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Modeling a solar-heated anaerobic digester for the developing world using system dynamics

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MODELING A SOLAR-HEATED ANAEROBIC DIGESTER FOR THE DEVELOPING WORLD USING SYSTEM DYNAMICS

By

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Degree of Master of Science
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Mahatma Gandhi

To my loved ones, for your support and inspiration to do great things.

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All modeling performed during analysis used Stella®, a systems modeling program created by isee systems. This software offers a practical way to dynamically visualize and communicate the various aspects of the proposed design by showing interactions between variables with a combination of stocks, flows, and converters. Please refer to the attached CD for all modeling trials.

ABSTRACT

Modeling a Solar-Heated Anaerobic Digester for the Developing World Using System Dynamics

Johanna Lynn Bentley

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Much of the developing world lacks access to a dependable source of energy. Agricultural societies such as Mozambique and Papua New Guinea could sustain a reliable energy source through the microbacterial decomposition of animal and crop waste. Anaerobic digestion produces methane, which can be used directly for heating, cooking, and lighting. Adding a solar component to the digester provides a catalyst for bacteria activity, accelerating digestion and increasing biogas production. Using methane decreases the amount of energy expended by collecting and preparing firewood, eliminates hazardous health effects linked to inhalation of particles, and provides energy close to where it is needed. The purpose of this work is two fold: initial efforts focus on the development and validation of a computer-based system dynamics model that combines elements of the anaerobic digestion process in order to predict methane output; second, the model is flexed to explore how the addition of a solar component increases robustness of the design, examines predicted biogas generation as a function of varying input conditions, and determines how best to configure such systems for use in varying developing world environments. Therefore, the central components of the system: solar insolation, waste feedstock, bacteria population and consumption rates, and biogas production are related both conceptually and mathematically through a serious of equations, conversions, and a causal loop and feedback diagram. Given contextual constraints and initial assumptions for both locations, it was determined that solar insolation and subsequent digester temperature control, amount of waste, and extreme weather patterns had the most significant impact on the system as a whole. Model behavior was both reproducible and comparable to that demonstrated in existing experimental systems. This tool can thus be flexed to fit specific contexts within the developing world to improve the standard of living of many people, without significantly altering everyday activities.

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1 INTRODUCTION

Much of the developing world lacks access to energy. In order to meet their energy needs, people turn to local natural resources, such as trees; but this is only a short-term solution. Many countries rely on farming to provide food, but few have coupled their agricultural practices to energy production. Anaerobic digestion, the decomposition of animal and crop waste by microbacteria, provides an economical and sustainable solution to improve the quality of life of people in the developing world.

Although anaerobic digestion as a renewable energy technology has been seen in much of the developed world in agricultural settings, it can easily transform to meet people's basic needs, while still being economically appealing. The digestion process produces methane, a gas nearly equivalent to natural gas, which can be used directly for heating, cooking, and lighting. Biogas not used immediately could be stored or distributed to a larger network, depending on the size of the community. Since many developing countries lie close to the equator, a solar component to the digester would act as a catalyst for the bacteria, speeding the entire digestion process, and subsequently increasing the amount of biogas produced. In addition, in the developing world there is a need to improve health conditions. Many countries rely on firewood as a main source of fuel. Using methane would not only cut down the amount of energy expended by collecting and preparing wood for use, but also eliminate hazardous health effects linked to inhalation of particles. The digester would provide energy close to where it is needed, such as homes, schools, and hospitals.

Worldwide, methane emissions from agricultural production comprise about 33% of global anthropogenic methane release (Weir, 2006). Methane exhibits an important climatic twin effect; the use of renewable energy reduces the CO_2 emissions through a reduction of the demand for fossil fuels, and simultaneously, capture of uncontrolled methane emissions reduces the second most potent greenhouse gas. Environmentally, smaller agricultural units can additionally reduce the use of forest resources for household energy purposes, which slows deforestation, soil degradation, and resulting natural catastrophes like flooding and desertification. If fossil fuels and firewood are replaced with methane, additional CO_2 emissions can be avoided, saving forest resources which are a natural CO_2 sink.

A solar-heated anaerobic digester is therefore capable of improving the standard of living of many people, without significantly altering everyday activities. Methane is advantageous because it can be used in existing equipment and appliances. Many developing countries currently rely on propane for cooking, and

would easily be able to switch to methane instead since the gas will effectively fire almost any appliance whether it was designed for oil or gas. Replacing current practices with biogas could reduce global anthropogenic methane emissions by about 4% (Weir, 2006).

According to previously documented literature, research, and mathematical models, anaerobic digestion is a context specific process. Currently, many agricultural systems exist on a large scale in the developed world, but few exist in the developing world, where the users would receive the most benefit from the system's outputs. Therefore, the first aim of this work will focus on the development and validation of a computer-based system dynamics model that combines the most important elements of the anaerobic digestion process in order to predict methane output. The second aim is to flex the model to explore how adding a solar component increases the robustness of the design, examine predicted biogas generation as a function of varying input conditions, and determine how best to configure such systems for use in varying developing world environments.

This approach will allow for an analysis of how sensitive outcomes are to changes in stated assumptions. The assumptions that deserve the most attention will depend largely on the dominant behavior and cost elements, and the components of greatest uncertainty of the design. Once the interactions between components are well defined, the system can be evaluated to meet economic, social, and environmental constraints. In order to verify the model, the behavior of the model must be reproducible. Following verification, validation of the model will be in a reflective mode, in which the testing is designed to uncover flaws and hidden assumptions, challenge preconceptions, and expose assumptions for critique and improvement. This mode builds confidence in the model and ultimately increases the chances for sustained success. Model analysis will use several tests to uncover flaws and improve results, including structure assessment, dimensional consistency, testing extreme conditions, and sensitivity analysis.

Two developing countries, Mozambique and Papua New Guinea, were selected as the focus points of model analysis because they are both agriculture-based societies in the developing world, as defined by the United Nations Human Development Index (HDI), high indoor air pollution deaths, according to the World Health Organization, and fit within the optimal geographical location and climate for a solar-heated anaerobic digester system. The following chapters explore the background information on the internal components of the digester, provide examples of existing systems, analyze the model for both locations given initial assumptions and constraints, present a discussion on how the model compares to real-world experimental results, and draw conclusions on the overall performance of the system, while recommending additional areas of focus for future system work and improvement.

2 BACKGROUND

Anaerobic digestion relies on the activity of methane-producing microorganisms called methanogens. Although digester design may vary, the ultimate goal remains: to produce as much useable methane as possible. Digesters must be designed and operated to maintain optimum conditions necessary for growth of these organisms. There are numerous factors to take into account. According to Isaacson (1991), these conditions can be separated into two general areas: chemical and physical environments, as shown in Table 2.1:

Table 2.1. Chemical and Physical Components of Anaerobic Digestion

CHEMICAL	PHYSICAL
Anaerobic Conditions	Temperature
Substrate	Water
Nutrients	Particle Surface Area
pH	Loading Rate
Toxics	Retention Time
	Mixing

These chemical and physical environments are important to help determine the methodology used to design digesters by size. These methods are based on the concept of mean cell residence time, which is the average time that a microorganism spends in the activated sludge process.

2.1 Anaerobic Conditions

According to Price (1981), the microbiological degradation of organic material in an anaerobic environment can only be accomplished by microorganisms able to utilize molecules other than oxygen as hydrogen acceptors, as shown in Equation 2.1:

Equation 2.1. Anaerobic decomposition

$$\textit{organic matter} + \textit{anaerobic microorganisms} \rightarrow CH_4 + CO_2 + H_2 + N_2 + H_2S$$

Anaerobic decomposition is generally considered to progress in two stages: an acid production stage and a methane production stage. Process instability is usually indicated by a rapid increase in the concentration of volatile acids, with a concurrent decrease in methane gas production, indicating that the more fastidious methane bacteria are the most susceptible to upset.

2.2 Substrate and Nutrients

One of the biggest challenges arising from this process is accurately predicting the amount of methane produced based on the feedstock used. This is because the nature and composition of substrate material dictates the microbial regime present, and no single set of parameters is valid for all situations. Many organic compounds may inhibit anaerobic digestion. These include organic solvents, alcohols, and long chain fatty acids at high concentrations.

According to the Sustainable Development Department (SD) of the Food and Agriculture Organization of the United Nations (FAO), any biodegradable organic material can be used as inputs for processing inside the digester. However, for economic and technical reasons, some materials are more preferred as inputs than others. Although existing digesters commonly use animal waste for gas production, plant materials also serve as a viable input feedstock. Since different organic materials have different biochemical characteristics, their potential for gas production varies. Therefore, substrate materials can be mixed as long as the basic requirements for gas production and normal growth of methanogens are met.

One of the most important factors impacting these characteristics is the ratio of carbon to nitrogen present in the organic materials. A C/N ratio between 20 and 30 is considered optimum for anaerobic digestion. If the ratio is too high, the nitrogen will be consumed rapidly by the methanogens in order to meet their protein requirements, and will no longer react with the remaining carbon content of the material. This results in low gas production. If the ratio is too low, nitrogen will be liberated and accumulate as ammonia (NH_4). The ammonia will increase the pH of the digester content. While animal waste typically has a C/N ratio ranging between 10 and 24, plant materials contain a higher percentage of carbon, and therefore have a much higher ratio. According to Price (1981), there are four potential rate-limiting steps in the anaerobic conversion of cellulose to methane:

1. Conversion of cellulose to soluble sugars by extracellular enzymes
2. Formation of volatile acids by acid forming bacteria
3. Conversion of volatile acids to CO_2 and CH_4 by methanogens
4. Transfer of dissolved products from the liquid to gas phase

However, the combination of animal waste with the crop waste helps overcome these steps, and puts the C/N ratio into the optimum range. Agricultural settings therefore provide the ideal components for this renewable technology.

2.3 pH

Optimum pH ranges of 6.4 to 7.6 have been reported for the methanogenic bacteria, which cannot tolerate fluctuations of more than a few tenths of a pH unit from neutral. Non-methanogenic organisms are not nearly as sensitive and are able to function in a pH range from 5.0 to 8.5 (Price, 1981). A pH higher than 8.5 is toxic to the methanogen population. The pH is also a function of the retention time. In the initial period of fermentation, as large amounts of organic acids are produced, the pH inside the digester can decrease to below 5 (FAO, 1997). This inhibits or stops the digestion or fermentation process. As the digestion process continues, the concentration of ammonia increases, raising the pH above 8. Therefore, in order to produce the most gas, and stabilize the bacteria population, the optimum range must be maintained.

2.4 Toxics

Toxicity can be due to an excess of any material, even if the substance is a nutrient, which makes the concentration at which a substance starts to exert a toxic effect hard to define. The organic loading and biological solids retention time can cause a stress on the process, effecting toxicity. Mineral ions, heavy metals, and detergents are some of the toxic materials that inhibit the normal growth of pathogens in the digester. While small quantities of mineral ions such as sodium, potassium, calcium, magnesium, ammonium, and sulfur, stimulate the growth of bacteria, heavy concentrations of these ions will have a toxic effect. Heavy metals such as copper, nickel, chromium, zinc, and lead are essential for the growth of bacteria, but only in small amounts. Detergents such as soap, antibiotics, and organic solvents inhibit bacteria activity (FAO, 1997). Therefore, it is important to monitor the content of any material used as feedstock in the digester to prevent bacteria inhibition and death.

2.5 Temperature

The physical environment provides a platform for the chemical reactions. Maintaining a constant temperature in the optimal range for the bacteria is critical for maximizing gas production. Anaerobic bacteria can endure temperatures ranging from below freezing to above 57°C, but thrive best at mesophilic temperatures of about 36.7°C (98°F) or thermophilic temperatures of about 54.4°C (129.9°F). In the thermophilic range, decomposition and biogas production occur more rapidly than in the mesophilic range. However, digesters operated in the mesophilic range are less sensitive to upset or change in operating routine. Table 2.2 (Cheng, 2010) shows the temperature ranges, operating hydraulic

retention time (HRT), the average length of time liquids and soluble compounds remain in the digester, growth and digestion rates, and tolerance to toxicity for the three anaerobic processes. Increasing HRT allows more contact time between substrate and bacteria, but requires a slower feeding rate or larger digester volume.

