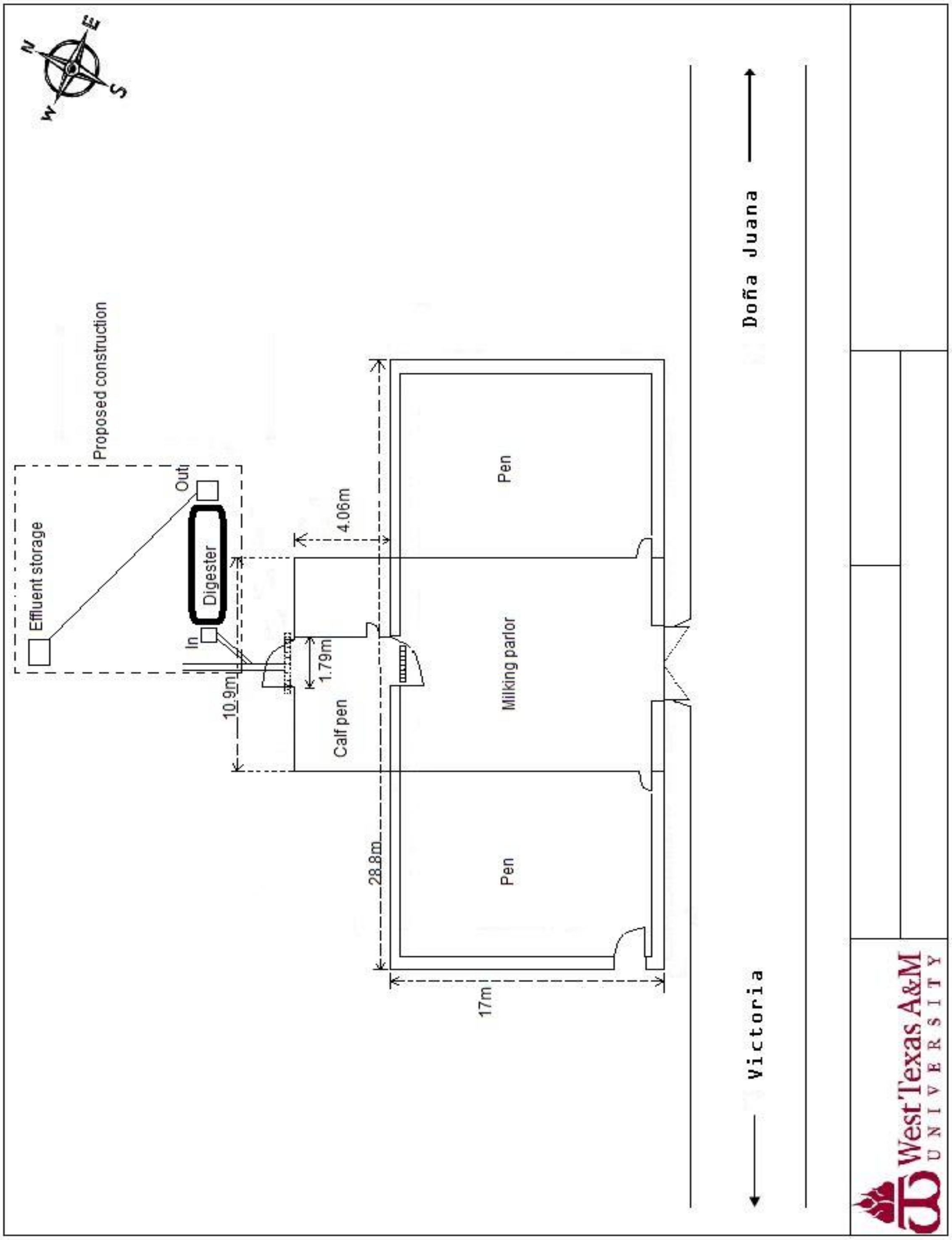


Figure 12. Milking parlor and proposed biogas system location

Flandes has been working for more than 15 years on mixed breeding to maximize milk yield. Normally, the farm uses the breeds Guir, Brahman, Zebu, and Holstein.

Currently, the farm has 25 milking cows and 26 calves. Cows are brought at 4:30 AM and milked by hand. Milk is picked up at 7:30 AM daily, by a third party. The cattle stay in the pens for supplemental feeding composed of sugarcane, jumbo grass, molasses, and macro and micro minerals. After the cows are fed, they are moved to a new field. Then, the milking parlor is scraped and washed to remove manure out of the milking parlor (See Pictures 11 and 12). Historically, manure was washed to a field of jumbo grass (see Pictures 13 and 14)

Picture 11. Supplemental feeding is provided after milking. The parlor is left with manure, food residues, and leaves from nearby trees.

Picture 12. Milking parlor after being scraped and washed

Picture 13. Jumbo grass crop behind the milking parlor

Picture 14. Manure accumulation from milking parlor wash

7.1 Methodology

The digester proposed for Flandes was a tubular or sausage-style digester. To meet the farm needs the digester needs to provide around $4m^3$ of biogas per day for cooking, water heating and drying the collected cocoa seeds. Thus, this digester was designed to have a total capacity of 20 m^3. Approximately 80% of the digester volume was utilized by the wastewater, and 15%-20% by the biogas. The digester was built using HDPE 40 mil material which allows the biogas system to perform at higher pressures than a conventional tubular LDPE (8 mil) digester. Following are the calculations made to design and construct the digester.

Calculations of Digester Using Linear and Tubular Measurements

a. Initial Calculations

The initial calculations were based on the length of the material and width of the HDPE roll.

