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EVALUATING THE ANAEROBIC CODIGESTION POTENTIAL OF STILLAGE AND DAIRY MANURE IN A TUBULAR DIGESTER

Brad J. Weiss

Michigan Technological University, bweiss@mtu.edu


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EVALUATING THE ANAEROBIC CODIGESTION POTENTIAL OF STILLAGE AND DAIRY
MANURE IN A TUBULAR DIGESTER

By

Brad J. Weiss

A REPORT

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Environmental Engineering

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This report has been approved in partial fulfillment of the requirements for the Degree of
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Department of Civil and Environmental Engineering

Report Advisor: *Dr. Jennifer Becker*

Committee Member: *Dr. John Gershenson*

Committee Member: *Dr. Audrey Mayer*

Department Chair: *Dr. David Hand*

Table of Contents

List of Tables	iv
List of Figures	v
Abstract.....	vi
Chapter 1: Introduction.....	1
Chapter 2: Background	3
Chapter 3: Project Goals and Objectives.....	14
Chapter 4: Methods	15
Chapter 5: Results and Discussion	31
Chapter 6: Conclusions.....	40
References	41

List of Tables

Table 1: Characteristics of Sugarcane Juice Stillage	8
Table 2: Key advantages and disadvantages of anaerobic digestion.....	10
Table 3: Mixtures of stillage and manure evaluated in the five batch studies.....	16
Table 4: Summary of stillage:manure ratios	19
Table 5: Dairy manure influent concentrations	20
Table 6: Stillage characteristics applied to the BioWin model	21
Table 7: Summary of IS-1 & IS-2 for all simulations.....	22
Table 8: User defined BioWin influent wastewater fractions: IS-1	23
Table 9: User defined kinetic parameter values required for the inert conversion add-on	24
Table 10: User Defined Kinetic Parameters for the anaerobic digestion model in BioWin	25
Table 11: User defined stoichiometric parameters for the anaerobic digestion model in BioWin.....	26
Table 12: Description of BioWin parameters analyzed in sensitivity analysis.....	27
Table 13: Gas production measured using water displacement in batch assays of anaerobic codigestion of stillage and dairy manure	31
Table 14: Values of $S_{i,j}$ for influential ($S_{i,j} \geq 0.25$) parameters of the calibrated model.	32
Table 15: Parameters most influential to model outputs.....	32
Table 16: Summary of Model Calibration Simulations.....	34
Table 17: Simulated COD treatment efficiency in a tubular anaerobic digester treating manure and variable amounts of sugar cane stillage	35
Table 18: Simulated biogas production flow rate in a tubular anaerobic digester treating manure and variable amounts of sugar cane stillage	36
Table 19: Simulated volumetric methane content of the biogas in a tubular anaerobic digester treating manure and variable amounts of sugar cane stillage	36

List of Figures

Figure 1: Location of Pomacochas, Peru.....	3
Figure 2: Rural pot still constructed from a 55 - gallon drum in Peru	5
Figure 3: Two rural pot stills in Peru	6
Figure 4: Stillage sample collected from a rural still in Peru	7
Figure 5: Processes of anaerobic digestion	9
Figure 6: Tubular digester and gas storage bag in Pomacochas, Peru	11
Figure 7: Batch study vessels loaded with substrate.....	15
Figure 8: Ideal CSTR and Plug Flow reactor schematic.....	17
Figure 9: Tubular digester model constructed in BioWin.....	18
Figure 10: Configuration of a CSTR and a CSTR with recycle.....	18

Abstract

Evaluations of the anaerobic treatment of sugarcane stillage and dairy manure in a low cost tubular digester were performed in small scale batch experiments and using mathematical simulations. A local sensitivity analysis of the model was performed, and key input parameters were adjusted until the predicted COD removal was consistent with data obtained using two full-scale digesters. Simulations were performed to evaluate COD removal and biogas production for nine different mixtures of stillage and manure at four different temperatures ranging from 15°C to 30°C. Digestion of stillage alone was not effective, but when codigested with 20% or more manure, COD removals of >80% and substantial biogas production were predicted. COD removal and biogas production increased with temperature. The batch experiments and model simulations suggest that codigestion of stillage and manure in a tubular anaerobic digester may reduce the environmental impacts of stillage disposal while producing valuable biogas and organic fertilizer.

Chapter 1

Introduction

For twenty-seven months, from September 2013 to November 2015, the author was a volunteer with the United States Peace Corps in Peru. He served as a water and sanitation engineer and lived and worked in the town of Pomacochas, Peru.

During his time in Peru, the author noted that the stillage, the remnants of distillation of sugar cane into the traditional alcoholic beverage *cañazo*, was discharged to the environment without treatment. Improper disposal of stillage is detrimental to the environment because of the high concentrations of readily degradable organic matter, total nitrogen, and total phosphorus (Mohana, Acharya, & Madamwar, 2009). Stillage is a universal end-product of all distillation processes. Studies focusing on the treatment and disposal of stillage have been conducted but primarily have focused on large-scale distillers in developed countries (Pant & Adholeya, 2007; Wilkie, Riedesel, & Owens, 2000). In contrast, very little work has been done to address the need to treat stillage produced by small-scale distillers in developing countries. Thus, there is an urgent need for the development and demonstration of treatment technologies that can be used to successfully treat stillage and meet the requirements for environmental discharge, especially in developing countries like Peru. Because of its high organic matter content, there is the potential for energy recovery from stillage.

Anaerobic digestion has been shown to be an effective treatment method for stillage in conventional anaerobic digesters in developed countries (Wilkie et al., 2000). Through anaerobic treatment, the chemical oxygen demand (COD) and biochemical oxygen demand (BOD) of the stillage can be reduced. Additionally, anaerobic digestion produces biogas, the primary component of which is methane gas (Wilkie et al., 2000), and thus is a technology that can be used to produce renewable energy. While previous studies have shown that anaerobic treatment is a viable stillage treatment option, they focused on digesters typically found in the developed world. No studies have focused on the use of the low-cost, simple, anaerobic digesters popular throughout the developing world for the treatment of stillage.

This study focused on analyzing the potential for anaerobic codigestion of dairy manure and sugarcane stillage. Specifically, the goals were to determine if this

treatment approach could be optimized to: (1) reduce the negative environmental impact of the stillage, and (2) provide the distiller with biogas and an organic fertilizer. There were two components to this study: (1) field observations and preliminary proof-of-concept experiments performed in Peru, and (2) simulations of anaerobic codigestion of dairy manure and stillage in field-scale digesters.

This report is organized in chapters to present and discuss the problem, the tools and methods used for data collection, and an evaluation of the results. Chapter 2 provides background information on sugarcane distillation and the stillage generated, rural anaerobic digestion, and the opportunity for the anaerobic treatment of the stillage. The project goals and hypotheses are listed in Chapter 3. Chapter 4 provides an overview of the experimental methods used in the proof-of-concept experiments and the modeling approach that was used. The experimental data, model simulations, and some potential topics for future studies are presented and discussed in Chapter 5. Key conclusions are presented in Chapter 6.

Chapter 2

Background

2.1 Pomacochas, Peru

Pomacochas, which is indicated with a red star in Figure 1, is the capital of the District of Florida. This district is located within the Province of Bongará in the northern Peruvian region known as Amazonas.



Figure 1: Location of Pomacochas, Peru (Image source: CIA World Factbook)

Pomacochas is a town of approximately 4,500 people in the northeastern Andes Mountains. The elevation is approximately 7,500 feet above sea level and the average ambient year-round temperature is approximately 16°C (Mendoza, n.d.). Pomacochas is located in a valley surrounded by steep mountains. The society is primarily agrarian. The local residents work in dairy production, small scale fruit and vegetable production, and fishing. While not grown directly in the town of Pomacochas sugarcane is grown throughout the region, primarily at elevations lower than 6,600 feet above sea level.

As part of the cultural identity of the region, two alcoholic beverages are made from sugar cane juice: (1) *guarapo* and (2) *cañaso*. *Guarapo* is made by fermenting the sugarcane juice and *cañaso* is distilled from *guarapo*. The process used to distill sugarcane juice to *cañaso* is described later in this chapter.

2.2 Sugarcane production

Sugarcane requires several key growing conditions: fertile soil, abundant sunshine, warm temperatures, and abundant rainfall (Rolph, 1917). Sugarcane production is generally constrained by the 30°N and 30°S latitudes because it is susceptible to freezing. Thus it is typically cultivated in the tropics and subtropics regions of the world. Additionally, sugarcane does not grow well in high altitudes. Its maximum growing elevation is 3,000 m above sea level ("*Saccharum officinarum* L.," 2005). Northeastern Peru, where the author lived and worked for two years, features all of the necessary characteristics for strong sugarcane growth and indeed, sugarcane is an important crop in that region.

The Food and Agriculture Organization of the United Nations (FAO) notes that over 100 countries produce sugarcane (R. Pérez & Fujita, 1997). In 2007, approximately 85% of the global sugarcane production took place in 15 countries, with Brazil, India, and China producing over 60% of the global harvest.