Table 2.2. Comparison of Anaerobic Processes

Anaerobic Process	Operating Temperature (°C)	Operating HRT (days)	Microbial Growth and Digestion Rates	Tolerance to Toxicity
Psychrophilic	10 – 25	> 50	Low	High
Mesophilic	30 – 37	25 – 30	Medium	Medium
Thermophilic	50 – 60	10 – 15	High	Low

2.6 Water

Moisture is required for all bacteria activity; they are able to tolerate conditions ranging from slight amounts of water to dilute solutions of nutrients. This means that very wet waste feedstock can be used without loss of energy consumed. Buswell (1956) estimated that the anaerobic process finds its greatest economy in wastes that contain 1 to 3% digestible solids.

2.7 Particle Surface Area

Tests show that the size of the solid waste particles has a noticeable effect on the rate of gas production. Decreasing the size by a factor of 10 increased the rate of gas production by a factor of 4.4, and the relation appeared to be linear in the tested range (Price, 1981).

2.8 Loading Rate, Retention Time, and Mixing

Figure 2.1 helps illustrate the resulting components of a standard-rate (conventional) batch anaerobic digester (Fry, 2010). As shown, the waste is transformed into solid, liquid, and gaseous states. The uses for these by-products is shown to the right:

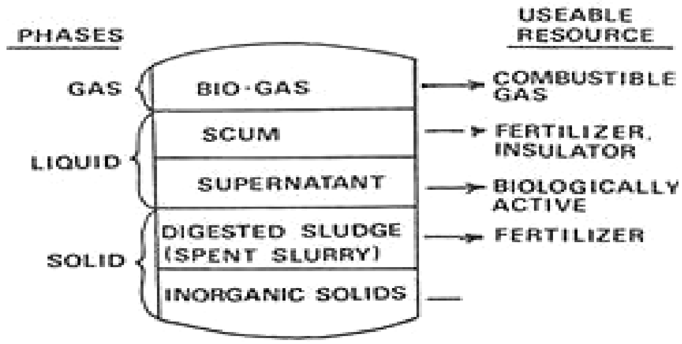


Figure 2.1. Digestion Phases for Standard-Rate Digester

Standard-rate digestion is usually carried out as a one-stage process; the functions of digestion, sludge thickening, and supernatant formation occur simultaneously. Untreated sludge is added at frequent intervals, usually two or three times a day.

As decomposition proceeds, zones develop. A scum layer is formed at the top, and forms as gas rises to the surface, lifting sludge particles and other materials such as grease, oils, and fats. The biogas produced will float to the top of the tank, and be pumped out of the digester. The gas then travels through a filter if it needs to be scrubbed of impure components such as hydrogen sulfide and carbon dioxide, to a compressor for storage if the gas will not be used immediately. As a result of digestion, the sludge become more mineralized, increasing the percentage of fixed solids, and it thickens due to gravity. The water separated from the sludge (supernatant) is normally removed as the sludge is added. Digested sludge is removed at less frequent intervals. The biological stabilization of sludge by anaerobic digestion results in the production of methane gas which is insoluble in water and escapes as gas. This means that if no methane gas is produced there can be no waste stabilization. The solid digestate below the supernatant, consisting of spent slurry and inorganic solids, refers to material that the bacteria can no longer use or reactivate for further gas production. Both the spent slurry and the liquid scum are rich in nutrients that can be used as a fertilizer. Unfortunately the inorganic solids provide no further use, and must be removed from the system so to not pollute the remaining material.

As a result of the stratification and lack of continuous mixing, not more than 50% of the volume is used (Price, 1981). Therefore, without mixing, digester design is most suitable for small installations. With an increased budget, mixing equipment and pumps can be added to the system, allowing for larger design, a faster loading rate, and shorter retention time.

One of the most common methods used to size digesters is to determine the required volume on the basis of the loading factor. Two critical factors involved are the kilograms of volatile solids added per day per cubic meter of digester capacity, and the kilograms of volatile solids added per day per kilogram of volatile solids in the digester. Because of the storage requirements for the digested sludge and supernatant in a single-stage digestion system, and the excess capacity provided for daily fluctuations in sludge loading, the volumetric loading is low. Detention times based on cubic meters of untreated sludge varied from 30 to more than 90 days for this type of tank and the recommended solids loadings were 0.5 to 1.6 kg/m^3d (Price, 1981). If the digester is overfed, methane production will be inhibited. If the digester is underfed, gas production will be low.

Retention, or detention, time is the average period that a given quantity of input remains in the digester acted upon by the methanogens. This time can be calculated by dividing the total volume of the digester by the volume of inputs added daily. The retention time is also dependent on the temperature. Up to 35°C, the higher the temperature, the lower the retention time (Lagrange, 1979). Factors influencing the solids retention time (SRT) are the volatile solids loading on the digester, the volatile percentage in the total suspended solids, and the suspended solids concentration in the raw sludge. The volatile solids loading should always be adjusted based on the volatile solids concentration in the sludge so that a detention time above the minimum SRT is maintained. The regeneration rate for the slowest methane formers is about 10 days at 35°C (Price, 1981). The critical solids retention time (SRT_c) is the time period below which digestion falls as a result of washout of the slow-growing methane formers.

2.9 Digester System Design

The system in which anaerobic digestion occurs can vary greatly, depending on the context. The needs of the community will determine the size, type, and complexity of the system. The complexity of the system is often coupled to cost and amount of required maintenance, but not to efficiency and quality of the biogas produced. Therefore, it is critical that the right design is chosen for the right context, in order to avoid complications. The following paragraphs describe several of the more prominent systems currently used, and discuss the advantages and disadvantages of each.

2.9.1 Plug Flow

Plug flow, or standard-rate batch digester vessels are generally long and narrow, typically with a 5:1 ratio, such that the length is five times as long as the width. The tank is insulated and heated, and usually made

from reinforced concrete, steel, or fiberglass, with a gas tight cover to capture the biogas. The digester can operate in both mesophilic and thermophilic temperature ranges, and can be loaded with thicker waste of 11-14% total solids. Retention time is usually 15 to 20 days; so this system works well with a routine inflow of material that doesn't have to be extremely accurate (Penn State, 1998). Figure 2.2 shows a typical design for a plug flow system (AgStar, 2010).

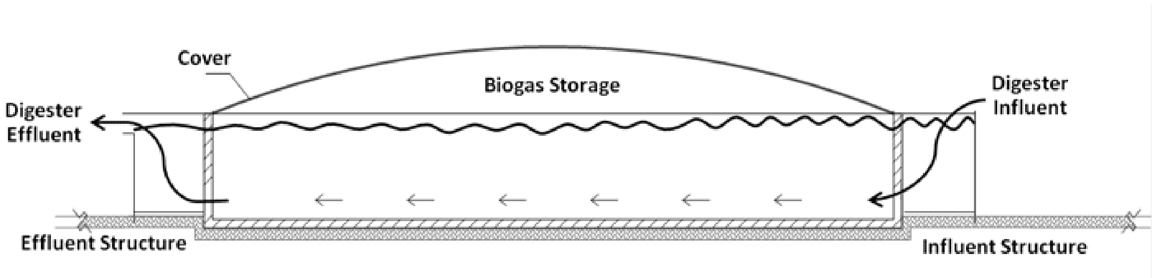


Figure 2.2. Plug Flow Digester Diagram

Theoretically, waste in the plug flow system does not mix longitudinally as it passes through the digester, but as a plug advancing toward the outlet whenever new waste is added. When the waste reaches the outlet, it discharges over a weir, a wall or obstruction used to control the flow and ensure a uniform flow rate, to maintain a gas tight atmosphere. In actuality, the waste does not remain as the plug, and some portions of the waste flow through the digester faster than others, while other portions settle or float and remain inside. A single pump can be used to both agitate the waste and pump it into the digester. If an external heat exchanger is used, the heat exchanger can either be placed inside the vessel, or the waste can be pumped through the heat exchanger on the way into the digester.

Biogas produced can be used to heat the digester and maintain the desired temperature. Excess biogas can be used to run an engine generator. Heat from the generator could be used for space or floor heating, water heating, or steam production to offset the cost of purchased electricity, propane, natural gas, or fuel oil used for daily operations (Penn State, 1998). The disadvantages of a plug flow system include poor temperature control, potential existence of undesired thermal gradients, and no easy method to remove solids without shutting down the entire system. However, with simple insulation and proper maintenance planning, these dilemmas are minimized. Advantages of the design include high conversion per unit volume, low operating labor cost, continuous operation, and good heat transfer. Therefore, a plug flow system is easy to implement and manage if monitored properly, able to produce gas with a wide variety of input materials and consistencies, low-cost, and reliable, making is an extremely versatile system that would thrive in a variety of contexts.

2.9.2 Complete Mix

Complete mix systems are generally associated with large enterprises, with substantial money to invest in the digester. They are insulated and maintained at a constant elevated temperature, in either the mesophilic or thermophilic ranges. The digester is usually a round tank, that can be situated above or below ground, and is made from reinforced concrete, steel, or fiberglass. Heating coils with circulating hot water can be placed inside the digester to increase bacteria activity, or depending on the consistency of the feedstock, the contents of the digester can be circulated through an external heat exchange to maintain the desired temperature range. Most complete mixed systems are mixed with a motor driven mixer, a liquid recirculation pump, or compressed biogas. The lid of the tank is a gas tight cover, either floating or fixed to trap the biogas inside. This type of system is best suited to process waste with 3-10% total solids, with a retention time between 10 and 20 days (Penn State, 1998). An example of such a system is shown in Figure 2.3 (AgStar, 2010).

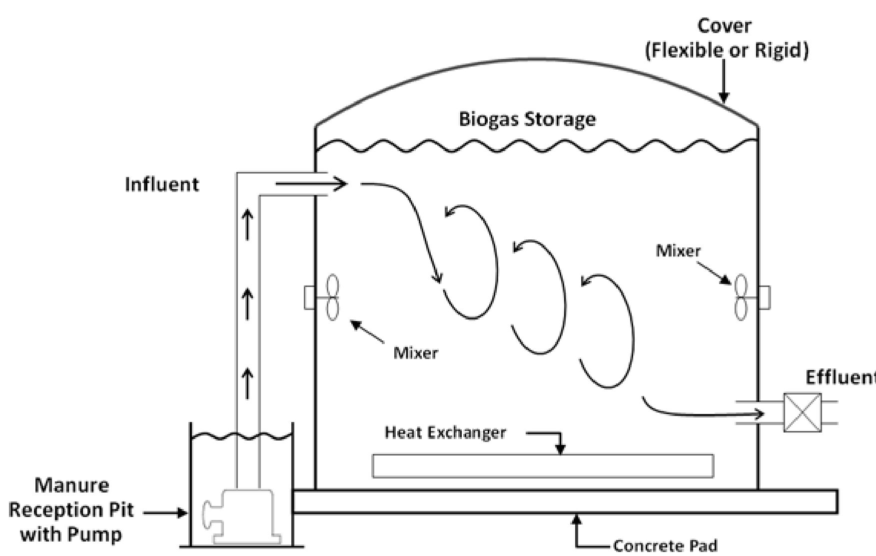


Figure 2.3. Complete Mix Digester Diagram

Compared to standard-rate digestion, high-rate digestion has a higher loading ratio and improved mixing. The mixing equipment should be more powerful and should reach to the bottom of the tank. The gas piping will be larger, with fewer multiple sludge drawoffs to replace the supernatant drawoffs. In this system, the sludge is generally pumped into the digester continuously or in designated 30 to 120 minute cycles. The incoming sludge displaces digested sludge into a holding tank or to a second digester for supernatant separation and residual gas extraction (Price, 1981). Since there is no supernatant separation

in the high-rate digester, total solids are reduced by 45-50% on average and given off as gas, with the digested sludge only half as concentrated as the untreated sludge feed. If the system is installed indoors, the user must check that no biogas is escaping from the tank. Biogas is lighter than air and can accumulate under roofs and ceilings, and create a fire or explosion hazard. The system is reliable and predictable, but the complexity of the components and operation make the design more suitable for a community with an extensive budget and ability to fund repairs and labor.

2.9.3 Covered Lagoon

Covered lagoon anaerobic digesters are advantageous for their long retention time and high dilution factor. They are typically used with flush waste systems that discharge waste at 0.5-2% solids. The digester is buried underground and earth lined with a flexible or floating gas tight cover. The system is not heated, but retention time is usually about 30-45 days or longer depending on the size. In locations with elevated year round temperatures, the digesters can produce stable, reduced odor, nutrient rich fertilizer for crops. Very large lagoons are needed to produce enough gas to run an electric generator (Penn State, 1998). Figure 2.4 shows a typical covered lagoon design, with cell 1 holding the waste that produces biogas and cell 2 holding digester effluent used for fertilizer (AgStar, 2010).