Length = 6 m

Width = 6.4 m

Calculation of radius, area of circumference and volume:

$P = 2\pi r$

$6.4\ m = 2\pi r$

$\frac{6.4\ m}{2\pi} = r$

$1.02 = r$

$A = \pi r^2$

$A = \pi * (1.02)^2$

$A = 3.26\ m^2$

$\forall = A * L = 3.26\ m^2 * 6\ m = \mathbf{19.56\ m^3}$

b. On-site Calculations

These calculations were performed after inflating the digester on-site and determining its true volume.

Length = 4.3 m

Diameter = 2.04 m

Calculation of the circumference area and volume:

$A = \pi r^2$

$A = \pi * (1.02\ m)^2$

$A = 3.26\ m^2$

$$\forall = A * L = 3.26\ m^2 * 4.3\ m = \mathbf{14.01\ m^3}$$

$NOTE\!: The\ loss\ from\ original\ length\ was\ about\ 30\%. Total\ length\ initally\ needed\ would\ be\!: 8\ m\ long\ to\ build\ a\ 20\ m^3$

c. Calculations of volume based on organic matter load

This volume is used to determine the daily load needed to feed the AD based on the results of the dairy waste evaluation section.

Current load = 12 fresh manure patties

Average weight per fresh manure patty = 5 kg

Daily organic load $= 5\ kg * 12 = 60\ kg/d$

Dilution ratio with water = 1:3

Water needed: 180 L ≈ 200 L/d

Total mass entering the system: 260 kg/day or 0.26 m^3/day

Hydraulic Retention Time (HRT): 33 days

HRT Correction factor: 1.05 (Vargas, 1992)

HRT_{adj}: 35 days

Volume of digester: Biomass x HRT_{aj}

Volume of digester: 0.26 m^3/day x 35days = 9.1 m^3

Considering that liquid phase normally occupies 75-80% of the total volume of the digester, it is necessary to add 20% to store the biogas

Volume of digester 9.1 m^3 + 1.82 m^3 ≈ 11 m^3

To the total 11 m^3, a factor of 20% was added to prevent overload either by excessive loading or an event of rainfall. The final volume for the digester based on the amount of manure and water added was 13.2 m^3. The lack of experience adapting HDPE 40 mil to a tubular form reduced the holding volume of the digester from 20 m^3 to 14 m^3. This volume reduction had direct repercussions on biogas generation, reducing the amount generated from 4 m^3 to around 2 m^3 per day.

d. Water flow calculation

A 20 L container was utilized to calculate water flow. It was timed how long it would take to fill the container. This time was utilized to determine the time needed to provide the necessary water to reach the 1:3 dilution ratios with the manure.

Water capacity = 20 L in 1 min 5 sec; 200 L would take 10 min 50 sec ≈ **11 min.**

e. Biogas generation

Biogas generation was calculated utilizing literature values since grazing cattle diet is composed mainly of grass and supplemental feeding such as raw corn and sugar cane (Mantilla, 2015).

1 manure = 5 kg * 12 = 60 kg

It is assumed that this manure has a 16% of volatile solids,

60 kg * 16% = 9.6 kgVS

and that only 50% is converted to biogas;

9.6 kg * 50% = 4.8 kgVS

From that, 0.22 m^3 are generated from 1 kg of VS

so, 4.8 kgVS * 0.22 m^3/kg VS = 1.05 m^3/day

The initial design for the proposed anaerobic digester with a capacity of 20 m^3 is shown in Figure 13.