2.3 Sugarcane distillation

Ethanol is produced through the fermentation of sugars and then separated from the remaining liquid via distillation. In a distillation process, a liquid is heated until it boils, and the desired vapors are collected through selective evaporation and condensation steps. The ethanol used to make alcoholic beverages will be referred to in this report simply as alcohol.

The alcohol produced from sugarcane in Central and South America is referred to as *cañaso* in Peru, *cachaça* in Brazil, and almost universally throughout the region as *aguardiente*. The distillation process used to produce *cañaso* observed by the author in the highlands of Peru and is a quick, simple, and highly variable process.

After the sugarcane has matured and is ready for harvest, the stalk is cut low to the ground by hand. The stalk is then cleaned of excess debris and leaves in preparation for liquid extraction. The stalk is fed through a press, either motorized or

animal-powered, and the extracted juice is collected in a large, open-top container. Depending upon the traditions of the distiller, the sugarcane juice is boiled briefly or maintained at the ambient temperature. If boiled, the juice is transferred to large, metal, open top vessels situated above a heat source, typically a wood-burning fire. After being brought to a boil, the juice is allowed to cool and then transferred back to the collection vessel. Previously fermented juice, is added to the fresh juice to introduce fermentative bacteria. The juice is mixed, and loosely covered with readily available materials, such as plastic sheets or wood planks, to prevent the introduction of "wild" microorganisms to the mixture, which is allowed to ferment.

After a fermentation time of approximately two to three days, the fermented sugarcane juice, now called the wash, or *guarapo* in Peru, is ready for distillation. The wash is filtered and transferred to the still. Rural stills, vary in size and construction materials. Rural stills can be made of copper, stainless steel, or even a recycled 55-gallon drum. However, it is critical that all stills can be sealed to prevent the vapor distillate from escaping. The stills observed by the author were all of the "pot still" variety, which have three components: (1) a boiling chamber, or pot, that is used to boil the wash; (2) a lyne arm used to transfer the vapor distillate to the condenser; and (3) a condenser for condensing the vapor distillate to a liquid. Two examples of rural pot stills found in rural Peru are shown in Figures 2 and 3.



Figure 2: Rural pot still constructed from a 55 - gallon drum in Peru (Image source: Author)



Figure 3: Two rural pot stills in Peru (Image source: Author)

After the wash has been transferred to the still, the temperature of the wash is slowly raised until the wash boiling point is reached and liquid distillate is collected from the condenser. This distillate is separated into four fractions, which are referred to (in the order of lowest to highest boiling point) as the foreshot, the head, the heart, and the tail. The foreshot is the first portion of the liquid that leaves the condenser and has, among other trace chemicals, a high methanol content. The head comprises acetone, methanol, ethanol, and other trace chemicals. The heart makes up the bulk of the collected distillate and primarily contains ethanol. The tail comprises small amounts of ethanol and other alcohols such as propanol and butanol. In the developed world, it is common to dispose of the foreshot due to the negative health impacts of consuming methanol, recycle the head and the tail into future distillation runs, and retain the heart (Bougas, 2009). In the developing world, the decision of what fractions to retain is left to the distiller. Due to the desire to produce the highest possible volume of *cañazo* and lack of regulatory oversight, it is common to see all of the fractions collected for human consumption.

Once the distiller has determined, through taste testes, that the condensed distillate is primarily composed of water and thus has no real value, the fire is extinguished. The liquid remaining in the still is the stillage and, as discussed below, can have a substantial volume. This stillage is then drained from the still. Typical stillage disposal practices are described below.

2.4. Sugarcane stillage characteristics and disposal

2.4.1 Stillage characteristics

Generally speaking, stillage is characterized by its low pH, dark brown color, and high COD concentration. Initially, stillage also has an elevated temperature, which typically ranges from 70 to 80°C. As discussed further below, the low pH, high COD concentrations, and elevated temperature of stillage can negatively impact the environment when it is discharged without treatment.

Figure 4 shows a sample of stillage remaining from the distillation of sugarcane juice in Peru. Depending upon the substrate, eight to 20 liters of stillage are produced for every liter of ethanol distilled.



Figure 4: Stillage sample collected from a rural still in Peru (Image source: Author)

The physicochemical properties of stillage derived from sugarcane juice have only been detailed a few times. Wilkie et al. (2000) documented the characteristics of a number of different stillage types and included a brief description of the characteristics of the cane juice stillage in their study. Table 1 below, describes the average characteristics of stillage produced from sugarcane juice.

Table 1: Characteristics of Sugarcane Juice Stillage¹

	Stillage yield (L/L Ethanol)	BOD (g/L)	COD (g/l)	COD/BOD	Total N (mg/L)	Total P (mg/L)	K (mg/L)	pH
Average	16.3	16.7	30.4	1.96	628	130	1952	4.04
Std Dev	5.3	3.4	8.2	0.35	316	110	1151	0.49
No. of literature sources used	2	5	6	4	6	6	5	7

¹Adapted from Wilkie et al. (2000).

2.4.2 Environmental impacts of stillage

Currently, sugarcane stillage is discharged to the environment without prior treatment in rural Peru. There are two main routes of disposal, land disposal and aquatic disposal. The author noted that distillers in the region of Pomacochas primarily practice land disposal methods due to the locations of their stills, which tended to be located far away from surface waters. The disposal consisted of opening a drain on the still and allowing the release of stillage from the still to the surrounding environment.

Application of untreated stillage to vegetated land has negative impacts on soil properties and vegetation cover. Studies have shown that stillage disposal on land can decrease the alkalinity and manganese availability in the soil, which inhibits seed germination (Christofolletti et al., 2013). In fact, in the areas where the stillage was released from the still on to the land surface, the author noted a distinct lack of vegetation and soil instability, which presumably resulted from the land application of stillage. Even diluted stillage, land applied at low concentrations, has been reported to inhibit vegetative growth and germination. Furthermore, the long term land application of stillage can result in the stillage leaching into an underlying aquifer, resulting in salinization of the groundwater (Belhadj et al., 2013; Jiang et al., 2012).

Disposal of stillage in waterways is also particularly harmful. The dark color reduces the amount of sunlight that can penetrate into the water reducing photosynthesis and dissolved oxygen in the water, which negatively impacts aquatic life (Espana-Gamboa et al., 2011; Mohana et al., 2009). Studies have found that the addition of

stillage to water bodies, can negatively impact aquatic life with the primary effects being respiratory inhibition and possible asphyxiation in fish (Mohana et al., 2009). In the area where the author worked, frequent rain events resulting in large-scale surface runoff could increase the potential for stillage to enter nearby surface waters.

2.5 Anaerobic digestion

2.5.1. Overview of anaerobic digestion

Anaerobic digestion is traditionally used to treat high-strength organic wastes ranging from the treatment of municipal wastewater solids to animal manure. It is a biological treatment process that involves fermentative and methanogenic microbial communities that, in the absence of oxygen, convert complex organic matter to methane, carbon dioxide, and other trace gases (McCarty, 2012). This mixture of gases is known as biogas.

Converting organic matter to methane is a three step process with each step utilizing the end products of the previous process, shown in Figure 5. The first step, hydrolysis, is the conversion of complex organic matter, by bacteria, to simple carbohydrates and acids. Fermentation is the second step and consists of the use of carbohydrates and acids, by acidogenic bacteria, to produce organic acids and hydrogen. Acidogenic fermenting bacteria further oxidize the organic acids to produce hydrogen and acetic acid. The third process consists of methanogens that convert the hydrogen and acetic acid into methane (McCarty, 2012).

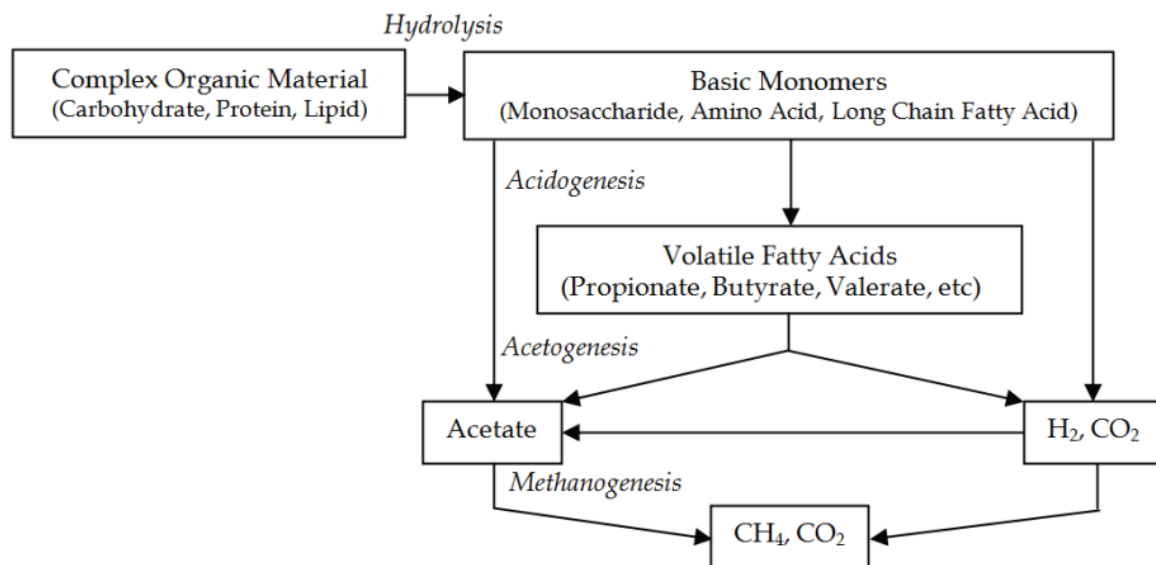


Figure 5: Processes of anaerobic digestion Image source: (Samer, 2015)

Typically, the methanogens grow slower than the fermenting bacteria. This slow growth, in combination with low biomass yields, lead methanogens to, more often than not, be the rate limiting step in the process (McCarty, 2012). Because of their low growth rates and yields, they are very sensitive to environmental conditions and can be quickly "washed out" of treatment reactors when unfavorable conditions develop, resulting in the failure of the anaerobic digestion process (Grady Jr, Daigger, Love, & Filipe, 2011).