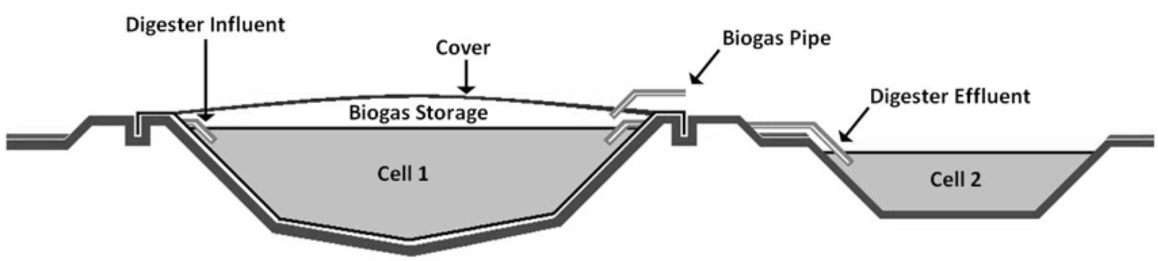


Figure 2.4. Covered Lagoon Digester Diagram

Although this design seems like a low-cost and low maintenance choice for the developing world, the gas production is inconsistent and low quality. The capital cost is low, but the operating cost is high in order to make it a reliable source of energy. Once all the material inside the lagoon is spent, the digester must be emptied, cleaned, and rebuilt. This creates large gaps in biogas production. Because there is no regulation of heat, and no insulation, the temperature fluctuation makes biogas production unpredictable. In addition, it is difficult to collect gas from under the cover. In order to meet the needs of the community, and provide healthy alternatives to current heating and cooking methods, the source of energy must be reliable.

2.9.4 Fixed Film

In a fixed film digester, the tank is filled with an inert medium or packing that provides a very large surface area for microbial growth. Influent wastewater passes through the media and anaerobic microbes attach themselves, creating a thin layer of anaerobic bacteria called biofilm. The microbes continue to grow by removing material from the wastewater as it flows past. In most digesters, a portion of the floating microbes is continuously discharged with the effluent. The bacteria however, remain attached to the media throughout. Figure 2.5 shows an example of a fixed film digester, with the cross-hatched area representing the treatment media (Friedman, 2010).

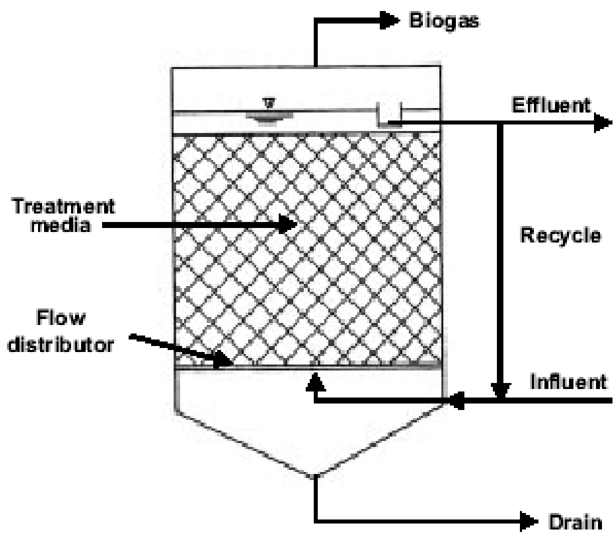


Figure 2.5. Fixed Film Digester Diagram

Fixed film digesters are advantageous because of their small size, but their short retention time of only 3 to 5 days requires constant attention, and the system must be loaded with feedstock that will easily flow through the media without clogging. Therefore, the complexity of the design and the amount of necessary maintenance and care does not make a fixed film digester a good candidate for implementation in the developing world.

2.9.5 Two-Stage Digestion

With a two-stage process, the first tank is used for digestion, operating in the thermophilic range, while the second tank is used for storage and concentration of digested sludge, and formation of a relatively clear supernatant, and operates in the mesophilic temperature range. The first tank is heated and equipped

with mixing facilities consisting of sludge recirculation pumps, gas recirculation using mixing tubes, mechanical draft-tube mixers, or a turbine or propeller mixers. Frequently the tanks are identical, with either one as the primary. The tanks may have fixed roofs or floating covers (Price, 1981). Figure 2.6 shows a typical two-stage digester set-up (Jones, 1980).

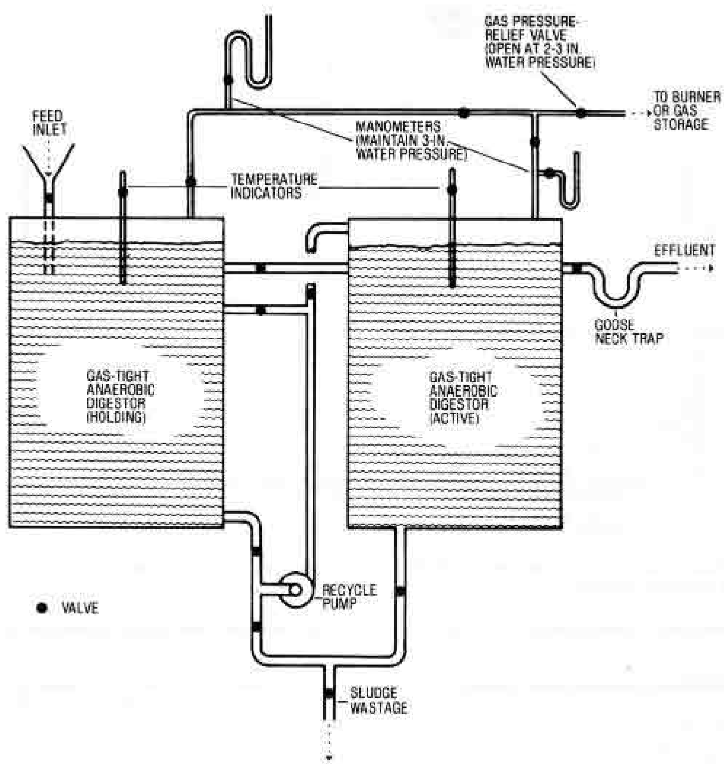


Figure 2.6. Two-stage digester diagram

This system works best with diluted waste, and is advantageous because two digestion processes typically destroy more pathogens and volatile solids, resulting in high quality solid effluent that can be used for crops as a nutrient rich soil amendment (Penn State, 1998). The two-stage process can operate at various loading rates, and therefore cannot be easily defined as standard or high rate. It evolved as an attempt to provide additional gas production as well as a separate settling and thickening process in the secondary digester (Price, 1981). The process is successful when primary sludge or combinations of primary sludge and limited amounts of secondary sludge constitute the feedstock of the system. However, adding so much material to the system often creates clogs, and depending on the consistency of the feedstock, some materials do not settle well. Therefore, this system is not practical in a developing world context due to high operating costs and poor efficiency, unless the facility is outfitted with advanced technology and equipment.

3 LITERATURE REVIEW

As described in the background in Chapter 2, there are many variations on anaerobic digester design. This chapter aims to discuss previous design attempts to utilize waste in order to produce a reliable fuel source – methane. Many of these designs are too complex for a developing world context, but serve as good templates for a revised system that would meet the objective aims of this thesis. The advantages and disadvantages of the examples are provided in order to localize the most important design constraints for the desired context.

A design proposed in U.S. Patent 4,274,838 as shown in Figure 3.1 demonstrates a plug flow digester that utilizes a heat exchanger to transversely stir the slurry and gas jets along the bottom of the tank to prevent the settling of solids (Dale, 1981). In this setup, the slurry is formed in a sump and pumped into the digester. The heat exchanger is fed with hot water.

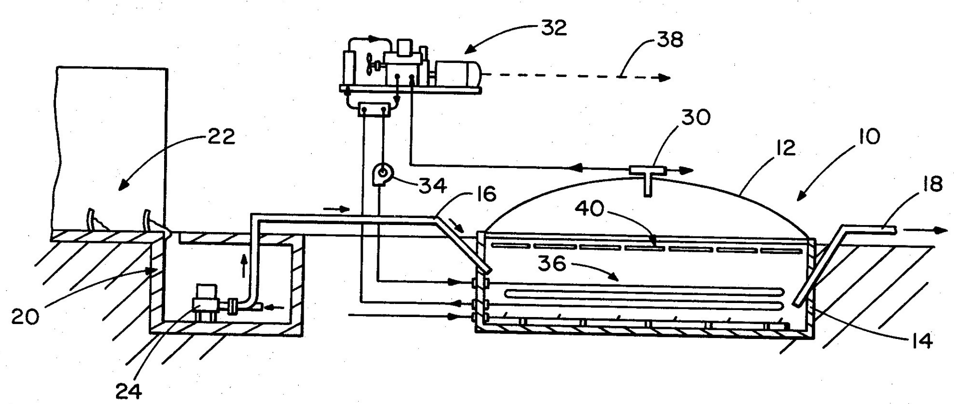


Figure 3.1. Plug flow design as described by Dale in U.S. Pat. No. 4,274,838

This design is advantageous because it minimizes the difficulty in handling the waste slurry and the cost of maintaining ideal digesting conditions to obtain satisfactory yields of gas. Unlike other designs, this digester does not require elaborate plumbing and pumping systems, or mechanical agitators in order to obtain effective digestion. In addtion, this design minimizes the formation of thick surface scum which effectively blocks the release of gas from the slurry into the collection chamber, and adversely affects the generating process itself. The heat exchangers lining the bottom of the tank prevent digested solids from collecting, which would require frequent draining and cleaning. Too much interruption to the process will inhibit reliable gas production.

A non-mixed vertical tower anaerobic digester, as described in U.S. Patent 4,735,724, provides passive concentration of biodegradable feed solids and microorganisms in an upper portion of a continuous digester volume and effluent withdrawl from the middle to bottom portion, resulting in increased solids retention times, reduced hydraulic retention times, and enhanced bioconversion efficiency (Chynoweth, 1988). The design also accomodates high solids loadings and provides separation of microbial phases within the continuous digester volume to achieve thorough bioconversion of the biodegradable feedstock. Figure 3.2 shows the design, including the sectioned layers, pumps, and valves.

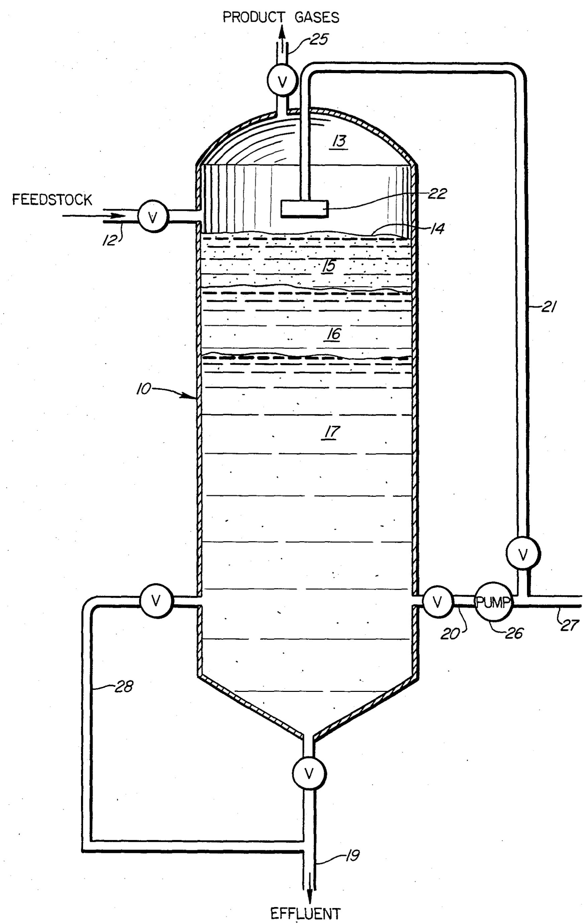


Figure 3.2. Non-mixed vertical tower digester as described by Chynoweth in U.S. Pat. No. 4,735,724

The motivation for this design is to overcome the problems of scum buildup, temperature fluctuations, unequal microbial activity, and limited contact between the organic material and the bacteria, without installing expensive stirring devices. Unlike horizontal plug flow digesters, this design is not limited to the use of homogenous solids feedstock, and has an improved conversion efficiency of the biodegradable fraction due to fewer biologically unreactive zones. This design aims to reduce or eliminate supplemental

nutrient requirements and reduce or eliminate scum formation by recycling a small portion of the digester contents withdrawn from the middle to bottom of the digester to the surface of the reactor contents without disturbing the solids concentration gradient established. The digester can be operated at high solids loadings, which provide separation of microbial phases within the reactor, and provides uniformly high rates of bioconversion and increased process stability and efficiency. The ability to accommodate higher solids loadings, from two to five times greater than conventionally used stir tank digesters, this design provides a lower digester volume per pound of solids converted to useful products (Chynoweth, 1988). In addition, the design is economically advantageous because it requires less energy to operate and less equipment and maintenance. Instead of using mechanical stirring mechanisms, product gas bubbles up through the digester contents, gently agitating the contents without disrupting the solids concentration gradient. All pumps and valves are located externally to the digester contents and can be conveniently replaced, requiring little or no digester down time.