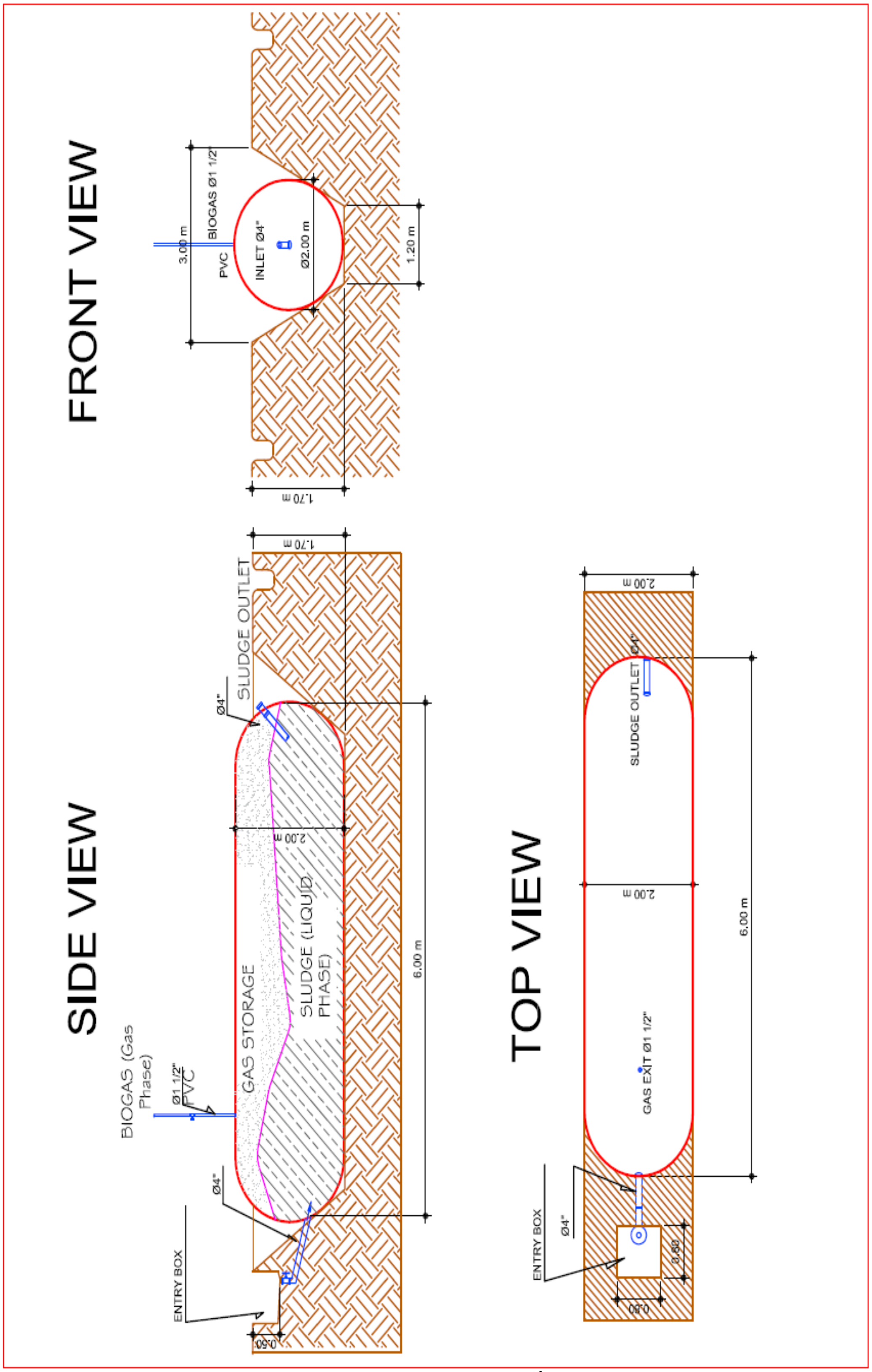


Figure 13. Proposed design of the 20 m^3 biogas system for Flandes

Materials and Construction of the Digester

The project had the goal of designing and constructing an anaerobic system for a small dairy of 25 cows using a highly resistant material that would require little or no maintenance from the farmer. The biogas system must also be resistant to UV light degradation, and puncturing. Aquapruf (2011), a Colombian company specialized in plastics, published a manual discussing in length the physicochemical characteristics of this liner and its uses in the oil, remediation, pond lining, and landfill industries. This liner is also used in the U.S. for holding ponds, water reservoirs, and lagoon-type biogas systems.

A piece of 6 meters in length of HDPE 40 mil was donated by Rocking R pond lining company, and the 76.2 mm entry and exit couplings for the project were acquired in the U.S., as well. The design and construction of the bag were carried out in the U.S., folded, and later transported via airplane to Colombia for installation (see Pictures 15, 16, and 17). GD Montajes provided all the materials for the installation and construction of channels, PVC connections and piping, valves, and HDPE piping.

Picture 15. Cutting HDPE from the roll

HDPE 40 mil is a highly resistant material, more rigid than LDPE. To cut at one point, it became necessary to use a sharp blade in the form of a hook. It was important to make sure that the material was not lying on any sharp objects (i.e. rock, stump, metal) that could puncture it with the weight of the roll itself or a person walking on it. Later, the piece was laid on a flat surface, free of rocks and branches. The surface of the liner had been previously cleaned and inspected for any cracks, before welding the plastic. Since the design of the digester was tubular, the sides were folded and overlapped approximately 6”, making sure that there was enough material for the wedge-welding process.

Picture 16. Locating the 76.2 mm couplings and overlapping corners prior to welding

The welding process was performed with an automatic DEMTECH wedge welder. This type of welder works by heating a wedge to approximately 300-400 °C and then applying pressure throughout with a heated double track wedge. Further inspection of seams and welded material was necessary, to determine if any leaks were present (Müller, 2007).

Picture 17. Wedge-welding the folded sides and corners with the DEMTECH welder

After all seams were welded, the locations of the entry and exit couplings were estimated. Three couplings were installed; two couplings of 76.2 mm for the entry and exit of the wastewater, and one coupling of 38 mm for the exit of the biogas. The bag folded and ready for bagging is shown in Picture 18.

Picture 18. Folded bag with couplings ready for shipment

After finishing welding and installing the couplings, the bag was folded and packaged for shipment, as shown in Picture 19. The total weight of the bag, with the packaging, was 39 kg. After arrival, the bag was unfolded and inflated with a compressor to locate any leaks that may have happened during transportation, as seen in Picture 20.

Picture 19. Checking for leaks after the flight from the U.S. to Colombia

The bag was transported to the site and tested once more. The bag was transported as a check-in bag with double bag and bubble wrap plastic as protective layers. However, these proved to be insufficient to protect the bag against the mismanagement given by the airline. Several leaks were found and were fixed through mechanical and heat seals. The heat seals were made with a hot air gun, a roller, and pieces of HDPE (see Picture 20). This process occurs by warming both the piece and the bag and pressing them together with the roller. The mechanical seals were made using brass screws, rubber, and plastic from a 0.2 m^3 drum (see Picture 21).

Picture 20. Hot air procedure for sealing a leak using HDPE 40 mil trims

Mechanical seals are extremely useful whenever electricity is not available or location does not allow access through vehicles. These types of seals are more time-consuming, but they work just as well as extrusion or hot air seals. Mechanical seals normally use brass or stainless steel to prevent corrosion from the sludge or the biogas inside the bag as shown in Picture 21. The bag was fixed, and it was made sure it was able to hold pressure by inflating it again and measuring pressure loses.