These characteristics are important consideration during digester start-up. During the start-up, it is imperative to begin with small loading rates; if loading rates are high, the methanogens will be unable to process the hydrogen and acetic acid produced by the fermenting bacteria and will be killed, terminating the anaerobic digestion process (McCarty, 2012).

There are three primary anaerobic digester designs used in the different regions of the developing world, including: (1) the fixed dome or "Chinese" style digester; (2) the floating drum or "India" style digester; and (3) the plug-flow or "Taiwanese" style digester. These three digesters present the same advantages and disadvantages, which are reported in Table 2 (Rajendran, Aslanzadeh, & Taherzadeh, 2012):

Table 2: Key advantages and disadvantages of anaerobic digestion

Advantages	Disadvantages
Low production of waste biological solids	Slow growth rate of microorganisms
Low nutrient requirements	Susceptible to upset
Produces methane, a renewable form of bioenergy	Poor treatment efficiency at low temperatures
Can be operated at high organic loading rates	
Production of organic fertilizer	

The production of methane is considered an advantage of anaerobic digestion due to its potential as a biofuel. Methane, however, is also a greenhouse gas with a global warming potential approximately 21 times greater than CO₂. However, studies have found that the total atmospheric warming committed by a household that uses biogas as its energy source is 48% lower than a house using traditional fuel sources (Dhingra et al., 2011).

Plug-flow or "Taiwanese" digesters are commonly used throughout Central and South America, including rural Peru. A field-scale tubular digester that was installed in Pomacochas, Peru is shown in Figure 6.



Figure 6: Tubular digester and gas storage bag in Pomacochas, Peru (Image source: Author)

The Taiwanese-type digester is operated in a plug-flow fashion. The digester body is commonly made of a PVC geomembrane tube with openings at both ends for influent addition and effluent withdrawal and an additional port for biogas removal. These digesters function have a fixed volume; when waste is added to the digester, an equal volume of effluent must be withdrawn. The pressure within the gas storage bag is variable and dependent on biogas production and use (Rajendran et al., 2012). In Pomacochas, a tubed connection exists between the digester and the gas storage bag, allowing gas to flow freely from the digester to the storage. The storage bag is connected to a cook stove.

While the fixed dome and floating dome digesters require a high level of skill to construct, the tubular digester features no moving parts, relatively low material costs, portability, and easy operation. These reasons explain, at least in part, why the Taiwanese digester has risen to popularity in recent years (Pérez et al., 2014). However, tubular digesters also have several potential disadvantages. They are susceptible to UV damage, livestock damage, and temperature fluctuations which could impact the treatment process (Perrigault et al., 2012, Rajendran et al., 2012)

2.5.2. Potential cultural and social benefits of anaerobic digestion

Numerous benefits of anaerobic digestion have been thoroughly documented, particularly for rural farmers in developing countries. Low cost anaerobic digesters can help rural farmers solve both waste and energy problems. The impacts of anaerobic digestion extend beyond financial and environmental; the literature also describes health and social changes that can also be brought about with the installation of an anaerobic digester.

Fuel sources in developing countries, tend to generally be biofuels such as wood, animal dung, or agricultural remainders. In developing countries, one third of the energy consumed is sourced from these materials (Barnes & Floor, 2003). These biofuels, while low cost or free, produce smoke and particulate matter that can cause eye infections and severe respiratory disease, primarily in women and children who are frequently exposed to the cooking smoke (Katuwal & Bohara, 2009). Additionally, the use of traditional biofuels for energy production leads to emissions of greenhouse gases including, carbon monoxide and dioxide, nitrogen oxides and sulfur oxides (Garfí et al., 2012) .

The biogas produced from tubular digesters has been documented to contain approximately 50% - 70% methane. The balance is primarily carbon dioxide, but can also contain hydrogen sulfide and other trace gasses (Lansing et al., 2008b) . When conditioned properly for the reduction of hydrogen sulfide, biogas is generally considered to be a clean gas that can be used directly as a heat source (Lansing et al., 2008a) . The switch from traditional biofuels to biogas as a fuel source for cooking or other energy needs can improve the indoor cooking environment, positively impacting the health and wellbeing of women and children (Garfí et al., 2012).

The effluent from a tubular digester can be used as a high quality fertilizer (Van Groenendaal & Gehua, 2010). An initial study carried out in the Peruvian Andes showed increased yields in potatoes, a common staple crop in the region, from plots amended (or fertilized) with digester effluent compared to plots amended with compost and unfertilized plots (Garfí et al., 2012). The increase yield presents possible added income to the digester operator through increased revenue from crops or sale of the digester effluent to area farmers (Garfí et al., 2012).

Collection of traditional biofuels is frequently the responsibility of women and children; Garfí et al. (2012) documented that women and children spent an average

of five hours per week collecting firewood. The switch from traditional biofuels to biogas for cooking fuel allows that time to be spent in other activities. A case study in Nepal analyzed how women utilized their saved time after the installation of a biodigester. The study found that women primarily used the time previously devoted to collecting firewood in community activities (33%), income-generating activities (28%), and recreational activities (26%) (Katuwal & Bohara, 2009).

2.5.3. Co-digestion

Utilizing a mixture of substrates that together meet the metabolic needs or create suitable environmental conditions for the microbial community in anaerobic digestion is termed co-digestion. This approach is increasingly used to improve the anaerobic digestion process. Co-digestion is even being applied in rural settings and is facilitating the potential for anaerobic treatment of increasingly complex waste products (Mata-Alvarez et al., 2014). There are several different scenarios in which co-digestion of a mixture of substrates may improve the treatability and/or methane yield compared to anaerobic digestion of a single substrate. For example, a second substrate may be added to raise or lower the pH of the digestate if it is not within the optimal range of the microbial community or, similarly, to provide alkalinity to prevent acidic conditions from developing, which can rapidly cause the digestion process to fail. Microorganisms also require adequate amounts of carbon (C) and nitrogen (N) in order to grow and synthesize new cells. If either C or N is deficient in a given substrate, a co-substrate that provides the complementary growth factor can be added to create a balanced carbon-to-nitrogen (C:N) ratio (Álvarez et al., 2010). Finally, if the organic load of a waste material (quantified in terms of BOD or COD) is relatively low, a second, high-strength substrate may be mixed with the original waste material to boost the potential for recovery of methane when production of bioenergy, in addition to waste treatment, is a key goal. For example, food wastes are increasingly being co-digested with wastewater treatment solids in developed countries to improve energy recovery from these waste streams. When the substrates for co-digestion are properly selected, higher methane production, improved levels of treatment, and increased digester stability can be achieved (Mata-Alvarez et al., 2014; Maria Westerholm, Hansson, & Schnürer, 2012).

Chapter 3

Project Goals and Objectives

The goals of this study were to determine if the codigestion treatment of sugarcane stillage and dairy manure could be optimized to: (1) reduce the negative environmental impacts of the stillage, and (2) provide the distiller with biogas.

The specific objectives of this study were to:

- (1) Conduct proof-of-concept experiments to determine the feasibility of co-digestion of stillage and animal manure,
- (2) Develop a mathematical model of a tubular anaerobic digester in BioWin, and
- (3) Apply the model to simulate the anaerobic codigestion of several mixtures of dairy manure and stillage in field-scale digesters at four temperatures.

Chapter 4

Methods

4.1. Proof-of-concept batch fermentation assays

Proof of concept field tests were conducted in Pomacochas, Peru using anaerobic batch studies. Five vessels with threaded lids, each fitted with a rubber septum, were used in the study. Fresh dairy manure, diluted 1:1 with water for workability, was mixed with stillage and added to the vessel. The cumulative substrate volume, not including dilution water was 1.9 liters. 0.5 liters of effluent from an operating tubular digester was added to introduce an appropriate microbial community. The mix was then further diluted to achieve a dilution of 1:4, similar to digesters operating in the region. The cumulative volume of dilution water in the mix, including the initial volume used for workability of the manure, was 7.6 liters. The cumulative volume in each vessel was 10 liters. The vessel lids were added, sealed with a sealing compound, and left at ambient temperature for fifteen days, during which time the anaerobic treatment of the substrate took place. The sealed batch study vessels are shown in Figure 7. Volumetric biogas production was measured from the vessels using the water displacement method.