U.S. Patent 4,208,279 describes a plug flow design, which both processes and removes waste to a continuously supplied pit. The digester utilizes a ramp-like lid partially covering the pit such that the contents are partially sealed from the atmosphere, except where the waste products enter (Varani, 1980). As shown in Figure 3.3, the waste is flushed down a ramp into a holding pit. A gas-powered heater is buried in the material in order to maintain the temperature.

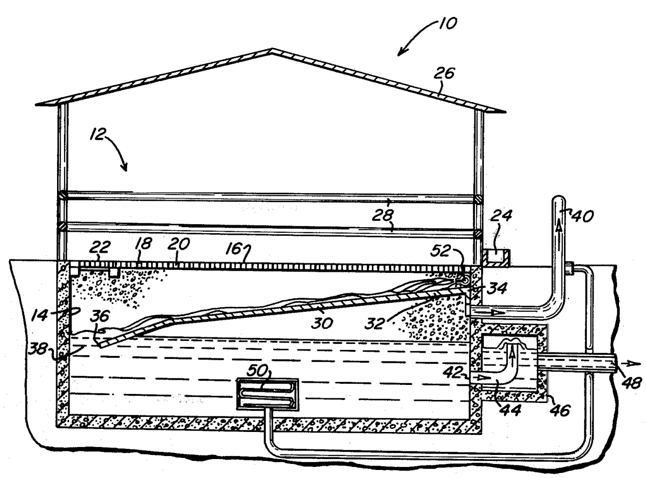


Figure 3.3. Plug flow digester with ramp as described by Varani in U.S. Pat. No. 4,208,279

This system provides an improved method for emptying the pit because the ramp partially covers the biodegradable material. A triangular space is formed to capture produced biogas that can easily be pumped out of the system without disturbing the concentration gradient of the pit. Spent slurry is pumped out of the pit and discarded, but uses a holding tank such that it does not need to be emptied often.

One of the most important design constraints, which will improve anaerobic digestion output in the developing world, is the addition of a solar component. A reliable heating source allows for increased activity of the bacteria. There exist several anaerobic digester design attempts that incorporate a solar component. A design proposed by Verani in U.S. Pat. No. 3,933,328 (Rhoades, 1980) involves a digester buried in the ground covered with a liquid filled pond to capture solar radiation. This liquid is then circulated through the digester to heat the contents. A translucent roof in the form of a dome or inflated bubble exterior of the pond establishes a regulated temperature environment for the digester. Another design, proposed by Boblitz in U.S. Pat. No. 4,057,401 (Rhoades, 1980), provides a solar heated digester that includes a series of sealed containers surrounded by crushed stones, enclosed in a large chamber. The roof over the chamber pivots to allow various levels of incline to accept the solar radiation. A black wire screen covered with transparent material is placed in the roof to absorb solar energy. This heats the air in the roof, which is then circulated throughout the tanks. However, these designs do not prevent heat loss to the outside environment during non-sunlight hours, which allows the temperature inside the digester to fluctuate considerably.

A revised design, as presented by Rhoades (1980) in U.S. Pat. No. 4,221,571, and shown in Figure 3.4, attempts to minimize this heat loss by involving a sealed digester wrapped in a layer of heating absorptive material followed by a series of abutting removable panels of insulating material. In this design, insulative panels, labeled by number 8 in Figure 3.4, may be temporarily removed to expose the heat absorptive material to solar rays and replaced when the radiation subsides. A layer of transparent material allows transmission of solar radiation and simultaneously provides protection against environmental elements. A secondary heating source pumps additional heat into the digester as needed. Although this solution allows for better control of the operating temperature range, it requires significantly more attention and maintenance, both due to the size of the system, and the complexity of the design.

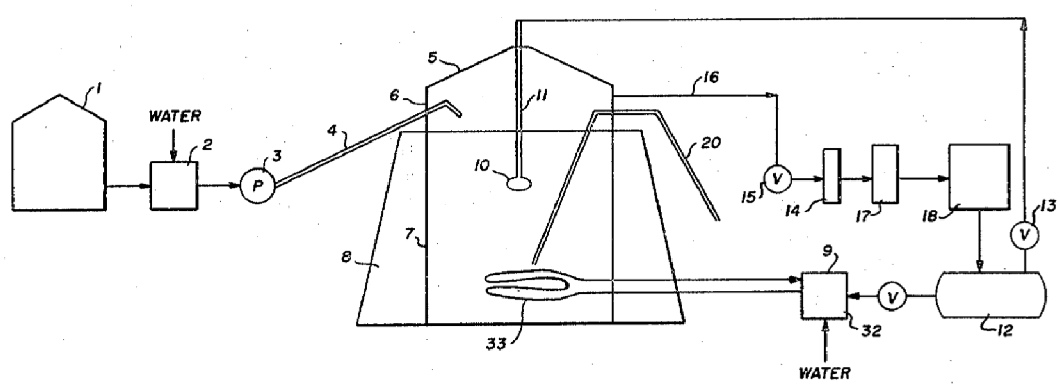


Figure 3.4. Rhoades design as seen in U.S. Pat. No. 4,221,571

A study in Beijing, China utilizes a solar collector system to transmit energy to the digester housed within a greenhouse, as shown in Figure 3.5 (Thomas, 2006). The greenhouse traps energy and reduces heat loss from the system, which minimizes overall temperature fluctuation. The digester uses a coiled heat exchanger to thermally stimulate bacteria activity.

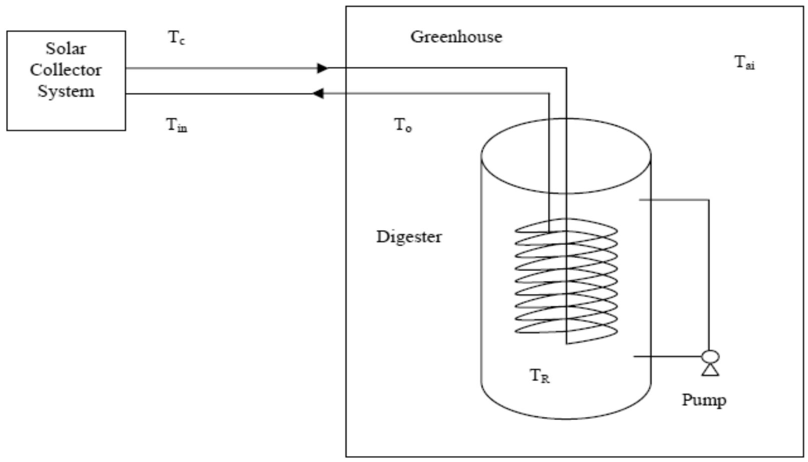


Figure 3.5. Schematic diagram of experimental greenhouse setup as described by Thomas

The solar energy heating system was found to be capable of maintaining the required mesophilic anaerobic digester operating temperature of 35°C during the periods of spring, summer, and autumn without the use of any additional energy source (Thomas, 2006). Although this design setup addresses the temperature component, and is situated above ground to facilitate waste addition and removal, it is complex and expensive. It is unlikely that the developing world would have a greenhouse available to help insulate the system. Therefore, another method of insulation should be explored.

A mathematical model for simulating a solar-heated anaerobic digester fed on solely manure was developed in Greece. As shown in Figure 3.6 (Axaopoulos, 2001), the digester sits below ground level to help minimize temperature fluctuation and better insulate the system. The solar collectors are an integral part of the roof structure. These collectors are coupled to a heat exchanger positioned along the bottom of the digester. At the upper part of the digester, under the tilted cover, a polyethylene plastic film forms an airtight enclosure that is used to collect and store the daily biogas produced.

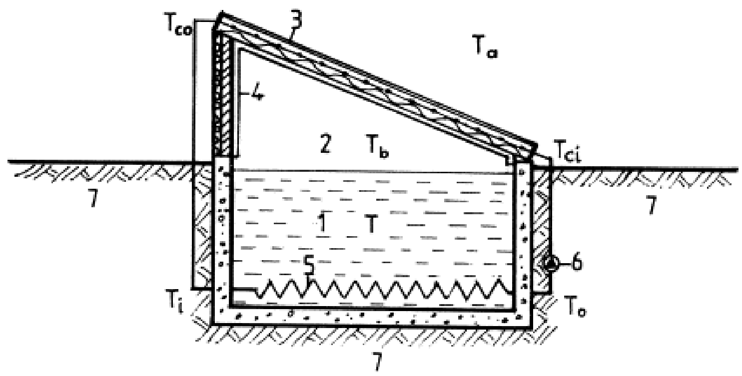


Figure 3.6. Schematic diagram of the biogas production system as described by Axaopoulos

This design is more practical for the developing world due to its size (total volume 60 m^3) and simplicity. However, the addition of a heat exchanger and pump may exceed the budget of many communities. If a heat exchanger were to be added, there is no storage tank for excess water, the heat transfer fluid. A more practical design would incorporate two storages tanks, one for excess water in case some evaporates, and one for hot water that could then be used for washing or cooking. Simple valves could control how much of the water is sent into hot water storage. Without a pump, it would be difficult to remove spent slurry and inorganic solids from the digester, minimizing available volume and bacteria activity. Therefore, if the digester rests below ground, another method of waste removal must exist.

After literature review, no design exists that incorporates a solar component, insulation, simple valves and pumps, and is designed for the low cost economic requirements of the developing world. As discussed, the complexity of the system is directly coupled to budget, available materials, and operation and maintenance. The geographical location would determine the amount of insulation necessary to maintain a mesophilic temperature range to maximize bacteria activity and gas production. However, incorporating a solar component shows an increase in the rate at which bacteria produce gas, and should be included in the design.

Figure 3.7 shows a water-to-water solar thermal system with drainback protection from ClimateMaster® that incorporates components of previously published work. Although this system is more complex than one built for the developing world, the components match the needs of the context. In this design, whenever the collector circulator is not operating, all water in the collector array and exposed piping drains back to the space at the top of the storage tank. As the water drains, the air in this space goes up into the collector array. For this system to operate properly, the collectors and all exposed piping must be pitched a minimum of ¼ inches per foot in the direction of drainage (ClimateMaster, 2012).