Picture 21. Mechanical seals included brass screws, rubber, and plastic layers

Once all the leaks were repaired, the excavation started for the bag and the entry and exit boxes. The local farmer contacted the town mayor, and a Backhoe was borrowed for a couple of hours to perform the excavation (see Picture 22). The excavation then was smoothed with shovels to make sure it was leveled and that no sharp points were in the trench that could hurt the bag during its expansion and contraction processes.

Picture 22. Main trench and exit box excavated based on the calculations and length of the bag

After removing the rocks, the holes left were filled with clay and smoothed, as shown in Picture 23.

Picture 23. Trench smoothed, rock holes filled with clay, and exit piping installed in place

Once the bag, entry, and exit excavations were ready, the construction crew proceeded to lay the bricks and concrete for the boxes while preparations for lowering the bag were made, as shown in Picture 24. Also, new leaks were found and were fixed in place with mechanical seals.

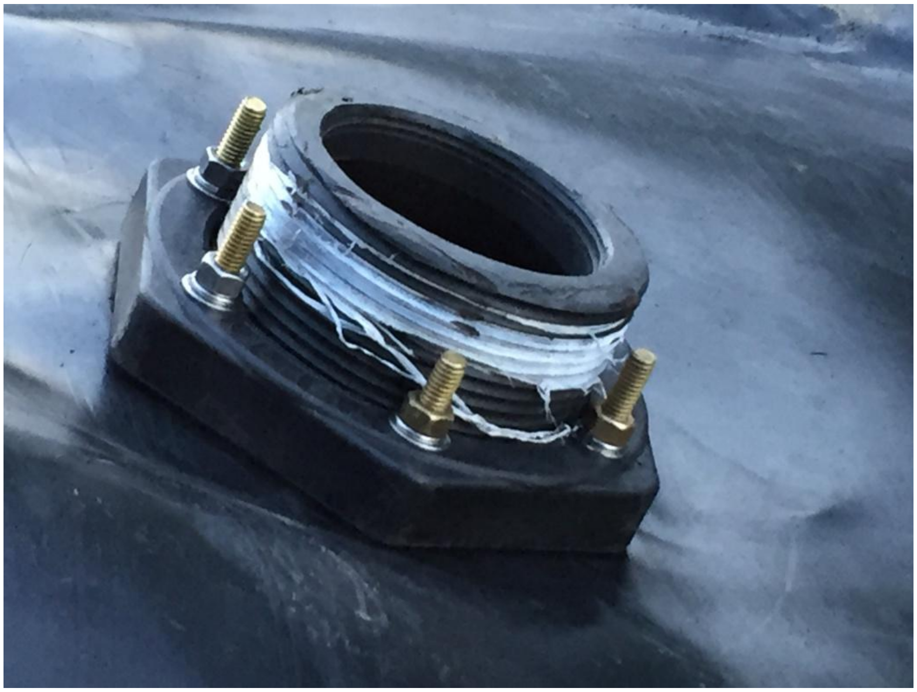
Picture 24. Exit box ready for the concrete and water sealing application

The initial design as shown in Figure 19 was modified to fit the biogas system to the field terrain. The outlet box was increased in size to facilitate the drainage, revision and control the digester dynamics.

From the exit coupling of the bag, a Y fitting was installed to provide a liquid seal and a fast flush exit. The first pipe was located at 0 degrees and serves to drain the digester whenever it becomes necessary. The second pipe was installed at an angle of 45 degrees to serve as a control valve, through a water seal. Upon inspection, it became evident that the exit fitting was located too high to drain the sludge, so it was relocated 0.6 meters out from its initial location, as shown in Picture 25.

Picture 25. Sludge outlet relocated 0.6 m lower from the initial location

This procedure was extremely time-intensive and it required several hours to detach and relocate. Furthermore, it was evident that the HDPE was not sealing completely with the rubber seals and plastic nuts, so brass screws were installed around the fitting to keep the HDPE and fitting in place as shown in Picture 26.



Picture 26. Fitting secured with brass screws and stainless steel nuts

The bag was inflated again to check for leaks. Once all the mechanical and heat seals were finished, fittings were connected to the 102 mm PVC pipe with test caps pending for final installation and connection to the boxes. The bag was located on top of the trench and pushed down as much as possible. Once the bag was not able to move any further, extra weight was applied by injecting water into the biogas outlet, forcing it to go down by water weight. Once the bag was in place, the installation of PVC pipes and final connections were made. Also, another search for leaks was performed to identify any holes that could have been made while lowering the bag. HDPE 40 mil was rigid, becoming a challenge to handle, but proved to be effectively resistant to the lowering and fitting process. A picture of the bag in the trench and entry and exit pipes before connection is shown in Picture 27.