Figure 7: Batch study vessels loaded with substrate

Digestion of five substrate mixtures, which are summarized in Table 3, were evaluated in five experiments. Four of the experiments were performed using fresh stillage and one experiment was conducted using stillage aged for approximately one month. Aged stillage was evaluated because, in practice, a distiller would not

be able to treat all of the stillage produced in a distillation run at one time without overloading the digester. Storage of the stillage could potentially alter the properties of the stillage and, hence, its digestion.

Table 3: Mixtures of stillage and manure evaluated in the five batch studies

Substrate Mix	Percent Stillage	Percent Manure
1	0%	100%
2	2.5%	97.5%
3	5%	95%
4	7.5%	92.5%
5	10%	90%

4.2 Steady-state simulations of anaerobic digestion of stillage

4.2.1 Model system

The tubular digester in Pomacochas, Peru was simulated in this study. The tubular digester has a volume of approximately 12 m³. Approximately 300 liters of diluted manure collected was added to the digester on a daily basis. Approximately 300 liters of digester slurry was released on a daily basis.

4.2.2. Modeling approach

All models of stillage treatment via anaerobic digestion were performed using BioWin Version 4.0 a wastewater treatment modeling software package created by EnviroSim (Hu et al., 2008). Michigan Tech has an academic site license to use BioWin. Using BioWin, a user can model a variety of treatment trains by selecting and connecting model elements, which represent different unit treatment operations or conveyance components within the treatment train. The large number of user definable inputs and parameters such as kinetic, stoichiometric, environmental, and process specific variables allows users to define and analyze the behavior of treatment plants. BioWin allows for multiple influent and effluent streams as well as user created flow patterns. The model elements and chemical feeds, along with the previously mentioned components, allow the user to model and simulate a large number of process train configurations (Meylan & Howard, 2000). Most relevant to this project is BioWin's anaerobic digestion model, which models the processes described in Chapter 2.

4.2.3. Model description

4.2.3.1. Model configuration

4.2.3.1.1. Tubular anaerobic digester

Continuous-flow biological treatment reactors are frequently modeled as plug-flow reactors or continuous-flow stirred tank reactors (CSTRs). In an ideal plug-flow reactor, there is no mixing in the longitudinal direction (Figure 8). Therefore, the residence times of all elements that enter an ideal plug-flow reactor equal the theoretical hydraulic residence time, θ [T] where $\theta = V/Q$, V = the reactor volume [L] and Q = the flow rate [$L\ T^{-1}$]. Conversely, in a CSTR (Figure 8), all elements that enter the reactor have an equal probability of leaving the reactor.

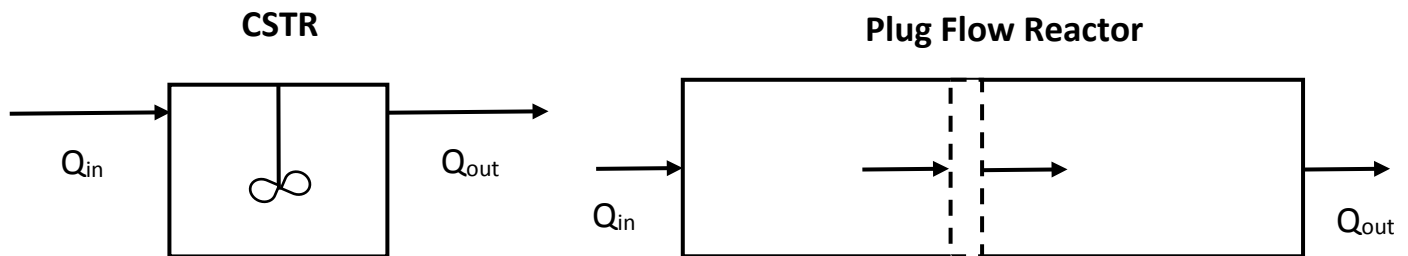


Figure 8: Ideal CSTR and Plug Flow reactor schematic

Therefore, the mean of the residence times of all of the elements entering a CSTR is equal to θ . In reality, tubular digesters and most full-scale treatment systems probably behave as non-ideal reactors with properties that are somewhere between that of an ideal CSTR and an ideal plug flow reactor (Grady Jr et al., 2011). If several CSTRs are operated together in series, their performance approaches that of a single plug-flow reactor with the same total volume. Karunarathne and Tarhnasiri (2015) found ten CSTRs in series to be an acceptable approximation representing the behavior of an actual tubular digester. However, Kinyua et al. (2016) studied the tubular digesters using computational fluid dynamics and determined that the digesters' behavior approached that of an ideal CSTRs, presumably due to mixing generated by biogas bubbles. Therefore, an intermediate approach was used to model the tubular digester in this study. Specifically, it was simulated using five anaerobic digester elements, each with a volume equal to one-fifth of $12\ m^3$, or $2.4\ m^3$, operated in series (Figure 9). The depth was set at 0.8 m based on a previous study of tubular digesters (Lansing et al., 2008a). All other properties of the anaerobic digester elements were set at default values.

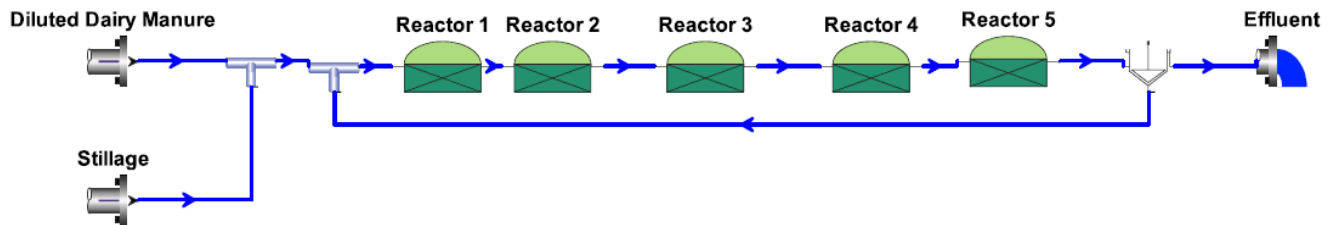


Figure 9: Tubular digester model constructed in BioWin

In ideal plug-flow reactors and CSTRs without solids separation and recycle, θ is equal to the theoretical solids residence time θ_x [T]. However, numerous papers report that θ_x is greater than θ in tubular, unmixed digesters, presumably because a portion of the solids settle to form a blanket in the bottom of the digester that is not transported out with the liquid when additions are made to the digester. For example, Kinyua et al. (2016) characterized the behavior and performance of a tubular digester in Costa Rica and found it had a mean θ of 22.8 days and a mean θ_x of 115 days.

In wastewater treatment practice, θ_x is increased relative to the θ in suspended-growth biological treatment processes by separating the biomass from the wastewater (using gravity or membrane filters) and returning a portion of the biomass to the biological treatment reactor. The schematic in Figure 10 shows the configuration of a CSTR with gravity biomass separation.

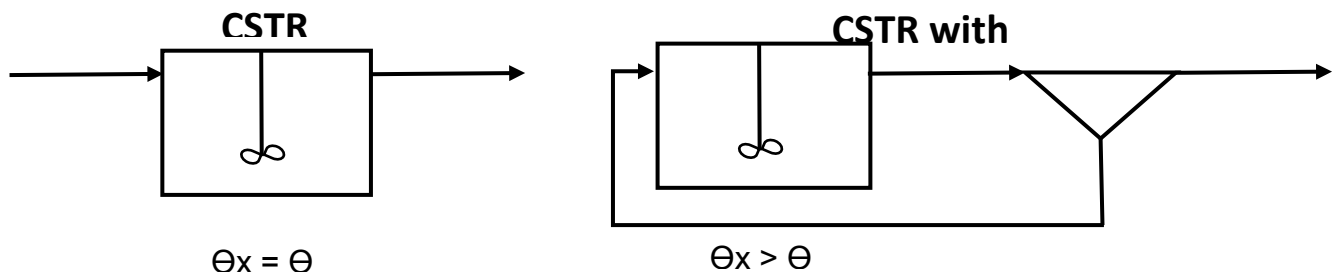


Figure 10: Configuration of a CSTR and a CSTR with recycle

This augmentation of biomass increases the rate of biological conversions. The same approach is used in BioWin to achieve a different θ and θ_x , as documented in an EnviroSim newsletter discussing the simulation of an upflow anaerobic sludge blanket reactor, by placing a point clarifier element in the digester effluent (EnviroSim, 2011). The point clarifier is a volume-less model element that models

the settling of particulate matter in a wastewater stream. Because the element is volume-less, biological processes are not modeled and the solid are instantaneously separated from the wastewater at a rate specified by the user. The separated solids are then routed back to the digester influent, resulting in a longer θ_x in the digester (Meylan & Howard, 2000). As shown in Figure 2, in this study, the solids were separated from the effluent from reactor 5 and returned to reactor 1.