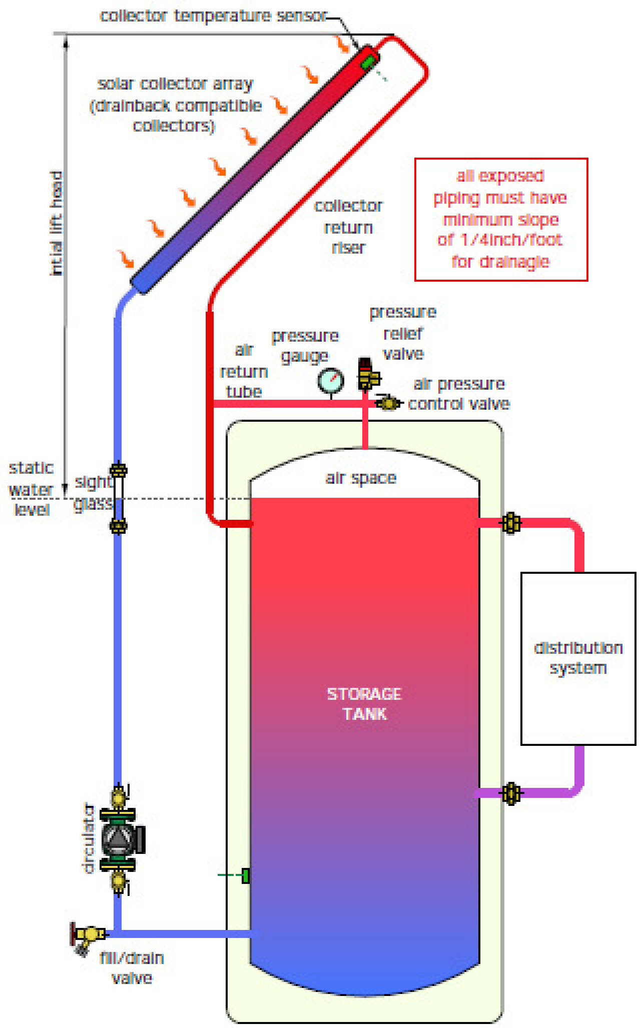


Figure 3.7. Proposed system with variable components

The proposed system utilizes solar energy as a catalyst to increase gas production, with plastic tubing directly connected to the heated surface. Water flows throughout the tubing of the system, heating upon solar energy capture. Once heated within an ideal range for anaerobic bacteria activity, the water continues through a heat exchanger coiled through the body of the digester. A pump allows for continuous water flow through the system. This simple heat exchanger has a smaller footprint than other configurations, and therefore requires lower total capital costs, requires less pumping energy, provides higher thermal efficiency, and lower energy costs. Waste feedstock is inserted in the top of the digester and removed through the door at the bottom out of the range of the heat exchanger. The gas produced can be used connected directly to a stove, converted to electricity, or stored for later use.

The box on the right side of the diagram entitled “distribution system” can be used for a hot water storage tank, connected to radiant heating for a home or barn, or attached to a fan coil to just blow out excess heat from the system. Therefore, the system does not waste any excess heat that is generated during operation.

If the budget prevents addition of a pump, the plastic tubing can be easily shifted such that the system is mixed manually. This prevents the buildup of non-useful sludge in the tank. The size of the solar collector and system are functions of the amount of waste produced by the community and available budget. Therefore, the most important attributes are digester size, waste addition and removal, and solar radiation. The addition of a heat exchanger and pump reduce the retention time, and allow for more waste to be processed more quickly, increasing overall gas production.

4 FORMAL PROBLEM STATEMENTS AND METHODOLOGY

Previous literature review of existing designs and mathematical models suggest that anaerobic digestion is a context specific process. Many systems exist, but none are able to incorporate the most important attributes, while minimizing temperature fluctuation and maximizing biogas output.

The purpose of this work is two fold. Initial efforts will focus on the development and validation of a computer-based model that combines the most important elements of the anaerobic digestion process in order to predict methane output. Following validation, the model will be flexed to:

1. Explore how addition of a solar component increases robustness and performance of the design
2. Examine predicted biogas generation as a function of varying input conditions, and
3. Determine how best to configure such systems for use in varying developing world environments.

4.1 A System Dynamics Approach

System dynamics is a simulation approach to dynamic problems arising in complex social, managerial, economic, or ecological systems, or any dynamic systems characterized by interdependence, mutual interaction, information feedback, and circular causality (Spencer, 2011). Due to the number of variables involved in defining digestion systems to meet the aims of the thesis, a system dynamics approach will be employed. This approach will allow for an analysis of how sensitive outcomes are to changes in stated assumptions. The assumptions that deserve the most attention will depend largely on the dominant behavior and cost elements, and the components of greatest uncertainty of the design. Definition of the interactions between components allows for evaluation of the economic, social, and environmental constraints of the system.

As described by Spencer (2011), the system dynamics approach involves:

- Defining problems dynamically in terms of graphs over time
- Striving for an endogenous, behavioral view of the significant dynamics of a system, a focus inward on the characteristics of a system that generate or exacerbate the perceived problem
- Thinking of all concepts in the real system as continuous quantities interconnected in loops of information feedback and circular causality

- Identifying independent stocks or accumulations in the system and their inflows and outflows
- Formulating a behavioral model capable of reproducing the dynamic problem of concern by itself
- Deriving understandings and applicable insights from the resulting model
- Implementing changes resulting from model-based understandings and insights

Mathematically, the basic structure of a formal system dynamics computer simulation model is a system of coupled, nonlinear, first-order differential or integral equations. Modern applications contain a mix of discrete difference equations and continuous differential or integral equations.

Conceptually, feedback is the central focus of the system dynamics approach. Diagrams of loops of information feedback and circular causality are tools for conceptualizing the structure of a complex system, and for communicating model-based insights. Intuitively, a feedback loop exists when information resulting from some action travels through a system and eventually returns to its point of origin, potentially influencing future action. If the tendency in the loop is to reinforce the initial action, the loop is referred to as a positive or reinforcing feedback loop. If the tendency is to oppose the initial action, the loop is referred to as a negative or balancing feedback loop. Balancing loops can be characterized as goal-seeking, equilibrating, or stabilizing processes, and can sometimes generate oscillations. Reinforcing loops are sources of growth or accelerating collapse, and are disequilibrating and destabilizing (Spencer, 2011). Combined, balancing and reinforcing circular causal feedback processes can generate all manner of dynamic problems. This is advantageous in modeling a biogas system, where the bacteria population balances and reinforces, depending on the waste available, as well as the temperature of the digester.

Once the underlying feedback and circular causality concepts are addressed, the model must look further into the active structure and loop dominance of the system because complex systems change over time. Therefore, a critical requirement of a dynamic system is the ability of the model to change the strengths of influences as conditions change. In a system of equations, this ability to shift loop dominance comes about endogenously from nonlinearities in the system.

The concept of endogenous change is fundamental to a system dynamics approach because it dictates aspects of model formulation. Exogenous disturbances are triggers of system behavior, where the causes are contained within the structure of the system itself. Corrective responses are not modeled as functions of time, but are dependent on conditions within the system because time itself is not seen as a cause (Spencer, 2011). The goal of using this approach is to uncover the sources of system behavior that exist

within the structure of the system itself.

According to Forrester (1969), the organizing framework for system structure is as follows, as shown in Figure 4.1:

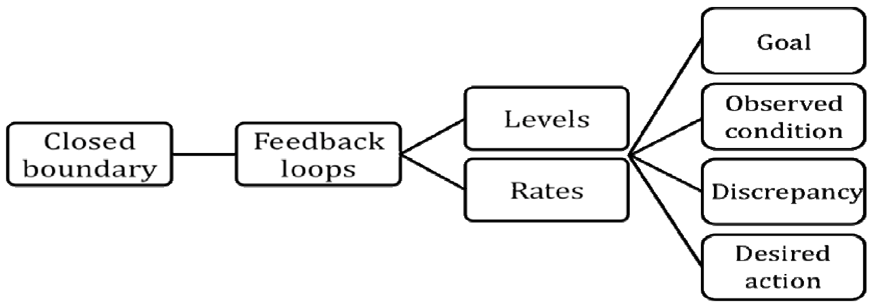


Figure 4.1. System dynamics framework as described by Forrester

The closed boundary indicates an endogenous point of view, as if viewing the system as causally closed. The goal of this approach is to assemble a formal structure that can, by itself, without exogenous explanations, reproduce the essential characteristics of a dynamic problem.

The causally closed system boundary at the top tier of this organizing framework identifies the endogenous point of view as feedback pressed to the extreme. Feedback thinking can be seen as a consequence of the effort to capture dynamics within a closed causal boundary (Spencer, 2011). Without causal loops, all variables must trace their sources of variation outside the system. Assuming instead, that the causes of all significant behavior in the system are contained within some closed causal boundary forces causal influences to feed back upon themselves, forming causal loops. Therefore, feedback loops enable the endogenous point of view and give it structure.

Stocks (levels) and the flows (rates) that affect them are essential components of system structure. A map of causal influences and feedback loops is not enough to determine the dynamic behavior of a system. A constant inflow yields a linearly increasing stock; a linearly increasing inflow yields an increasing parabolic stock, etc. Therefore, stocks are the memory of the dynamic system and the sources of its disequilibrium and dynamic behavior.

The importance of levels and rates appears most clearly when ones takes a continuous view of structure and dynamics. Although a discrete view, focusing on separate events and decisions, is entirely compatible

with an endogenous feedback perspective, the system dynamics approach emphasizes a continuous view. This view aims to look beyond events to see the dynamic patterns underlying them. Events and decisions are seen as surface phenomena that depend on an underlying system structure and behavior.

4.2 Underlying Methodology

In order to employ the underlying principles of a system dynamics approach, the following methodology, incorporating seven critical questions, as stated by Winebrake (2000), was used:

1. What are the important components of this system?
2. How are these components related conceptually and mathematically?
3. How can a systems diagram be constructed that illustrates these relationships?
4. What generic system constructs can be identified, and what do these constructs imply about system behavior?
5. How does the system react to various changes or perturbations?
6. How sensitive is the system to changes and what does this imply for system stability?
7. Where might the human-natural system interface occur, and what impacts are expected from human-caused perturbations in the system?

4.3 Identifying the Important Concepts

As described in the background information in Chapter 2, the purpose of a plug flow digester is to input waste on a set time interval and allow for gas production as the bacteria consume the waste. A solar component to this design will expedite gas production. Therefore, the most important components of the system are the digester, the solar insolation capture device, the bacteria population and consumption rates, and biogas production. These components will be related both conceptually and mathematically through a serious of equations, conversions, and a causal loop and feedback diagram.

4.4 Constructing a Systems Diagram

Stella®, a systems modeling program created by isee systems, offers a practical way to dynamically visualize and communicate the various aspects of the proposed design. Stella visually simulates interactions between variables with a combination of stocks, flows, and converters.

Stocks are the key variables in the model. They represent where accumulation or storage takes place in the system. Since they tend to change less rapidly than other variables in the system, stocks are responsible for the momentum of the system. Stocks are directly influenced by flows; they go together like nouns and verbs. Flow variables are measured in the same units as the stock variable, divided by the appropriate unit for time. Flows can be segregated into "one-way" flows and "two-way" flows. Converters help describe the flows. If the stocks and flows are the nouns and verbs of the model, the converters are the adverbs. As many converters can be added as necessary to make the explanation of flows as clear as possible. The most important role of converters is to dictate the rates at which the flows operate, and therefore the rates at which the stock contents change. In addition, converters calculate measures of system performance (Ford, 1999).

Equations are written within the dialog box of each variable. When simple functions do not best describe data trends, Stella has graph functions in which the user can draw the trend they wish to define. Graph pads are used to show the general trends over the entire simulation. Table pads are used to show the precise numerical results from each time period of the simulation, and can easily be exported to Excel for further analysis.

One of Stella's most useful features is the ease of conducting a sensitivity analysis on the system. This is a collection of simulations that reveals the importance of one of the model inputs. Therefore, each attribute of digester design can be manipulated to determine the importance it plays in the system as a whole. It is evident that the program serves as a powerful tool, not only to describe the interactions of the system through a modeling simulation taking core assumptions into account, but through visually displaying results in a way that is easy to comprehend.

4.5 Defining the System Constructs

Using the software, the anaerobic digester design can be segregated into four subsystems: digester temperature, waste in the digester, bacteria in the digester, and gas in the digester. Once each subsystem is defined within it's own parameters using stock variables, it can be incorporated into the overall design through a series of flows and converters. The interactions between subsystems provide a detailed analysis of the system as a whole.

The waste flow of the system consists of the storage, input, and output of the waste stream. The waste in digester stock variable is described by four other stock variables: waste storage, fertilizer collection, spent

slurry, and waste eaten by bacteria. Therefore, waste input flows into the digester from storage, and useful waste flows out of the digester will be collected as fertilizer, while non-useful waste flows out of the digester will be collected as spent slurry. The fourth flow, waste eaten by bacteria, describes how much feedstock the bacteria consume. A consumption rate converter links the amount of waste eaten by the bacteria to the temperature inside the digester. These interactions will be visualized in the following chapters, as the model is developed and executed.

The bacteria stock is defined by a "two-way" flow representing bacteria growth and death. A converter describes the net growth rate of the bacteria population as a function of how much waste is available.