Picture 27. HDPE bag and entry pipe before connection to the entry box

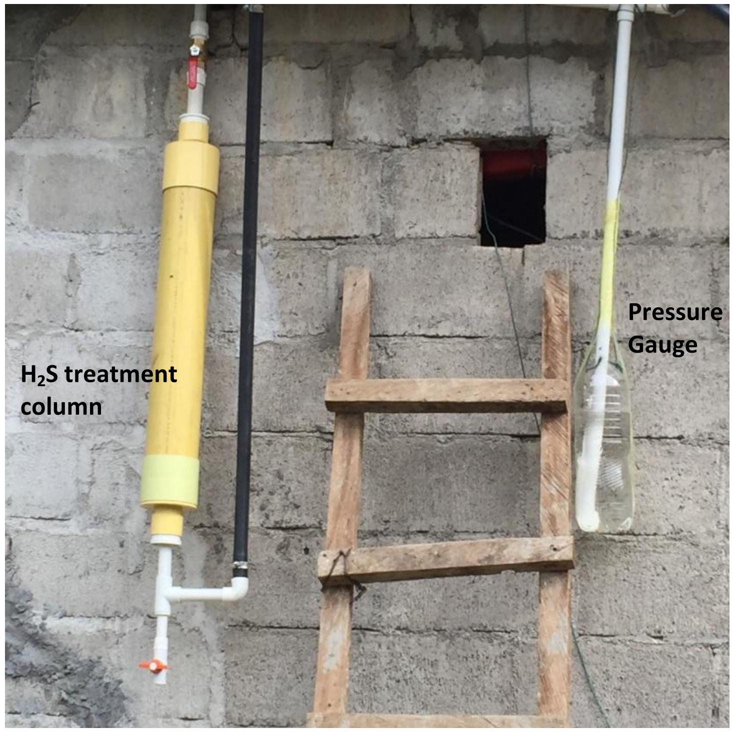
The trench was initially designed with a 60-degree slope to prevent any wall collapsing; however, on the field the soil proved to be much stronger and, with the bag in place, the trench ended up having a 70-degree slope. The inlet box was connected to the main channel through a 0.3 m x 0.15 m x 2 m concrete channel. The inlet box was initially designed with a constant depth but, in the field, the design was changed to a bottom with slope. The initial depth of the box was 0.7 m and it ended at 0.5 m. The inlet pipe was elevated by 0.1 m from the bottom of the box. These modifications had the objective of reducing the concentration of large solids in the effluent that could be entering the system, therefore, increasing the longevity of the digester by reducing sedimentation and formation of floating matter that could hinder the collection of the biogas. The entry box is shown in Picture 28, while the AD was being loaded.

Picture 28. Entry box receiving the effluent and affluent entering the biogas system

The farm feeds sugarcane and jumbo grass every morning to the cows after they have been milked. Food leftovers are mixed with the manure at the moment of cleaning the milking parlor, potentially reaching the digester. If these solids reach the digester, this could potentially reduce its life or plug up the inlet. Thus, to reduce the number of gross solids that could plug up the system, a pre-filtration was installed. This screen was designed to be highly cost-effective. A metal frame was built with another frame inside to hold a plastic screen that can be replaced once it starts breaking (Picture 29). This design was intended to reduce costs and maintenance from the farm workers.

Picture 29. Pre-screening of the effluent prior to entering the entry box and later the digester

The outlet box has a 51 mm pipe at the bottom connected to a one-cubic-meter container. This container is filled with the effluent that later will be used to fertilize the crops in the farm. The biogas, composed mainly of methane, carbon dioxide, and other minor gases is filtered to remove the hydrogen sulfide (H_2S) before sending it to the kitchen through 25.4 mm HDPE pipe. An H_2S treatment column composed of treated metal shavings and a trouble-free check valve was designed to show the internal pressure of the biogas system were also installed as shown in Picture 30. Since this AD was made of HDPE 40 mil, the internal pressure of the system was raised from 14 to 25 centimeters of water. Traditional LDPE 8 mil anaerobic systems can safely handle pressures of approximately 14 centimeters of water in normal conditions (Mantilla Garavito, 2015).



Picture 30. Pressure gauge/check valve and the hydrogen sulfide removal column

The gas line was sent above ground to the kitchen at an angle, to prevent any kind of condensation that could block the flow of the biogas to the kitchen. Increasing the pressure in the system allowed the gas flow to the stove, potentially improving combustion and amount of fuel burned, increasing heating power.

Starting the biological reaction

To start the digester, four 6-gallon containers full of activated sludge were collected from a nearby pork farm. The activated sludge was applied with the first load of manure and water into the digester. After the digester was charged, it was expected to start generating enough biogas to inflate the bag by day 7. This day was based on the results from previous experiments performed with the Panhandle dairy waste streams. The digester loaded with the seed, and the first load is shown in Picture 31.

Picture 31. Biodigester after installation and charging

The digester was charged every day as calculated for fresh manure and water. The installation of the whole system was finished the day before the Community Outreach Event on June 18th. The biogas system was shown to over 90 nearby ranchers, dairies, waste management company, state environmental agency, University of Caldas, Local Agricultural and Environmental Agency (UMATA), current major and future candidates for the town of Victoria Caldas, local high school students, and other community members attending.

Fine-tuning biogas generation to meet expected demands

The biodigester was generating biogas for a total of two hours and 30 minutes of continuous burning. However, it was not meeting the minimum cooking time needed to feed the family and the two other farm employees. The family was able to cook one meal and warm liquids (coffee, water, and milk) during the day. Thus, a new goal was established to generate enough fuel to cook 3 meals a day for a total of six people. Different alternatives were explored to address this situation:

- *Storage bag:* a bag used to store biogas next to the kitchen. If biodigester is not producing enough, the bag is squeezed to maintain pressure in the line. Normally this bag is made of LDPE and stores from 3-5 m^3. To install this bag in the current system, it would become necessary to reduce the pressure from 25 cm of water to 14 cm of water. It is time-consuming and it reduces pressure in the system.
- *Compression of gas:* a compressor will be needed for this case. The gas line is connected to a compressor of a specific volume. The compressor stores the biogas at higher pressure. As the gas is being utilized, the compressor extracts more gas from the digester to replenish its initial amount. A compressor and a more stringent H_2S removal unit will be needed. This alternative is time-consuming, costly, and a redesign of the gas line will be needed.
- *Construction of a second digester:* a second digester in sequence to extract as much or more biogas possible. This second digester will be connected to the gas line as well. Retention times and loads will need to be recalculated to meet the organic load of both digesters. This alternative is time-consuming, costly, and a redesign of the gas

line will be needed. Excavation and setting up a new inlet-outlet box and piping will be needed.