The properties of the point clarifier element were optimized through trial-and-error until a $\theta:\theta_x$ ratio of approximately 1:5 was achieved. A percent solids removal of 79% was needed to achieve this ratio. The point clarifier and the recycle stream provided for a θ of 40 days and a θ_x ranging between 214 days to 232.37 days; the simulated θ_x was 5.35 – 5.88 times longer than the θ . This corresponds well with the modeling work of Kinyua et al., (2016), which showing that θ_x in a tubular digester was over five times greater than θ .

4.2.3.2. Influent streams

When using manure for use as substrate in a tubular biodigester it is recommended that it be diluted with water so that it can be easily loaded into the digester. For simulations performed in this study, a total flow rate of 300 L/d was supplied to the digester. One-third of this flow (100 L/d) was composed of a mixture of manure (provided in IS-1) and stillage (IS-2) and the remaining 200 L/d (provided via IS-1) was water. Because a major goal of this study was to determine the mixture of manure and stillage that would achieve optimal codigestion the relative percentage of manure and stillage in the 100 L/d flow was varied in each simulation. In all, nine stillage:manure mixes were evaluated, as summarized in Table 4.

Table 4: Summary of stillage:manure ratios¹

Simulation	Stillage (%)	Dairy Manure (%)
1	0	100
2	5	95
3	10	90
4	15	85
5	20	80
6	40	60
7	60	40
8	80	20
9	100	0

¹The total volumetric flow rate of stillage plus manure in each simulation was 100 L/d. The stillage plus manure flow rate was diluted with 200 L/d of water.

The two manure and stillage influent streams, were combined in BioWin using a side stream mixer element. The side stream mixer used in the model was assumed to have no volume. Therefore, the streams are instantaneously and completely mixed in the model.

4.2.3.2.1 Influent constituent concentrations

Influent Stream 1 (IS-1) represents a continuous-flow, diluted dairy manure waste stream. The volumetric flow rate of the stream was varied in different simulations, as described below.

The 10 influent concentrations specified for the dairy manure component of IS-1 are listed in Table 5. The sources used were manure slurries.

Table 5: Dairy manure influent concentrations

Characteristic	Concentration	Source
Total COD (mg COD/L)	106,000	Barret et al., 2013
Total Kjeldahl Nitrogen (mg N/L)	4,470	Rico, García, Rico & Tejero, 2007
Total P (mg P/L)	600	Barret et al., 2013
Nitrate N (mg N/L)	2,100	Barret et al., 2013
pH	7.4	Barret et al., 2013
Alkalinity (mmol/L)	13	Barret et al., 2013
ISS Influent (mg ISS/L)	10,000	Barret et al., 2013
Calcium (mg/L)	695	Rico et al., 2007
Magnesium (mg/L)	361	Rico et al., 2007
Dissolved Oxygen (mg/L)	0	Assumed

Influent stream 2 (IS-2) was applied to the model as the raw, undiluted, stillage. The 10 influent concentrations specified for the stillage (IS-2) are listed in Table 6.

Table 6: Stillage characteristics applied to the BioWin model

Characteristic	Concentration	Source
Total COD (mg COD/L)	28450	Hadetoft et al., 2011
Total Kjeldahl Nitrogen (mg N/L)	534	Required for BioWin simulations
Total P (mg P/L)	108	Required for BioWin simulations
Nitrate N (mg N/L)	0	Assumed
pH	4.15	Hadetoft et al., 2011
Alkalinity (mmol/L)	1	Kumar & Gopal, 2001
ISS Influent (mg ISS/L)	294.38	Hadetoft et al., 2011
Calcium (mg/L)	515.25	Hadetoft et al., 2011
Magnesium (mg/L)	225.64	Hadetoft et al., 2011
Dissolved Oxygen (mg/L)	0	Assumed

Most of the values were obtained from the literature, as noted in Table 13. Nitrate was assumed 0 mg/l, which is the BioWin default value, due to lack of sources at the time of modeling. The concentrations of two constituents (total Kjeldahl nitrogen concentration (TKN), which is equal to the organic nitrogen concentration plus the total ammonia nitrogen concentration and the total phosphorus concentration) were set at the minimum concentrations needed for the BioWin simulations to run until a steady-state solution was found.

A summary of the influent characteristics of IS-1, IS-2, and the combined flow (IS-1 + IS-2) is provided in Table 7.

4.2.3.2.2 Flow regime and rate

As described above, there are two influent streams in the tubular digester model. The full-scale digester in Peru that is being simulated in this study is supplied with diluted manure on a daily basis and this addition takes place over a time span of approximately 15 to 30 min. While it is possible to model a similar flow pattern in BioWin, it greatly increases the simulation run times. Therefore, in this study, the simulations were performed using continuous and constant influent flow rates.

Table 7: Summary of IS-1 & IS-2 for all simulations

Influent Characteristic	Influent Stream	Stillage:Manure ratios (v/v)									
		0:100	5:95	10:90	15:85	20:80	40:60	60:40	80:20	100:0	
Flow (m³/day)	IS-1	0.3	0.295	0.29	0.285	0.28	0.26	0.24	0.22	0.2	
	IS-2	0	0.005	0.01	0.015	0.02	0.04	0.06	0.08	0.1	
	Combined	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	
Total COD (mg/L)	IS-1	35333	34136	32897	31614	30286	24462	17667	9636.4	0	
	IS-2	28450	28450	28450	28450	28450	28450	28450	28450	28450	
	Combined	35333	34041	32748	31456	30163	24993	19823	14653	9483	
Total Kjeldahl Nitrogen (mg N/L)	IS-1	1490	1439.5	1387.2	1333.2	1277.1	1031.5	745	406.4	0	
	IS-2	534	534	534	534	534	534	534	534	534	
	Combined	1490	1424.4	1358.8	1293.2	1227.6	965.2	702.8	440.4	178	
Total P (mg P/L)	IS-1	200	193.2	186.2	178.9	171.4	138.5	100	54.5	0	
	IS-2	108	108	108	108	108	108	108	108	108	
	Combined	200	191.8	183.6	175.4	167.2	134.4	101.6	68.8	36	
Nitrate N (mg N/L)	IS-1	700	676.3	651.7	626.3	600	484.6	350	190.9	0	
	IS-2	0	0	0	0	0	0	0	0	0	
	Combined	700	665	630	595	560	420	280	140	0	
ISS Influent (mg/L)	IS-1	3333.3	3220.3	3103.4	2982.5	2857.1	2307.7	1666.7	909.1	0	
	IS-2	294.4	294.4	294.4	294.4	294.4	294.4	294.4	294.4	294.4	
	Combined	228.7	225.7	222.7	219.7	207.7	195.7	183.7	171.78	228.7	
Calcium (mg/L)	IS-1	231.7	223.8	215.7	207.3	198.6	160.4	115.8	63.2	0	
	IS-2	515.3	515.3	515.3	515.3	515.3	515.3	515.3	515.3	515.3	
	Combined	231.7	228.7	225.7	222.7	219.7	207.7	195.7	183.7	171.8	
Magnesium (mg/L)	IS-1	120.3	116.3	112	107.7	103.1	83.3	60.2	32.8	0	
	IS-2	225.6	225.6	225.6	225.6	225.6	225.6	225.6	225.6	225.6	
	Combined	120.3	118.1	115.8	113.6	111.3	102.3	93.3	84.2	75.2	
Dissolved Oxygen (mg/L)	IS-1	0	0	0	0	0	0	0	0	0	
	IS-2	0	0	0	0	0	0	0	0	0	
	Combined	0	0	0	0	0	0	0	0	0	

4.2.3.2.3 Wastewater fractions

The wastewater fractions in BioWin characterize the COD fractions, nitrogen ratios, phosphate fraction, microbial communities present, and endogenous material. Five of the wastewater fractions for IS-1 were modified from the default values, based on previous studies that characterized dairy manure (Table 8). The BioWin default values were used for the remaining IS-1 and all IS-2 wastewater fractions.

Table 8: User defined BioWin influent wastewater fractions: IS-1

Parameter	Description	Default Value	User Defined Value	Source
Fbs	Fraction of total influent COD which is readily biodegradable (dimensionless)	0.16	0.17	Fyfe, 2013
Fac	Fraction of readily biodegradable COD which is VFAs (dimensionless)	0.15	0.3	Fyfe, 2013
Fxsp	Fraction of biodegradable influent COD which is particulate (dimensionless)	0.75	0.57	Fyfe, 2013
Fup	Fraction of total influent COD which is particulate unbiodegradable (dimensionless)	0.13	0.18	Fyfe, 2013
Fpo4	Fraction of influent total phosphorus which is phosphate (dimensionless)	0.5	0.343	Lansing et al., 2008a

4.2.3.3. Kinetic model for conversion of inert organic matter

BioWin tracks the abundance of several different fractions of dissolved and particulate organic matter. Readily biodegradable fractions are assumed to undergo some degree of conversion at any θ_x . In contrast, several fractions of organic matter are modeled as being inert, i.e., they are not converted, at $\theta_x < 30$ d. EnviroSim recommends the inclusion of the "inert conversion add-on" into biological treatment models when cumulative $\theta_x > 30$ d. When this add-on model is used, the inert fraction of biomass (X_i), products of endogenous microbial decay (Z_e), and inert suspended solids (ISS) all undergo conversion. Ultimately, the add-on achieves a higher reduction of volatile suspended solids (VSS), or the organic portion of the

total suspended solids, than would be achieved without the add-on (Meylan & Howard, 2000).