The gas in the digester is defined by one other stock variable representing the amount of gas collected in terms of available energy content, and two flows, the amount of gas produced by the bacteria, and gas removal. Converters describe the rate at which this gas is removed, as well as conversions from waste in solid form to gaseous form so that the units of the model are compatible. One of the biggest challenges will be how to determine the optimal gas production based on the feedstock available. The inputs for each geographical location will vary, and therefore, the system must be designed such that these alterations will not significantly reduce the amount of methane output.

The heat flow of the system dictates the temperature inside the digester. There are three flows describing this stock: heat from the sun, heat loss from the digester, and an overheat control to keep the internal temperature in the optimum mesophilic range. Although bacteria activity inside the digester is an exothermic process, the added heat is considered negligible and not accounted for in the model. Numerous converters describe these flows. It is important to optimize the solar energy captured by the panels or other devices, and depending on the complexity of the design, be able to control the pitch or angle of incline of the capture device. This will allow for greater temperature control, and minimize temperature fluctuation. The material, angles, and size of the solar panel are design choices of the operating system that are governed by the geographical location of the digester.

4.6 Verifying the Model

Once the stocks, flows, and converters have been properly defined from available data, and the model operates smoothly, the results must be verified with the experimental results found in existing literature. The goal is simply to learn if the model runs as intended. According to Greenberger, Crenson, and Crissey (1976), verification of a model indicates that it has been faithful to its conception, irrespective of whether

or not it and its conception are valid. Verification may sound tautological but is a necessary check that the mechanisms of the model are in fact doing what the modeler thinks they are doing (Kitching, 1983). If the accuracy of the results does not match those from previous studies, troubleshooting begins. This continues until the results make sense, both numerically and logically. The variables should be tweaked such that the model is robust. Once the model runs properly, over a specified time span, it is important to compare the results with those found in the literature, and make sure the trends are reproducible.

4.6.1 Behavior Reproduction

The purpose of this test, as described by Sterman (2000), is to confirm that the model:

1. Reproduces the behavior of interest in the system, both qualitatively and quantitatively
2. Endogenously generates the symptoms of difficulty motivating the study
3. Generates the various modes of behavior observed in the real system, and
4. Verifies that the frequencies and phase relationships among the variables match the data

The quantity of existing exact data available is insufficient for direct comparison with data generated by the Stella model, which limits the amount of statistical testing that can be accomplished. However, any comparative data that is available will be statistically analyzed. In addition, model outputs and data will be compared qualitatively to confirm the accuracy of general modes of behavior, shape of the variables, asymmetries, relative amplitude and phasing, and unusual events. Finally, the response of the model to test inputs, shocks, and noise will be examined.

4.7 Validating the Model

Once verified, both statistically and behaviorally, the results must then be validated, to check that they satisfy the core assumptions and expected trends. In order to bolster confidence in the model, it must be able to reproduce past behavior of the reference system, respond to perturbations, critically examine premises and theories on which it is based, and be able to be put to use. Validation is not a general seal of approval but a more general indication of a level of confidence in the model's behavior under limited conditions and for a specific purpose (Greenberger, 1976). Data provide a tangible link between a model and its reference system, and a means for gaining confidence in the model and its results. The ultimate goal is to develop a model that closely reproduces data on observed past behavior of the reference system such that it gains credibility and wins the acceptance and trust of potential users, in this case, if it were to

be implemented into the developing world.

The aim of this model is to use validation in a reflective mode, in which the testing is designed to uncover flaws and hidden assumptions, challenge preconceptions, and expose assumptions for critique and improvement. The purpose of the reflective mode is to build confidence in the model and ultimately increase the chances for sustained success. Several tests are employed to uncover flaws and improve the model as part of the validation in the reflective mode. These tests include structure assessment, dimensional consistency, testing extreme conditions, and sensitivity analysis, and are describes in more detail in the subsequent paragraphs.

4.7.1 Structure Assessment

The purpose of this test is to confirm that the model structure is consistent with relevant descriptive knowledge of the system, that the level of aggregation is appropriate, that the model conforms to basic physical laws, and that the decision rules capture the behavior of the variables in the system (Sterman, 2000). In order to verify the results of this test, each equation integrated into the stock and flow diagram will be inspected and checked for accuracy. Because no physical set-up of the digester design exists to perform laboratory tests, disaggregate submodels will be developed to compare behavior to aggregate formulations. Any prevailing suspect structures will be disaggregated further using sensitivity analysis.

4.7.2 Dimensional Consistency

The purpose of this test is to verify that each equation is dimensionally consistent without the use of parameters having no real world meaning. The model contains numerous conversion factors, such that the solid waste entering the system eventually produces a gaseous biogas product. In addition, there are many conversions between forms of energy consumed during the process. Therefore, it is critical that all equations account for these conversions, and that the end product is measured in a useful form for further analysis.

4.7.3 Extreme Conditions

Models should be robust in extreme conditions; meaning that under these conditions, the model should behave in a realistic fashion no matter how extreme the inputs imposed on it may be (Sterman, 2000). Once the model is verified with the numerical inputs, it must be stretched such that each equation makes

sense even when its inputs take on extreme values, and see whether it responds plausibly when subjected to extreme shocks and parameters.

Extreme condition testing can be carried out by direct inspection of the model equations and by simulation. By inspection, each decision rule or rate equation should be examined in order to see whether the output is feasible and reasonable even when the input takes on maximum and minimum values. Then the response to extreme values of each input in combination with other associated variables must be tested. It is important to consider the response of each equation when all inputs simultaneously take on their extreme values. Next, the model must be subjected to large shocks and extreme conditions by implementing tests that examine conformance to basic physical laws. The following extreme conditions will be explored:

1. Waste input ceases
2. Initial waste amount doubles, triples, in same time interval
3. Severe weather patterns which erratically affect solar insolation
4. No solar component
5. No overheat control
6. Fertilizer collection or spent slurry removal ceases
7. Overpopulation of bacteria in digester
8. Underpopulation of bacteria in digester

Simulation is an important component of extreme condition testing. The whole model conditions tests may reveal subtle flaws that direct inspection may overlook. When an extreme condition simulation generates implausible behavior, the equations of the affected formulations should be examined to identify the precise source of the flaw. Stella's graphical results will be crucial in identifying flaws in the system.

4.7.4 Sensitivity Analysis

Sensitivity analysis is a tool that asks whether conclusions change in ways important to the purpose of the model when assumptions vary over the plausible range of uncertainty (Sterman, 2000). Numerical sensitivity exists when a change in assumptions changes the numerical values of the results, whereas behavior mode sensitivity exists when a change in assumptions changes patterns of behavior generated by the model. Both analyses will be examined for the proposed model.

Sensitivity analysis requires much more than varying parameters. Sensitivity of results to assumptions about the boundary of the model, changes in the level of aggregation, and changes in the way decisions are made within the human-natural system interface must all be considered.

In addition, the uncertainly in parameter values is important and must be tested. In assessing sensitivity to parametric assumptions, first the plausible range of uncertainty in the values of each parameter or nonlinear relationship must be identified. These parameters must be tested over a wide range, because judgmental parameter estimates are likely to be more uncertain than one's intuitive confidence bounds suggest (Sterman, 2000).

Stella modeling software is equipped with sensitivity analysis tool, entitled "sensi specs" in which each variable can be manipulated over a set range. The variation type can be incremental, distribution, ad hoc, or pasted data from an outside source. The number of runs can be set, and then results will be output into a table or graph.

Given the limited time and resources of the scope of this thesis, sensitivity analysis will focus on the relationships and parameters suspected to be both highly uncertain and likely to be influential. Parameters around which no uncertainty exists need not be tested. Likewise, if a parameter has but little effect on the dynamics it need not be tested even if its value is highly uncertain because estimation errors are of little consequence (Sterman, 2000). In order to explore sensitivity efficiently, the best and worse case scenarios will be defined. In the best case scenario, the values of all parameters and relationships to the values most favorable to the desired outcomes are set. In the worst case scenario, the values of all parameters and relationships to the values least favorable to the desired outcomes are set. Although the extreme situations represented by the best and worst cases are not the most likely outcomes, the results from these scenarios will provide a plausible range for the optimal conditions of the variables.

5 Initial Conditions and Contextual Constraints

As mentioned in Chapter 1, there is a constant need to improve health conditions in the developing world. Many countries rely on firewood as the main source of fuel, with food preparers hovering over an inside stove or fire pit for numerous hours each day. According to current World Health Organization (WHO) estimates, more than half of the world's population (52%) cook and heat with solid fuels. It has been estimated that more than 2.4 billion people, generally among the world's poorest, rely directly upon biomass fuels to meet their daily needs. Indoor air pollution (IAP), generated largely by inefficient and poorly ventilated stoves burning biomass fuels, is responsible for the deaths of an estimated 1.6 million people annually. More than half of these deaths occur among children under the age of five (WHO, 2011). Biomass smoke contains thousands of health-damaging substances; small particles of less than ten microns in diameter are one of the most dangerous. Such pollutants penetrate deep into the lungs and are a critical contributor to the development of acute respiratory disease, chronic obstructive pulmonary disease, cancer, and other illnesses.

Biogas can replace firewood, dried dung, kerosene, and coal, reducing indoor air pollution, and eliminate hazardous health effects linked to inhalation of particles. Biogas technology is unique because it simultaneously reduces the need for firewood and improves soil fertilization, and therefore reduces the threat of soil erosion. Rapid deforestation due to increasing wood consumption contributes heavily to the acceleration of soil erosion. This, in conjunction with overgrazing, will permanently damage the soil, which hurts crop production and threatens the food supply. Therefore, production and utilization of biogas will make a substantial contribution to soil protection and amelioration. Most directly, biogas can replace firewood as an energy source. Additionally, biogas systems produce nutrient rich fertilizer, which can be used as fodder for domestic animals, which lessens the danger of soil erosion attributable to overgrazing. According to the Indian Council of Agricultural Research (ICAR) in New Delhi, a single biogas system with a volume of 2.8 cubic meters, can save as much as 0.3 acres of woodland each year (GTZ, 2010).

In conjunction with the ideal mesophilic or thermophilic operating conditions discussed in Chapter 2, small biogas systems can be most sustainable where there is need to overcome the problem of indoor pollution. Therefore, the best conditions for biogas dissemination are when the mean temperature is well above 15°C (GTZ, 2010).

In addition to mean temperature, seasonal variation and rainfall are also important environmental parameters to consider when choosing an appropriate context for biogas production. For example, a

longer retention time and a bigger digester would be needed to compensate for the lowest recorded temperature. Daily fluctuations should not be problematic (GTZ, 2010). The amount of seasonal and annual rainfall has an indirect impact on anaerobic fermentation. Low rainfall may lead to insufficient mixture of the substrate with water, which will in turn hamper digestion. Seasonal water scarcity or seasonal changes in temperatures do not allow for the development of a breeding system among the farm animal population, and therefore give little available waste for digester feed. This means that the use of biogas is possible only near permanent water sources or irrigated farms (IIASA, 2011). High precipitation can lead to high groundwater levels, causing problems in construction and operation of the biogas system.

Certain climatic zones are more suitable for biogas production than others. Tropical rain forests, with annual rainfall above 1,500 millimeters, mean temperatures between 24 and 28°C, and little seasonal variation, are climatically very suitable for biogas production. Tropical highlands, with annual rainfall between 1,000 and 2,000 millimeters, and mean temperatures between 18 and 25°C according to elevation, are climatically suitable for biogas production from agricultural systems with mixed farming and zero grazing. Wet savanna, with annual rainfall between 800 and 1,500 millimeters, and moderate seasonal changes in temperature, favors biogas dissemination due to mixed farming and day grazing (GTZ, 2010). Dry savanna, with seasonal water scarcity, seasonal changes in temperature, and pastoral systems of animal husbandry does not allow enough waste generation to support biogas production, unless near a permanent water source or irrigated, integrated farm. Desert, with permanent scarcity of water, considerable seasonal variations in temperature, and nomadic animal keeping practices, are unsuitable for biogas dissemination.

Worldwide, methane emissions from agricultural production comprise about 33% of global anthropogenic methane release (Weir, 2006). Methane exhibits an important climatic twin effect; the use of renewable energy reduces the CO_2 emissions through a reduction of the demand for fossil fuels, and simultaneously, capture of uncontrolled methane emissions reduces the second most potent greenhouse gas.