- *Increase daily load:* by increasing the amount of manure and water, biogas generation also increases. However, this increment will affect the Hydraulic Retention Time reducing the time organic matter spends inside the reactor. It is not time-consuming, does not incur additional costs to the farm.
- *Increase pressure on the digester with weight:* In LDPE digesters, the plastic acts as a weight and provides some pressure to the gas. However, due to its rigidity, HDPE maintained its tubular shape and did not provide any pressure to the gas. Placing an extra weight will increase the internal pressure. It is not time-consuming and does not incur additional costs to the farm.

From all of the options mentioned previously, increasing daily load and increasing pressure on the digester with a weight were the most cost-effective and least time-consuming.

The volume of manure and water was again calculated to determine the new Hydraulic Retention Time (HRT) and new organic load needs. These calculations are shown below:

New organic load **= 18** manure patties

Average weight per manure patty = 5 kg

Daily manure load $= 5\ kg * 18 = 90\ kg/d$

Dilution ratio with water = 1:3

Water needed: 270 L/d

Total mass entering the system: 360 kg/day or 0.36 m^3/day

Hydraulic Retention Time (HRT): 30 days

HRT Correction factor: 1.05 (Vargas, 1992)

HRT_{adj}: 32 days

Volume of digester: Biomass x HRT_{adj}

Volume of digester: 0.36 m^3/day x 32 days = 11.52 m^3

Due to the increase in daily load, no extra added factor can be applied. Considering that the liquid phase normally occupies 75-80% of the total volume of the digester, it is necessary to add 20% to store the biogas.

Volume of digester 11.52 m^3 + 2.3 m^3 = 13.8 $m^3 \approx$ 14 m^3

Colombia biogas system experiment results

The biogas system was successfully installed and is currently in operation, generating approximately 1.2 m^3/day. The AD also serves as a wastewater treatment unit removing approximately 90% of the Chemical Oxygen Demand and 80% of the Biochemical Oxygen Demand. These percentages are well within the ranges of efficiency for AD treatment systems (Mang, 2008).

The construction of this digester was projected to be carried out in the first 2 weeks of June 2015. However, it was delayed due to weather conditions, backhoe scheduling, and the concrete mason canceled at the last minute. After overcoming these difficulties, the project was finished June 17th, 2015. It was found that wrinkles and bends in the HDPE liner have a high risk of stressing the plastic, creating stress holes mostly due to its rigidity. These holes posed specific challenges that had to be addressed prior to putting the digester to work to prevent any gas or liquid losses. These holes were too small for mechanical seals and heat seals were not an option after loading the digester. Two techniques were used to attempt patching the bag while loaded; Sika^{TM} sealant and HDPE tape. It was found that when the HDPE tape gets wet, it will not attach to the bag and the sealant did not seal correctly if the liquid was leaking. However, it was found that the combination of both techniques worked best to patch these types of leaks. Gorilla tape could potentially become an alternative solution for small pinches and leaks. This tape has a water activated glue that could provide a better sealing combined with the HDPE tape.

After patching and charging the digester, biogas production commenced with the first flame at 15 days of installation. This flame lasted five minutes. By July 17th, or one month after installation, biogas production normalized to two and a half hours of continuous burning (Picture 32).

Picture 32. Biogas being burned and utilized in the kitchen

After applying these changes, the production increased by one hour, for a total of three hours and 30 minutes. The biogas system two months after installation and with the extra weight is shown in Picture 33.

Picture 33. The current state of the Colombia biogas project

These improvements will meet the minimum requirements to supply enough fuel for two complete meals for 6 people and sporadic use during the day. However, it will not meet the minimum requirements to supply cooking energy and heat for drying cocoa. A second digester will be needed to supply that demand.

7.3 Colombia biogas project Economics

This project targeted two economic points: materials and labor. If the HDPE 40 mil plastic was acquired in Colombia, the upfront cost would have been $918 USD. This cost assumes a digester's lifespan of 25 years with little or no maintenance. The HDPE biogas system costs were compared with the LDPE biogas system to determine which is most cost effective. These costs are shown in table 7.

Table 7. Biogas system cost comparison in US dollars for a 25 years lifespan system constructed with High Density Polyethylene and Low Density Polyethylene.

Costs*	Biogas system made of HDPE	Biogas system made of LDPE
Materials for biogas system construction	$416.90	$682.50
Transportation of materials	$42.35	$42.35
Labor (design + installation)	$440.18	$340.18
Other installations	N/A	$220
TOTAL	$918	$1,303.53

*Costs are calculated in a 25 years lifespan

Materials for biogas system construction

A standard anaerobic digester uses LDPE 8 mil as the material for the bag. This material does not have a high cost; $2.85USD a linear meter of 2 m diameter (conversion rate of $1USD = $2,800 COP). For a 20 m^3 digester, using 2 m diameter, 8 meters of plastic would be needed. Since LDPE 8 mil can be punctured easily and speed up degradation due to weather and UV light, it is standard practice to double it, for a total of 16 m. Then, it is necessary to add 30% extra for the pipe connections and compensate for other losses. This makes a total of 21 m for a 20 m^3 digester. Total initial investment in LDPE plastic is $60 USD. The digester was projected to last 25 years with a 3-year flush procedure to reduce sediments and sludge that could reduce the digester's productivity. LDPE 8 mil lasts between 3-5 years and, in conservative terms, the best management practice is to replace the plastic every time you flush the digester. However, for the purposes of this paper, the LDPE plastic will be changed every five years. Thus, for a 25-year digester, the plastic will be replaced 5 times which totals $300 USD, not including depreciation.