The cumulative θ_x in the tubular anaerobic digester model was significantly longer than 30 d; therefore, the inert conversion add-on was used. No kinetic parameter values for the conversion of X_i , Z_e , and ISS could be found in the literature. Consequently, they were estimated and refined through the trial-and-error method, during the model calibration, which is described below. The final values of the parameters estimated using this procedure are shown in Table 9.

Table 9: User defined kinetic parameter values required for the inert conversion add-on

Parameter	Description	Value (unitless)
Kd_ISS	Kinetic parameter controlling the reduction of inert suspended solids	0.0012
Kd_Z_e	Kinetic parameter controlling the reduction of endogenous products	0.037
Kd_X_i	Kinetic parameter controlling the reduction of inert organics	0.037

4.2.3.4. Kinetic and stoichiometric parameters

BioWin provides default values for the all of the kinetic and stoichiometric parameters included in the model, but they can also be user-defined. Because BioWin was developed to simulating municipal wastewater treatments, it was thought that the default values would not be suitable for simulating the performance of a tubular digester. Therefore, a number of the default kinetic and stoichiometric parameters in the model were replaced with values obtained from the literature to increase the accuracy and relevance of the simulations to the model system being studied (Meylan & Howard, 2000). Specifically, the kinetic parameters listed in Table 4 were obtained from a previous study of anaerobic digestion of cattle manure by an acclimated microbial community at low temperatures (6°C) (Vavilin et al., 1998).

Importantly, biological and chemical rate constants are a function of temperature. Rate constants increase with increasing temperature (up to an organism-specific maximum temperature for biological reactions). In BioWin, the default temperature is 20°C. When simulations are run at temperatures other than 20°C the Arrhenius equation is applied to correct the kinetic rate constants (Meylan & Howard, 2000).

Using the Arrhenius equation, the kinetic parameters relevant to 20°C were calculated based on the published kinetic parameters obtained at 6°C. The BioWin default values and the temperature-corrected manure digestion values that replaced them are summarized in Table 10.

Table 10: User Defined Kinetic Parameters for the anaerobic digestion model in BioWin

Microbial Population	Kinetic Parameter	BioWin Default Value	User Defined Value
Common	Hydrolysis Rate (d ⁻¹)	2.1	0.379
Fermenting Bacteria	Anaerobic Decay Rate of acidogenic fermenting bacteria (d ⁻¹)	0.131	0.015
	Fermentation Rate(d ⁻¹)	1.6	2.984
	Maximum Specific Growth Rate (d ⁻¹)	0.25	0.224
	Anaerobic Decay Rate of acidogenic fermenting bacteria (d ⁻¹)	0.05	0.045
Methanogens	Aceticlastic Maximum Specific Growth Rate (d ⁻¹)	0.3	0.373
	H ₂ -Utilizing Maximum Specific Growth Rate(d ⁻¹)	1.4	1.194
	Aceticlastic Anaerobic Decay Rate(d ⁻¹)	0.13	0.015
	H ₂ -Utilizing Anaerobic Decay Rate(d ⁻¹)	0.13	0.015

The modified stoichiometric parameters, obtained from Vavilin et al., 1998, are shown in Table 11 below.

Table 11: User defined stoichiometric parameters for the anaerobic digestion model in BioWin

Microbial Community	Stoichiometric Parameter	BioWin Default Value	User Defined Value
Fermenting Bacteria	Acidogenic Yield (Low H ₂)	0.1	0.2
	Acidogenic Yield (High H ₂)	0.1	0.2
Methanogens	H ₂ Utilizing Yield	0.1	0.04

4.2.4 Sensitivity analysis

Sensitivity analyses are used to determine how much changes in model input parameters will have on the model outputs. A model is said to be most sensitive to those input parameters that, when changed, have the greatest impact on the model output. This information is useful for evaluating the time and effort needed in calibrating the particular model. A local sensitivity analysis was performed on the data using a one-at-a-time approach. In local sensitivity analysis, the parameters to be studied are modified by a pre-determined factor and the impacts on the model are recorded and evaluated; global sensitivity analysis modifies the variables over a range and records the impacts to the model, giving the researcher a much finer scale with which to evaluate sensitivity. A sensitivity analysis of the model was performed on 21 anaerobic digestion model inputs, including 13 kinetic parameters, five stoichiometric parameters, and three cabinet model add-on parameters (EnviroSim, 2014). The evaluated model inputs are shown in Table 12.

The sensitivity of the model to the input parameters was quantified by calculating two different values: (1) a normalized sensitivity coefficient ($S_{i,j}$) and (2) a mean squared sensitivity measure ($\delta_{i,j}^{msqr}$) (Liwarska-Bizukojs & Biernacki, 2010).

Table 12: Description of BioWin parameters analyzed in sensitivity analysis

Parameter Type	Microbial Population	Parameter	Description
Kinetic	Common	Hydrolysis Rate (d^{-1})	Rate constant for hydrolysis of slowly degradable organics into readily degradable substrate
	Fermenting Bacteria	Anaerobic decay rate of acidogenic fermenting bacteria (d^{-1})	Decay rate under anaerobic conditions for acidogenic fermenting bacteria
		Maximum specific growth rate of acidogenic fermenting bacteria (d^{-1})	Maximum specific growth rate of acidogenic bacteria
		Fermentation Half Saturation (Constant)	Half saturation for regulation of growth, under anaerobic conditions
		Maximum Specific Growth Rate of acidogenic bacteria (d^{-1})	Maximum specific growth rate of acidogenic bacteria using propionate as substrate
		Substrate Half Saturation (constant)	Half saturation for regulation of growth rate, based on availability of propionate as substrate
		Anaerobic Decay Rate of acidogenic fermenting bacteria (d^{-1})	Decay rate of acidogenic fermenting bacteria under anaerobic conditions
	Methanogens	Aceticlastic Maximum Specific Growth Rate (d^{-1})	Maximum specific growth rate for the aceticlastic biomass
		H ₂ -utilizing Maximum Specific Growth Rate (d^{-1})	Maximum specific growth rate for the H ₂ -utilizing
		Aceticlastic Substrate Half Saturation (constant)	Half saturation for regulation of aceticlastic biomass growth rate, based on availability of acetate as substrate
		H ₂ -utilizing Substrate Half Saturation (constant)	Half saturation for regulation of H ₂ -utilizing biomass growth rate, based on

			availability of CO ₂ for synthesis
		Aceticlastic Anaerobic Decay Rate (d ⁻¹)	Decay rate of aceticlastic methanogens
		H ₂ -utilizing Anaerobic Decay Rate (d ⁻¹)	Decay rate H ₂ -utilizing methanogens
Stoichiometric	Fermenting Bacteria	Acidogenic Yield (Low H ₂)	Amount of biomass produced on one unit of complex substrate fermented, under low H ₂ concentration
		Acidogenic Yield (High H ₂)	Amount of biomass produced on one unit of complex substrate fermented, under high H ₂ concentration
		Acidogenic Yield	Amount of biomass produced on one unit of propionate converted
	Methanogens	Aceticlastic Yield	Amount of aceticlastic biomass produced using one unit of substrate (acetate). The rest of the substrate will be converted to CO ₂
		H ₂ -utilizing Yield	Amount of H ₂ -utilizing biomass produced using one unit of substrate (hydrogen). The rest of the substrate will be converted to methane and water
Model Builder Add-ons	ISS Conversion	Kd_ISS	First order rate constant for the conversion of inert suspended solids to slowly degradable particulates
		Kd_Xi	First order rate constant for the conversion of inert organics to slowly degradable particulates
		Kd_Ze	First order rate constant for the conversion of endogenous residue to slowly degradable particulates

The normalized sensitivity coefficient is defined by the US EPA as a ratio of the percentage change in the output variable (Δy_i), normalized to the baseline output value (y_i), resulting from a change in input variable (Δx_i), normalized to the baseline input value (x_i), (Brown & Barnwell, 1987):

$$S_{i,j} = \left| \frac{\Delta y_i / y_i}{\Delta x_i / x_i} \right| \quad \text{Eq. 1}$$

In this analysis a 10% increase was applied to the input variable.

The normalized sensitivity coefficient was calculated for the effluent Total COD concentration, the off gas flow rate (m^3/hr) for each of the five digesters, and the off gas methane content, reported as a mole fraction of the off gas flow rate, for each of the five digesters. These parameters were chosen as they were assumed to be the most important parameters to an operator. Additionally, the normalized sensitivity coefficient was calculated for two calculated model outputs: the cumulative off gas flow rate and the cumulative methane gas flow rate.