Biogas technology reduces the release of CO_2 from burning fossil fuels in two ways: first, biogas is a direct substitute for gas or coal for cooking, heating, electricity generation, and lighting; second, the reduction in the consumption of artificial fertilizer avoids CO_2 emissions that would otherwise come from fertilizer producing industries (GTZ, 2010). The spent digester substrate provides an odorless, chemical-free fertilizer. Environmentally, smaller agricultural units can additionally reduce the use of forest resources for household energy purposes, which slows deforestation, soil degradation, and resulting natural catastrophes like flooding and desertification. If fossil fuels and firewood are replaced with

methane, additional CO_2 emissions can be avoided, including saving of forest resources which are a natural CO_2 sink (Weir, 2006).

Two developing countries, Mozambique and Papua New Guinea, were selected based on the criteria mentioned above; specifically, agriculture-based societies in the developing world, as defined by the United Nations Human Development Index (HDI), high indoor air pollution deaths, according to the World Health Organization, and geographical location and climate. The Human Development Index represents a push for a broader definition of well-being and provides a composite measure of three basic dimensions of human development: health, education, and income. Meeting these criteria allows both countries to greatly benefit from implementation of the proposed solar-heated anaerobic digester system. The following paragraphs discuss general assumptions for initial conditions, as well as more in depth profiles of each country, and context specific modeling conditions.

The minimum amount of biogas required for cooking was estimated to be 2 m^3 per day for a family of 5 to 6 people (Katuwal, 2009). A study at the Department of Civil and Environmental Engineering at the University of Trento in Italy determined the minimum number of animals needed to produce this amount of biogas every day based on a design with a digester retention time of 30 days and an operating temperature of 15°C and 30°C (Ragazzi, 2010). The results for Africa and Asia, Middle East, and Latin America are shown in Table 5.1:

Table 5.1. Minimum Number of Animals Required to Meet Daily Biogas Needs

	Min. n_{pig}		**Min. $n_{chicken}$**		**Min. n_{cow}**	
	15°C	30°C	15°C	30°C	15°C	30°C
Africa	9	4	45	30	9	5
Asia, Middle East, Latin America	10	6	50	30	10	5

Although no results are specifically given for Papua New Guinea, it was assumed to be part of Southeast Asia. As seen, an increase in temperature drastically decreases the number of animals needed to meet daily biogas needs. Therefore, with an even higher temperature from solar-heated anaerobic digester, even fewer animals will be needed. This is advantageous to smallholders who may not own large quantities of livestock.

5.1 Mozambique, Africa

Latitude: 18° 15' 0" South
Longitude: 35° 0' 0" East
Elevation: 536 meters
*Average Daily Solar Insolation: 5.7 kWh/m²/day**

Mozambique is located in Sub-Saharan Africa, along the southeastern coast. The southern portion of the country has a semi-arid and subtropical climate, while the northern portion of the country is tropical. The average temperature in the country is 28°C. There is a wet season during the summer, between October and March and a dry season from April to September. There is little temperature variation between the seasons. The wet season brings the heaviest rain along the coast, along with cyclones and flooding. Northern areas receive almost twice the rainfall as the southern provinces. The average annual rainfall along the coast is between 800 and 900 millimeters, while some northern areas average up to 2,000 millimeters. The semi-arid wet savanna in the south occasionally experiences severe and prolonged droughts (IIASA, 2011).

In order to determine a daily solar insolation value to use as a model variable, radiation averages were measured in three stations along the coast of Mozambique (Maputo, Beira, and Pemba) and three stations inland of the country (Maniquenique, Chimoio, and Lichinga) as shown in Table 5.2. According to these calculations, the average daily solar radiation for the country is 5.7 kWh/m²/day (Cuamaba, 2006).

Table 5.2. Global solar radiation averages taken for a period of 30 years

	Maputo	*Beira*	*Pemba*	*Maniquenique*	*Chimoio*	*Lichinga*
Latitude	25° 58'	19° 48'	12° 59'	24° 44'	19° 07'	13° 18'
Longitude	32° 36'	34° 54'	40° 32'	33° 32'	32° 28'	35° 14'
Altitude	79m	39m	75m	58m	1,352m	729m
Global solar radiation (kWh/m²/day)						
January	6.9	6.6	5.9	7.4	6.7	5.1
February	6.6	6.3	5.3	7.0	6.5	5.1
March	5.8	5.9	5.8	6.3	6.2	4.8
April	4.9	5.5	5.9	5.4	5.5	5.0
May	4.1	4.7	5.5	4.5	4.9	5.0
June	3.8	4.2	5.1	4.1	4.5	4.4
July	3.8	4.4	5.2	4.3	4.7	4.8
August	4.5	5.0	6.0	5.0	5.3	5.3
September	5.0	5.7	6.8	5.7	5.9	6.0
October	5.7	6.4	7.3	6.5	6.2	6.1
November	6.0	6.7	7.3	6.8	6.6	5.8
December	6.8	6.6	6.7	7.5	6.1	5.2
Partial station averages	**5.3**	**5.7**	**6.0**	**5.9**	**5.8**	**5.2**
Country's average:* 5.7						

* Country's average means an arithmetic average of the six stations considered

According to the 2011 United Nations Human Development Reports, between 1980 and 2010, Mozambique's HDI rose by 1.3% annually from 0.195 to 0.284, which gives the country a rank of 165 out of 169 countries with comparable data. The HDI of Sub-Saharan Africa as a region increased from 0.293 in 1980 to 0.389, placing Mozambique below the regional average (Hamel, 2011).

The World Health Organization has estimated that there are between 400 and 610 deaths per million people from indoor air pollution, which is the highest range recorded worldwide (WHO, 2011). Almost two-thirds of population depend on agriculture, and out of these about 90% depend on subsistence agriculture (IIASA, 2011). The main staple crops produced in the family agriculture sector are maize, sorghum, rice, millet, potatoes, sweet potatoes, cassava, and beans. Cash crops include corpa, cashew nuts, sesame, sugar beans, sunflower, and sugar cane.

According to a special report issued by the Food and Agriculture Organization of the United Nations, livestock numbers are low, because herds have not yet recovered from losses incurred during the civil war, and in the southern provinces, from floods in 2000. The livestock census in 2002 identified the presence of 720,000 cattle, 5 million goats, 25 million chickens, and 2.3 million pigs. Cattle, sheep, and goats are reared in extensive grass-based systems, and at such low stocking rates that body condition is generally excellent and numbers are estimated to be increasing at about 8%, which translates to about 910,000 current national head of cattle and 6.3 million goats. Chickens and pigs are kept under back yard, scavenger systems and the numbers are expected to remain constant, as the husbandry system limits expansion of holdings (Economic and Social Development Department, 2005).

The Agricultural and Livestock Census 1999-2000 classifies livestock holdings into three main categories, as shown in Table 5.3:

Table 5.3. Livestock Holding Categories

	Livestock Type		
Holding Size	Cattle	Goats, Sheep, and Pigs	Chickens
Small	< 10	50	< 5,000
Medium	10 - 100	50-500	5,000 – 20,000
Large	> 100	500	> 20,000

It is estimated that 2.4 million farm families, 80% of the total small, medium, and large holdings, are livestock keepers. The majority of these fall within the category of small holders (Economic and Social

Development Department, 2005). Cattle production is concentrated in the south and west due to the occurrence of tsetse fly and associated trypanosomiasis in the wet, northern and central areas. However, given the extremely low stocking densities and dispersed nature of the holdings, animal disease in not generally a problem.

The utilization data of staple food supply/demand balance in 2005-2006 in Mozambique (Economic and Social Development Department, 2005) is shown in Table 5.4:

Table 5.4. Staple Food Supply/Demand Balance Utilization in 2005-2006

	Crop Type (tons)					
Utilization	Maize	Rice	Wheat	Sorghum	Total Cereals	Cassava
Feed Use	50	-	-	-	50	1,146
Other Uses/Losses	222	12	-	21	254	3,437

5.1.1 Initial Conditions and Assumptions for Mozambique

Following the discussion of the important attributes of Mozambique's geographical and agricultural profile, the next step is to make realistic assumptions and define initial conditions to model a solar-heated anaerobic digester in this specific context. The following assumptions were made:

1. The digester is located on a farm within the small holding category
2. Digester feedstock is a combination of animal and crop waste
3. Crop waste is based off of other uses/losses utilization, and will not displace animal feed

Bioconversion, or gasification, is the conversion of organic waste into a methane energy source by a fermentation process involving living organisms. The process is affected by several groups of bacteria working collectively. The process of conversion of waste into useable methane was previously discussed in Chapter 2, but it is important to note that each group of bacteria during the multi-stage process relies on the next to consume its products. This prohibits inhibition that occurs when excess concentrations of the compounds related to fermentation and acetate, are allowed to develop.

All organic material contains some water. Total solids (TS) are a measure of the actual solid content of a substance. This is an important factor in digesters because only a portion of the solid material is actually

bioconverted. Low solids anaerobic digestion systems contain less than 10% TS, medium solids systems about 15-20% TS, and high solids process range from 22-40% TS (U.S. EPA, 2008). Systems generally run the best with high solids. The average temperature of both Mozambique and Papua New Guinea are around 28ºC, so the feedstock material could be dried to reduce moisture content. Volatile solids (VS) are a measure of this portion of the total solids that are actually available for bioconversion. According to a report by the U.S. Environmental Protection Agency, food waste contains more biodegradable solids, with a higher VS/TS percentage (86-90%) than municipal wastewater solids (70-80%) in general. The upper percentage was used in the calculations. However, the higher VS/TS percentage and the volatile solids destruction (VSD) of food waste digestion also results in half the biosolids produced compared to wastewater solids (U.S. EPA, 2008).

According to Table 5.1, at 30ºC, the minimum number of animals required to produce 2 m^3 of biogas daily varied by animal. For a farm in Mozambique, this would require the waste from at least 5 cows or 30 chickens. As described previously, the C/N plays a significant role in the consistency and reliability of biogas production. Therefore, it is assumed that both maize and cassava, two of the staple crops, are included in the mixture of feedstock waste. This increases the solid material of the feedstock as well. Assuming a 30 day operating hydraulic retention time (HRT), the average length of time liquids and soluble compounds remain in the digester, growth and digestion rates, and tolerance to toxicity for the anaerobic processes, a methane density of 1.14 kg/m^3, and that the biogas contain 65% methane. Table 5.5 shows the sequence of calculations used to optimize the size of the digester a farm would need with these input values. These predicted values, based on calculations from the McElvaney Associates Corporation (2010), will later serve as inputs for the computer-based system dynamics model, and eventually a comparison to those generated by the system dynamics model.

Table 5.5. Optimization of Digester Size and Methane Production Rate for Mozambique

	Cow Manure	*Chicken Manure*	*Maize*	*Cassava*	**Total**
Batch Size/System Volume					
Waste from animal or crop (kg)	108.9	1.4	6.9	17.0	
Dry material % of waste	8%	25%	65%	70%	
TS in animal or crop waste (kg)	8.7	0.4	4.5	11.9	
TS % of batch	10%	10%	10%	10%	
Batch size (kg)	87.1	3.5	44.9	119.0	**254.5**
Required system volume (m^3)	2.6	0.1	1.3	3.6	**4.1**
Organic Loading Rate					
TS in animal or crop waste (kg)					
VS % of TS	8.7	0.4	4.5	11.9	
VS in animal or crop waste (kg)	92%	75%	80%	80%	
Organic loading rate (kgVS/m^3-	8.0	0.3	3.6	9.5	
day)	2.0	0.1	0.9	2.3	**5.3**
Methane Yield					
VS in animal or crop waste (kg)					
Digestion efficiency	8.0	0.3	3.6	9.5	
VS converted (kg)	45%	45%	82%	82%	
Total gas (m^3)	3.6	0.1	2.9	7.8	
Total methane (m^3)	3.2	0.1	2.6	6.8	
VS in animal or crop waste (kg)	2.1	0.1	1.7	4.5	**8.3**
Methane yield (m^3 CH_4/kg VS	8.0	0.3	3.6	9.5	
added)	0.3	0.3	0.5	0.5	
Methane Production Rate					
Total methane (m^3 CH_4)	2.1	0.1	1.7	4.5	
Methane production rate (m^3/day)	0.5	0.02	0.4	1.1	**2.0**

The total weight of material for each feedstock component was calculated based on data from the Ohio State University Extension (2006), including amount of waste generated by cows and chickens daily, the dry material percentage of the waste, and the amount of VS in the TS. For Mozambique, the ratio of feedstock consists of waste from 3 cows, 12 chickens, 3 stalks of maize, and 5 cassava tubers. The amount of TS in the entire batch must be calculated from the total amount of waste produced from the animals and crops, minus the water weight. Since some materials contain more moisture than others, this is an important observation. According to the Ohio State University Extension, cow manure has a moisture content of 92% and chicken manure has a moisture content of 75% (2006). The moisture content was 35% for maize (Uhrig, 1992) and 30% for cassava (International Starch Institute, 2012).