LDPE systems require shelter from UV radiation, weather conditions, animals and humans. Producers and families using biogas systems normally will build shelters with metal sheets, wood, and chicken screen. The cost of a shelter using these materials and 1 week of labor to complete its construction totals $220 USD.

For a digester using HDPE 40 mil the cost increases to $4.30 USD (conversion rate of $1USD = $2,800 COP) per linear meter of 7 m width. For a 20 m^3 digester, it would need a length of 6 m of plastic. The HDPE lifespan exceeds 40 years of use in exposed conditions to weather and UV light. It is also resistant to abrasions and larger materials such as branches that could puncture through the material. After this experiment, it was discovered that an extra of 30% should be enough to compensate for losses to a total length of 7.8 m or approximately 8 m for a 20 m^3 digester. Thus, the total investment in HDPE plastic is $34.40 USD, not including depreciation. If breaks in the plastic cannot be repaired through mechanical seals, HDPE tape, and Sika™, the digester can be repaired with a piece of HDPE 40 mil and a hot air gun or an extrusion welder.

Other materials, such as PVC pipes, fittings, connections, HDPE pipe are similar, except the 3” couplings previously installed in the HDPE liner. The total amount of other materials was $382.5 USD.

Labor

Biogas system design

LDPE does not require special handling or highly skilled labor for its handle and installation. It is small and light enough to carry in a small box and it can be installed without any special types of equipment. HDPE normally uses a welder (extrusion, hot air, or wedge welding) to seal the plastic, but a mechanical seal can also be put in place and it will meet the requirements needed to create an anoxic environment. This experiment used a wedge welder handled by a trained person. This person normally would charge $50 USD/hr. The welding was estimated to take 2 hours of time for a total of $100 USD using the wedge welder.

Installation

Biogas systems using LDPE and HDPE require the same amount of installation hours. Installation labor for this project was estimated to be $340.18 USD total.

Transportation

Plastics and materials need to be transported from the main city nearby. Bogotá and Manizales are the closest cities that could provide all the materials, including the plastic. This project procured most of its materials in Bogotá and later the farm owners transported the materials. Bogotá is located approximately 5 hours and a distance of 189 km from the project site. Transportation cost is an important factor in determining the total costs of a project. A Mazda gasoline truck was utilized for the transportation of materials. This truck has an average gas consumption of 28 km/gal. Gasoline in Colombia costs $2.82 USD a gallon. Total gasoline used was $18.53 USD.

Local travel from the farm to the town of Victoria, Caldas was performed to procure perishable or consumable materials, such as PVC glue, rubber, and PVC pipes that were not accounted for due to unforeseen events. Total consumption of gas for local transportation was $42.35 USD.

Payback period

A biogas system provides many benefits for the family or agricultural operation using the system, such as improved sanitation, a low-cost energy source, low-cost fertilizer, improved living conditions, and improved air quality. Biogas provides an alternative source that could replace traditional energy sources. For example, the biogas system implemented in Colombia uses 90 kg of fresh manure which replaces 18 kg of wood, 5.4 kg of charcoal, and 2.2 liters of kerosene per day based on Hivos' (2014) calculations.

The farm uses one propane bottle of 40 lb/mo with a cost of $17 USD/mo and approximately 136 kg/mo of wood which takes about 2-3 hr/day to collect, transport, and cut. If an employee performs this task, this will cost $8.3 USD/mo to the farm (monthly salary is $357.15USD). By using the biogas system, the farm will save $25.37 USD/mo in fuel costs. Furthermore, biogas is a clean fuel that reduces human exposure to indoor pollution (particulate matter and volatile organic compounds) caused by wood burning. Replacing wood with biogas will minimize costs such as doctor's appointments due to respiratory and eye problems, medications, and transportation to health centers (WHO, 2012).

The effluent can also be used to minimize or completely substitute chemical fertilizers in crops, reducing the farm operation costs. Currently, the farm pays about $40 USD/mo for urea and a triple 15 (P-K-S) fertilizers for only the cocoa crops. The effluent was characterized and based on the agronomist's technical analysis, only micronutrients are needed to balance the effluent and use it as a fertilizer on a 1-to-1 water to effluent ratio.

Considering a lifespan of 25 years, a biogas system constructed with HDPE 40 mil costs $918 USD, while an LDPE biogas system would cost $1,304 USD. This shows that, as a long-term investment, the HDPE proved to be cheaper by $386 USD. Furthermore, if the farm substitutes 100% of the heating energy and fertilizer the project will be paid off in 14 months.

7.4 Colombia biogas project Community Outreach

Dr. Rogers has always said that 1% of the project is technical and 99% is cultural, and this project was not the exception. This project focused mainly on testing different materials for small-medium scale biodigesters that can provide or exceed LDPE digesters. Also, demystify AD by showing that constant supervision, vulnerability to UV light and weather, and complexity are challenges that can be overcome. Furthermore, shift the paradigm that AD is more expensive if more resilient materials are utilized. While searching for the potential project location, it was determined through the Colombian biogas network (RedBioCol) and the Latin-American Biogas Network (RedBioLac) that massive socialization of sustainable/cleaner production projects focused towards the improvement of communities and micro, small, and medium enterprises were needed. It was also manifested that this type of projects needed governmental support through policy, incentivizing the adoption of cleaner technologies. These two organizations have tried to communicate to universities, communities, and producers that alternatives sources of energy can improve quality of life, environmental stewardship, health, and resiliency. However, most communities are not aware of which technologies are available, even less what types of technologies were fit for their situation. Furthermore, technologies such as biogas normally do not resonate well with the public due to the nature of its most common input material; animal manure.