$\delta_{i,j}^{msqr}$ is a measure of the mean sensitivity of the model output to a change in input parameter x_i (Brun, Kühni, Siegrist, Gujer, & Reichert, 2002) and is calculated according to:

$$\delta_{i,j}^{msqr} = \sqrt{\frac{1}{n} * \sum_{i=1}^n S_{i,j}^2} \quad \text{Eq. 2}$$

where n = the number of normalized sensitivity coefficients included. A high $\delta_{i,j}^{msqr}$ demonstrates that a parameter has a large influence on the model results, whereas a low value of $\delta_{i,j}^{msqr}$ demonstrates that a parameter has little influence on the model results. A parameter that yields $\delta_{i,j}^{msqr}=0$ signifies that the model results are independent of that particular variable.

4.2.5 Model calibration

After the model was constructed in BioWin, it was calibrated using published data. The digester volume, influent characteristics, and environmental characteristics of the model were set to the values used in previous studies that evaluated the performance of tubular anaerobic digesters that were used to treat dairy manure in Costa Rica as described in Lansing et al., 2008a and Lansing et al., 2008b. The calibration procedure primarily involved changing the kinetic parameters of the inert

conversion model add-on, using a trial and error approach, until the reported effluent COD concentrations were predicted. The calibration procedure focused on the adjustment of the inert conversion kinetic parameters because these values were not based on literature sources.

4.2.6. Temperature

Each of the nine model scenarios was run at four different temperatures. The temperatures were selected to simulate average ambient temperatures in different zones where sugar cane is grown. The input temperatures were as follows: (1) 15°C, (2) 20°C, (3) 25°C, and (4) 30°C. The cooler temperatures reflect conditions at higher elevations, and the warmer temperatures reflect conditions at lower elevations.

Chapter 5

Results and Discussion

5.1 Proof-of-concept batch fermentation assays

5.1.1 Results of the batch fermentation assays

The water displacement results, recorded in centimeters and measured during the proof-of-concept field tests, are shown in Table 13.

Table 13: Gas production measured using water displacement in batch assays of anaerobic codigestion of stillage and dairy manure

Stillage type	Replicate number	Measured gas production of different codigestion mixes				
		Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
Fresh Stillage	1	0 cm	0 cm	1.8 cm	4.7 cm	4 cm
	2	0 cm	12.2 cm	20 cm	0 cm	21.5 cm
	3	11 cm	4 cm	10 cm	2.9 cm	19 cm
	4	4 cm	10.2 cm	0 cm	0 cm	3.5 cm
Aged Stillage	1	0.5 cm	0 cm	0 cm	1 cm	0 cm

5.1.2 Discussion of the batch fermentation assay results

There are significant gaps in the recorded data. Nine out of the 25 tests did not produce any gas. These results are thought to be due to flaws in the vessels. Although the vessels were checked for air leaks at the start of each round of study, it was not uncommon for leaks to develop several days later. However, these results show that biogas will be produced from the anaerobic codigestion of stillage and dairy manure at ambient temperatures.

5.2 Sensitivity analysis

5.2.1 Results of the model sensitivity analysis

Following the procedure described in Liwarska-Bizukojs and Biernacki (2010), the influence of an individual parameter on a model output was interpreted as follows: (1) $S_{ij} < 0.25$ indicates that a parameter has no substantial influence on the model output; (2) $0.25 \leq S_{ij} \leq 1$ means that a parameter is influential; (3) $1 \leq S_{ij} < 2$ means

that a parameter is very influential; and (4) $S_{i,j} \geq 2$ means that a parameter is extremely influential on the model output.

The model was found to be sensitive to two kinetic parameters, the hydrolysis rate and the acidogenic anaerobic decay rate, and one stoichiometric parameter, the acidogenic yield (Fermentation, Low H_2). The influential parameters and the corresponding $S_{i,j}$ values are summarized in Table 14.

Table 14: Values of $S_{i,j}$ for influential ($S_{i,j} \geq 0.25$) parameters of the calibrated model

Parameter	Hydrolysis Rate	Acidogenic Anaerobic Decay Rate	Acidogenic Yield (Low H_2)
Total COD (Effluent)	--	--	0.8
R2 Off Gas Flow Rate	1.3	0.8	--
R3 Off Gas Flow Rate	0.6	0.6	1.1
R4 Off Gas Flow Rate	--	--	1.6
R5 Off Gas Flow Rate	--	--	1.2
R1 Off Gas CH_4 Content	0.5	0.3	0.3
R2 Off Gas CH_4 Content	0.3	--	3.1
R3 Off Gas CH_4 Content	0.3	--	3.4
R4 Off Gas CH_4 Content	--	--	3.6
R5 Off Gas CH_4 Content	--	--	3.5
Cumulative CH_4 Gas Flow Rate	--	--	2.1

All parameters analyzed produced a $\delta_{i,j}^{msqr} > 0$, showing that all input parameters will impact the model outputs to a certain extent. The ten most influential parameters are shown in Table 5.

Table 15: Parameters most influential to model outputs

Parameter Type	Population or process affected	Parameter	$\delta_{i,j}^{msqr}$
Stoichiometric	Fermenting bacteria	Acidogenic Yield (Low H_2)	1.276585
Kinetic	Common	Hydrolysis Rate	0.537389

Kinetic	Fermenting Bacteria	Anaerobic Decay Rate of Acidogenic Bacteria	0.472857
Model Builder Add-on	ISS Conversion	$K_d_{X_i}$	0.201995
Kinetic	Methanogens	H ₂ -utilizing Maximum Specific Growth Rate	0.187265
Stoichiometric	Methanogens	H ₂ -utilizing Yield	0.126486
Kinetic	Methanogens	Aceticlastic Anaerobic Decay Rate	0.107308
Model Builder Add-on	ISS Conversion	$K_d_{Z_e}$	0.102964
Kinetic	Methanogens	H ₂ -utilizing Anaerobic Decay Rate	0.091296
Kinetic	Methanogens	H ₂ -utilizing Substrate Half Saturation	0.090528

5.2.2 Discussion of the sensitivity analysis

A sensitivity analysis is often performed to help a modeler prepare for model calibration. The results of the sensitivity analysis allow the modeler to determine where to focus their resources during the determination of parameters; more resources should be placed on accurately defining highly influential parameters than on parameters which have little impact on the model. In the case of this study, the sensitivity analysis was used to help define the ISS conversion parameters as the current literature does not discuss these parameters.

While all parameters impact the model to some extent, several kinetic and stoichiometric parameters were found to be much more influential than other parameters in the model; in fact, the top three most influential parameters were found to be over two times more influential to the model than all others analyzed. While these kinetic and stoichiometric parameters are able to be measured in controlled environments, they were defined using literature values which necessitated temperature correction before their use in the model. Model accuracy could likely increase if studies were performed to further define the most influential parameters of the model using microbial communities acclimated to the anaerobic treatment of dairy manure at the four temperatures studied in this report

Knowing that the BioWin package is not likely to be available in rural regions of developing countries. The results of the sensitivity analysis could be beneficial in any work attempting to develop simplified tools for use in predicting the COD treatment and biogas production in a tubular digester. Many of the least influential model parameters could likely be eliminated to create a simplified model focused on the most influential parameters and processes in tubular anaerobic digesters. This

simplified tool could then be distributed and used by rural distillers and digester operators to assist with optimization of the treatment process.

5.3 Model calibration

5.3.1 Results of the model calibration

The COD of the effluent, the biogas flow rate, and the methane content of the simulations were compared to the published results of Lansing et al. (2008a,b) and are shown in Table 146.

Table 16: Summary of Model Calibration Simulations

	Calibration Study 1 ¹			Calibration Study 2 ²		
	Published ³	Simulated	Percent Error	Published ³	Simulated	Percent Error
Influent Total COD (mg/L)	5720 ± 610	5720	--	3220 ± 630	3220	--
Effluent Total COD (mg/L)	796 ± 128	808.1	1.5%	714 ± 83	696.06	2.6%
Biogas Production (m³/day)	27.5 ± 2.7	2.2	92%	NR ⁴	--	--
Methane Content (%)	62.6 ± 0.6	26.1%	57.9%	61.7 ± 24	59.1%	4.2%

¹Lansing et al., 2008a

²Lansing et al., 2008b

³Published results are given as averages ± standard error

⁴NR: Not Reported

5.3.2 Discussion of the model calibration

The calibration of the model was used to define the ISS conversion parameters. The calibration study was completed when the model was able to simulate the COD reduction of the literature studies. The model calibration was evaluated based on the calculated percent error between the literature data and the simulation of effluent Total COD, biogas production, and methane content of the biogas. The developed model was considered qualified to simulate the COD reduction of the two literature sources and unable to simulate biogas production and methane content of the gas. It is important to note that with only two literature studies used, this calibration study is limited in scope and further studies are needed to fully calibrate the model.

The sensitivity analysis of the anaerobic digestion model in BioWin would be helpful for future work to further calibrate the model. The three most influential parameters found in the sensitivity analysis should be further defined through lab studies, as previously discussed, or through trial and error methods in the model until the model is considered able to simulate the COD treatment, biogas production, and methane content of the biogas.

5.4 Steady-state simulation

5.4.1 Results of the steady state simulations

The calibrated model was run until steady state was achieved as determined by effluent Total COD. Generally this required approximately 650 days or less. The steady-state effluent COD, biogas production rate, and methane content of the biogas of the simulations were recorded.

Treatment efficiency was calculated as shown below:

$$\text{COD Treatment efficiency} = \frac{(\text{Influent COD} - \text{Effluent COD})}{\text{Influent COD}} * 100\% \quad \text{EQ. 3}$$

The results of the simulated treatment efficiency, biogas production rate, and methane content of the biogas from the BioWin model are shown in Table 17, Table 18, and Table 19 respectively.

Table 17: Simulated COD treatment efficiency in a tubular anaerobic digester treating manure and variable amounts of sugar cane stillage

Stillage Content	COD Treatment Efficiency at Different Temperatures			
	15°C	20°C	25°C	30°C
0%	83.7%	84.6%	85.5%	86.3%
5%	83.7%	84.6%	85.6%	86.3%
10%	83.7%	84.6%	85.5%	86.4%
15%	83.7%	84.7%	85.6%	86.4%
20%	83.7%	84.7%	85.6%	86.4%
40%	83.8%	84.9%	85.8%	86.6%
60%	84.1%	85.1%	85.9%	86.6%
80%	83.6%	84.8%	85.6%	86.2%

100%	15.0%	16.4%	18.2%	19.9%
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There are several trends found in the table above. The first trend is that COD treatment appears to be positively impacted by temperature. The second trend is that the addition of approximately 20% dairy manure is necessary for substantial levels of COD treatment.

Table 18: Simulated biogas production flow rate in a tubular anaerobic digester treating manure and variable amounts of sugar cane stillage

Stillage Content	Biogas Production (m³/day) at Different Temperatures			
	15°C	20°C	25°C	30°C
0%	4.51	4.66	4.73	4.91
5%	4.35	4.49	4.53	4.74
10%	4.20	4.33	4.39	4.51
15%	4.04	4.07	4.22	4.34
20%	3.88	3.91	4.05	4.21
40%	3.26	3.28	3.38	3.49
60%	2.57	2.65	2.73	2.83
80%	2.02	2.03	2.09	2.22
100%	0.21	0.23	0.25	0.27

Based on the results of the calibration studies, the model was unable to simulate biogas production. As such, the results presented in the table above cannot be considered accurate. More work is needed to calibrate the model in order to simulate biogas production.

Table 19: Simulated volumetric methane content of the biogas in a tubular anaerobic digester treating manure and variable amounts of sugar cane stillage

Stillage Content	Methane Content of Biogas at Different Temperatures			
	15°C	20°C	25°C	30°C
0%	73.2%	72.9%	77.1%	77.7%
5%	73.2%	72.9%	74.8%	77.8%
10%	73.1%	72.9%	77.3%	76.0%
15%	73.1%	74.0%	77.2%	76.0%
20%	73.0%	74.7%	77.0%	78.0%
40%	72.6%	70.0%	72.4%	75.4%

60%	67.5%	67.3%	69.1%	74.6%
80%	70.5%	70.6%	73.8%	81.7%
100%	73.0%	73.7%	75.1%	76.9%

Based on the results of the calibration studies, the model was unable to simulate methane content of the biogas. As such, the results presented in the table above cannot be considered accurate. More work is needed to calibrate the model to simulate methane content of the biogas.

5.4.2 Discussion of the Steady-state Simulations

The treatment of Total COD in stillage-manure mixtures was positively impacted by both the stillage concentration and the treatment temperature. The positive relationship between temperature and treatment efficiency in anaerobic digestion was expected based on the temperature dependency of kinetic rate constants described by the Arrhenius equation and the well-established positive relationship between temperature and anaerobic digestion performance reported in the literature (Rajendran et al., 2012).

All simulations containing dairy manure resulted in treatment efficiencies above 80%, while treatment of stillage as the sole substrate resulted in treatment efficiencies less than 20%. The benefit of co-digestion was expected based on the literature review (M. Westerholm, Hansson, & Schnurer, 2012). The optimum pH for anaerobic treatment is generally between 6.5 and 7.6 (McCarty, 2012). The pH of stillage used in the simulations is substantially lower than the optimal range for anaerobic digestion (4.15) while the pH of the dairy manure used in the simulations is within optimal range (7.4). It is believed that the addition of manure to the substrate stream provided pH balance in the digester allowing the digester to operate within the optimal range.

5.5 Motivation for the Optimization of the Tubular Digester Codigesting Stillage and Manure

The motivation to anaerobically treat stillage may vary depending upon the land use practices of the region. Should a distiller be located in a rural area with a low population density and abundant land, the motivation for this treatment would likely be the biogas production capabilities of the digester. As land becomes increasingly scarce, likely due to an increase in the population density or poor land management practices, it is expected that these motivations would change. The motivation for the anaerobic treatment of stillage in an urban or land stressed area would likely be the

COD treatment capabilities of the digester in order to minimize the impact on the available land. These different motivations would likely result in a desire to optimize the digester conditions for either maximum COD treatment or maximum biogas production.

There seems to be several opportunities for optimizing the tubular digester function associated with utilizing anaerobic digestion processes in close proximity to a still. It is known that these anaerobic processes are positively influenced, to an extent, by temperature and that tubular digesters are susceptible to temperature fluctuations; logically, if the temperature of the digester can be raised above the ambient temperature, the anaerobic treatment will proceed at a higher rate.

There are several sources of heat loss during rural distillation, the first being the heat lost to the environment during the heating of the still, and the second being the heat lost to the environment as stillage cools. Stills are traditionally heated on open fires; no fire box or combustion chamber is used and the still is uninsulated. This method of heating results in substantial heat loss to the surrounding environment which, if captured, could raise the internal temperature above the ambient temperature. Water filled piping, running between the digester and the still, could act as heat exchangers which could capture a portion of the heat loss during combustion and transfer it to the tubular digester in order to raise the internal temperature. Furthermore, the addition of stillage to the digester, at an elevated temperature following distillation, presents the opportunity to raise the internal temperature of the digester with zero modifications to the digester or still.

Should the digester be located too far from the house to use the biogas for cooking fuel, the biogas could still serve in the distilling process. The use of the biogas in distilling could decrease the need for traditional biofuels currently used to heat the still, and depending upon the distillers operating practices, may entirely replace the need for these traditional fuels. The amount of biogas available to heat the still would depend upon the size of the digester and the gas storage bag installed. Predictor tools would benefit the distiller in this aspect as they could be able to adequately size a new digester or easily evaluate operating changes to the digester and predict the effect on the fuel requirements for distilling.

5.6 Future Work

As mentioned above, in some cases, the primary motivation for developing an anaerobic digestion may be to achieve waste treatment. In that case, additional

simulations should be performed in which the stillage concentration in the codigestion mixtures is varied to determine the optimum codigestion ratios needed to achieve the desired treatment outcome. The results of this work could be developed into a set of mathematical tools which would allow the digester operator to select the inputs and practices best suited to their treatment goals.

The characteristics of dairy manure vary greatly based on species, food source, and manure handling practices, which creates numerous difficulties in properly characterizing manure for a study. Field work documenting the conditions and practices found across a particular country or region coupled with the associated manure characteristics would be beneficial for future work on this topic. This characterization of manure handling practices and the resulting characteristics would allow the modeler to calibrate a model much more closely to a specific region of interest. Additionally, digester operators would be able to further optimize their digesters based on the handling practices of manure they are using as substrate.

While co-digestion with dairy manure was determined to positively impact the treatment efficiency, dairy manure is just one of the many options for co-digestion substrates. Additional future work, modeling, field scale, or controlled studies, could focus on the anaerobic treatment of stillage co-digested with various other substrates such as swine manure, which is common worldwide. Locally relevant wastes could be studied as well; guinea pig and llama, for example, are common livestock throughout the South American Andes (Garfí, Ferrer-Martí, Villegas, & Ferrer, 2011). Optimizing co-digestion using different manure types would aid in the application of anaerobic treatment in other parts of the world.

Future modeling work would greatly benefit from additional experimental data on influent and effluent characteristics of tubular anaerobic digesters, biogas production and the methane content of biogas. This information is needed to further calibrate the BioWin model. However, as was mentioned previously, while these tubular digesters are common throughout Central and South America, the rural location of the digesters would likely complicate collecting the physicochemical characteristics of the influents and effluents, as well as the biogas composition and flow rates. Tubular digesters located in the United States could present opportunities considered more convenient for collecting the desired data than digesters located in Central and South America.

Chapter 6

Conclusions

The field work and model simulations in this report showed that the anaerobic digestion of stillage produced from sugarcane juice is possible in low-cost tubular digesters. Additionally, the simulations showed the benefit of anaerobic codigestion using diluted dairy manure as a cosubstrate in regards to treatment efficiency. Based on the results of this study, the optimal mixture for COD reduction is 60% stillage mixed with 40% manure.

The field work and model simulations presented in this study suggest that substantial biogas could be produced from the codigestion of stillage and dairy manure. However, there is a need for future work to further calibrate the developed model and to optimize the treatment process. While future work is needed to further this subject, it appears to be a promising treatment option for rural distillers in developing regions of the world.

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