Therefore, a social component was included in this project, aiming at the whole region of Victoria, Caldas, and other nearby towns.

The date for this event was set to June 18th, 2015 and the event was planned to have at least 50 members of the community, the local government (town mayor, environmental and health departments), the departmental environmental regulatory agency, the local high school, the University of Caldas, Colombian Cattle Association – FEDEGAN (Federación Colombiana de Ganaderos), and the municipal unit for agricultural technical assistance - UMATA (Unidad Municipal de Asistencia Técnica Agropecuaria). For this project, assistance was requested from Texas A&M University – Kingsville to perform an analysis and close the meeting through encouraging socializing and replicating biogas as a source of clean and reliable energy.

Invitations were sent, and the event was announced through social media (Facebook, Twitter, and WhatsApp), email, and phone calls. Also, a flyer with the event schedule was made and sent through email to all the groups named previously. More than 90 people attended the demonstration, including community leaders from other regions of the department, meat-processing plant delegates, solid waste management company delegates, and political candidates for the town of Victoria Caldas (Picture 34).

Picture 34. Technical tour of the biogas system

This event was extremely successful. The community saw the opportunity to resolve questions regarding the technology, applicability, and benefits. These questions were answered expecting to increase the probability of replicating AD throughout the region. Also, questions regarding compression, storage, and segmentation of production came up, opening new opportunities for continuing AD research in this region.

In addition, new opportunities to develop biogas projects in Colombia emerged from this meeting. FEDEGAN (Colombian Association of Cattlemen) is studying the possibility of implementing biogas in meat-packing plants and requested technical assistance to develop a national proposal that would cover potential heat and electricity generation from slaughterhouse waste streams.

Furthermore, it was also discovered that a previous administration attempted to start a biogas implementation program with the community and funded 17 different projects in a wide array of agricultural activities such as dairies, cheese, swine, chicken, and local communities. From those 17, only three were working with no plans of using the gas or the effluent for any further processes.

The challenge continues, and working with communities is critical to achieving successful implementation of these projects. Constant communication and assistance become a keystone for the continuation and replication of biogas projects nationwide. RedBioCol and RedBioLac are aware of these needs, and they continue supporting their local communities all over South America.

CHAPTER EIGHT

CONCLUSIONS

This project was successfully carried out, generating critical information regarding biogas generation and served as a roadmap to aid rural communities in Colombia to implement AD as a reliable alternative source of energy and fertilizers for their crops.

This project effectively identified, constructed, and implemented a biogas system as an alternative source of energy in rural areas of Colombia by using HDPE 40 mil as an alternative substitute to LDPE 8 mil digesters.

Biogas is a clean energy source that can be utilized in developing countries to substitute for dirty energy sources, reducing chronic exposure in women and children that could lead to a medical and economic burden to families and nations. The use of biogas meets and exceeds the objectives of the World Bank and United Nations to promote the adoption and use of clean fuels for cooking, reducing household indoor air pollution worldwide.

Anaerobic Digestion can address a wide array of issues such as energy availability, wastewater treatment, control of obnoxious odors, and surface and groundwater protection.

For a period of 25 years, HDPE 40 mil appears to be more economical than LDPE 8 mil, with a return on the investment of 14 months, compared with wood and propane and fertilizer.

Anaerobic Digestion provides a near-perfect alternative source of fertilizer for growing crops. After analyses, the effluent from the biogas system was found to be nearly perfect for fertilizing cocoa trees. It had high concentrations of nitrogen, phosphorus, and potassium, requiring only small concentrations of micro elements (Noreña, 2016). This will reduce the fertilizer costs for the farm and possibly substitute the totality of chemical fertilizers, if managed correctly.

The dairy waste AD evaluation demonstrated that water content, total solids, fixed solids, and volatile solids are related to biogas generation. These parameters can be used to calculate a theoretical amount and determine optimum water content to maximize biogas production from a substrate.

Biogas optimization of preferred dairy waste showed that a laboratory set up is needed to determine the best substrate and water content to maximize biogas production.

Lowering the pH and temperature have a considerable impact in the proper function of the AD, reducing up to 98% biogas generation, this shows the importance of maintaining pH to neutral and internal temperatures to mesophilic levels.

This dissertation through a field day demonstrated that it is possible to local farmers and local institutions (private and public) that biogas is a completely viable alternative source of energy, cost-effective, and clean for cooking or agricultural operations.

Implementing biogas allows the farm to increase farm resilience, reducing fuel dependency on fossil fuels and wood availability.

CHAPTER NINE

RECOMMENDATIONS

Develop new potential projects that would allow biogas to extend its implementation through experimenting with new or additional materials.

A new set of experiments are needed where securing the clear solar cover to the drum instead of a general cover to determine heat losses.

It is important to identify if volume affects heat losses and to what percentage. It could be assumed that the larger the digester, the less heat it is going to lose. This could create tremendous opportunities for agricultural industries that are using or are about to use biogas in their processes.

Further experiments are needed to determine whether other water-activated glues such as Gorilla tape will prove ideal to patch holes in digesters made from HDPE.

It could be assumed that by flooding the surrounding area of the digester, it could potentially increase the pressure from the outside to the inside, increasing gas pressure.

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