The TS is calculated by multiplying the dry material percentages by the total weight of the material. According to McElvaney Associates, batch TS% is generally kept around 10% due to processing equipment limitations (2010). Therefore, this is the value that was assumed in the calculations. The batch size includes all material, bacteria, and water.

The organic loading rate (OLR) is a measure of the organic material (VS) per bioconverter volume added to the system daily. For a given system size, higher organic loading rates generally result in lower bioconversion efficiency. Any value greater than 3.3 kg VS/m^3-day is considered high-rate bioconversion. This rate is determined by dividing the amount of VS by the system volume. Considering all feedstock components, the overall OLR for the system in Mozambique is approximately 5.3 kg/day.

The methane yield is a measure of the quantity of methane produced from the VS added to the system. The value is dependent upon the type and digestibility of the feedstock and the retention time in the system. It is also affected by the condition of the fermentation, or raw gas quality. Methane production rate is a measure of the quantity of methane per bioconverter volume generated by the system on a daily basis. The biodegradability of manure is only 45%, whereas the biodegradability of food or crop waste is 82% (El-Mashad, 2010).

In Mozambique, there is a harvest period at the end of the wet season, from January to February, and then a second one at the end of the dry season, from October to December. The amount of crop waste produced from these harvests was calculated using the quantities listed in Table 5.5 for other uses or losses for maize and cassava, and determining the approximate number of farm families, which includes about 62% of the total population of the country (Economic and Social Development Department, 2005). Although these months only cover 151 days out of the year, for simplicity, the calculations for Table 5.6 assume that the crop waste is stored over the entire year, and added to the feedstock mixture for daily input.

Based on these conditions, the daily methane production rate is 2.0 m^3; matching the 2 m^3 daily production required for cooking fuel for a family of 5 to 6 people. Based on these calculations, the total methane yield for the system is 1.4 m^3 per kilogram of VS added to the system. In order to generate 2.0 m^3 of methane every day, the volume of the digester must be about 4.1 m^3. This requires a batch size of approximately 254.5 kilograms.

As discussed in Chapter 2, one of the most important factors impacting the substrate characteristics is the ratio of carbon to nitrogen present in the organic material, and it was determined that a C/N ratio between 20 and 30 is optimum for anaerobic digestion.

Since Mozambique tends to produce enough crop waste to use for animal feed, it is assumed that some of this waste will be fed into the digester, ideally loaded at the bottom of the tank. As the most prevalent crop types, only maize and cassava were considered in the calculations. Additionally, as the most prevalent animal types, only cattle and chicken waste were considered in the calculations, with associated C/N ratios (FAO, 1997). The initial loading amount is 254.5 kilograms, as determined in Table 5.5. From these results, the waste type, C/N ratio, and the amount of waste produced daily from each source helped determine the overall C/N of the feedstock mixture, as shown in Table 5.6.

Table 5.6. Initial Inputs for Digester Feedstock for Mozambique

Waste Type	Waste (kg)	Total Batch (kg)	Waste % of Total Batch	C/N Ratio	% x C/N Ratio
Cow	87.1	254.5	0.3	24	8.2
Chicken	3.5	254.5	0.01	10	0.1
Maize	44.9	254.5	0.2	60	10.6
Cassava	119.0	254.5	0.5	22	10.3
Total					**29.2**

* Numbers based on calculations from the Ohio State University Extension (2006)

With a feedstock waste mixture containing these four materials, the overall C/N is 29.2, which falls at the upper limit of the optimal range. There is a noticeable spread in the amount of each feedstock component which allows for the proper chemical balance. Cassava roots and cow manure make up the majority of the mixture since they have C/N ratios ideal for anaerobic digester performance. A significant amount of maize is used to add dry material to the system. However, it is important not to add too much additional maize due to its high C/N ratio. Based on the results provide in Table 5.1, it is assumed that the waste produced from each cow equates to that produced by 6 chickens. The calculation results in Table 5.6 verify a realistic distribution of waste for initial modeling conditions.

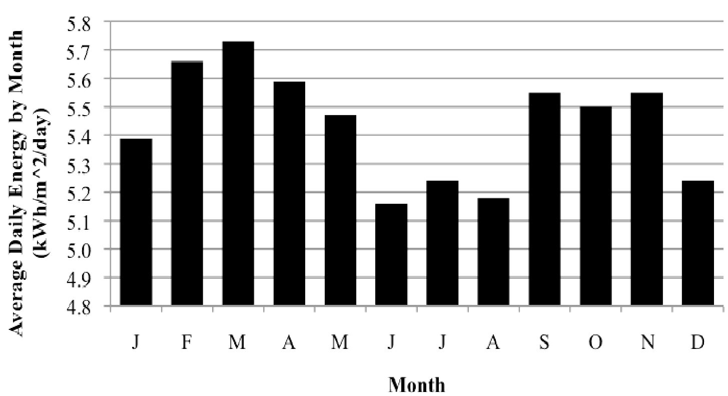
5.2 Papua New Guinea, Oceania

Latitude: 06°0' 0" South
Longitude: 147°0' 0" East
Elevation: 0 meters
*Average Daily Solar Insolation: 5.438 kWh/m^2/day**

Papua New Guinea (PNG) is a country occupying the eastern half of the island of New Guinea and numerous offshore islands located in the southwestern Pacific Ocean. The terrain consists mostly of mountains with coastal lowlands and rolling foothills. Almost half of all rural Papua New Guineans live in lowland environments. The climate is tropical, with monsoons from the northwest coming between December and March, and from the southeast between May and October. Papua New Guinea is one of the wettest countries in the world, with much of the country receiving 2,000 to 4,000 millimeters of rain annually, and some parts receiving more than 7,000 millimeters. The ideal annual rainfall for tropical crops is between 1,500 and 3,000 millimeters, and most of the rural population lives in places where annual rainfall is between 1,800 and 3,500 millimeters (Allen, 2009). Annual rainfall does not vary greatly from year to year. Occasionally, the country experiences periods of uncharacteristically low rainfall due to the El Nino Southern Oscillation phenomenon.

In order to determine a daily solar insolation value to use as a model variable, radiation averages from NASA were measured monthly over the course of the year as shown in Table 5.7 According to these calculations, the average daily solar radiation for the country is 5.438 kWh/m^2/day (Russell, 2011).

Table 5.7. Average Daily Solar Insolation in Papua New Guinea



Between 1980 and 2010, Papua New Guinea's HDI rose by 1.3% annually from 0.295 to 0.431, which gives the country a rank of 137 out of 169 countries with comparable data. The HDI of East Asia and the Pacific as a region increased from 0.391 in 1980 to 0.650, placing Papua New Guinea below the regional average (Hamel, 2011).

The World Health Organization has estimated that there are between 300 and 400 deaths per million people from indoor air pollution, which is the second highest range recorded worldwide (WHO, 2011).

Papua New Guinea is rich in natural resources, including minerals, oil, gas, timber, and fish, and produces a variety of commercial agricultural products. The economy can generally be separated into subsistence and market sectors. Approximately 75% of the country's population relies primarily on the subsistence economy; mineral, timber, and fish sectors are dominated by foreign investors (Bureau of East Asian and Pacific Affairs, 2010).

The staple foods are starchy root crops, sago, and banana. Sweet potato is the most important staple food in the country, and it provides about two-thirds of the food energy from locally grown food crops. In 1996 it was calculated that rural villagers obtained 84% of their food energy from locally grown food (Bourke, 2009).

In addition to crops, the most important domestic animals in Papua New Guinea are pigs, chickens, cattle, sheep, goats, ducks, and rabbits. The most common animal is the domestic pig, with an estimated 1.8 million pigs being raised in villages. Table 5.8 provides a more detailed segregation of the pig industry. An estimated 1.5 million chickens are raised for meat and eggs. Cattle are not as prominent; about 80,000 head is maintained on large holdings, with only 20% owned by villagers. According to the 2000 census, about 47% of total rural households are engaged in some kind of livestock production (Bourke, 2009).

Table 5.8. Pig Industry Characteristics

Type of Holding	Herd Size	Number of Herds	Estimated Number of Pigs	Trends	Breeds
Smallholder (Traditional)	1 – 20	360,000	1,800,000	Static; may be increasing with human population	Native
Smallholder (Penned)	1 – 3	2,000	4,000	Growing rapidly	Native
Smallholder (Commercial)	10 – 100	100	6,000	Growing steadily	Modern Commercial
Middle-Sized Commercial	100 – 500	4	2,000	Static	Modern Commercial
Large-Scale Commercial	> 500	7	20,000	Declining slowly	Modern Commercial

Although pigs are the most prominent domestic animal, all livestock should be considered. Overall estimates are provided in Table 5.9, where off-take refers to the number of animals in a herd that are

removed for sale or slaughter in a given time period, typically a year. It assumes the herd is not growing, so the off-take is equal to the potential increase over the period if all animals are kept. This is then expressed as a percentage of the base herd, not of the total herd.

Table 5.9. Estimated Livestock Numbers and Meat Production in 2005 (Bourke, 2009)

Livestock	Component	Number of Animals	Off-take (%)	Production (tons)
Pigs	Village Commercial	1,800,000 32,000	50 -	27,000 2,300
Cattle	Large-Scale Ranch Smallholder	63,500 16,500	15 15	1,900 500
Sheep	Smallholder	15,000	30	54
Goats	Smallholder	25,000	30	90
Chickens	Commercial broilers Broilers (live sales) Village	- - 1,500,000	- - -	17,000 17,000 1,850
Rabbits	Village	30,000	-	168

5.2.1 Initial Conditions and Assumptions for Papua New Guinea

Following the discussion of the important attributes of Papua New Guinea's geographical and agricultural profile, the next step is to make realistic assumptions and define initial conditions to model a solar-heated anaerobic digester in this specific context. The following assumptions were made:

1. The digester is located on a farm of a villager
2. The digester feedstock is a combination of predominantly animal waste, and minimal crop waste

Again, according to Table 5.1, at 30ºC, the minimum number of animals required to produce 2 m^3 of biogas daily varied by animal. For a farm in Papua New Guinea, this would require the waste from at least 6 pigs or 30 chickens. Although the crops in Papua New Guinea are grown directly for consumption, it is assumed that there is some crop waste each year, which enhances the performance of the digester by raising the C/N ratio and increasing the dry total solids content.

Assuming a 14 day HRT, a methane density of 1.14 kg/m^3, and that the biogas contain 65% methane, Table 5.10 shows the sequence of calculations used to optimize the size of the digester a farm would need to meet their daily biogas usage given these input values. Since the system has less overall waste, a

shorter retention time is required to meet the daily biogas needs of a family. However, this would require more frequent maintenance or multiple systems. Again, these predicted values were based on calculations from the McElvaney Associates Corporation (2010) model.

Table 5.10. Optimization of Digester Size and Methane Production Rate for Papua New Guinea

	Pig Manure	***Chicken Manure***	***Sweet Potato***	**Total**
Batch Size/System Volume				
Waste from animal or crop (kg)	13.6	1.2	1.6	
Dry material % of waste	9%	25%	74%	
TS in animal or crop waste (kg)	1.2	0.3	1.2	
TS % of batch	10%	10%	10%	
Batch size (kg)	12.2	3.0	12.1	**27.3**
Required system volume (m^3)	0.2	0.04	0.2	**0.4**
Organic Loading Rate				
TS in animal or crop waste (kg)				
VS % of TS	1.2	0.3	1.2	
VS in animal or crop waste (kg)	86%	75%	80%	
Organic loading rate (kgVS/m^3-	1.0	0.2	1.0	
day)	2.7	0.6	2.5	**5.9**
Methane Yield				
VS in animal or crop waste (kg)				
Digestion efficiency	1.0	0.2	1.0	
VS converted (kg)	45%	45%	82%	
Total gas (m^3)	0.5	0.1	0.8	
Total methane (m^3)	0.4	0.1	0.7	
VS in animal or crop waste (kg)	0.3	0.1	0.5	
Methane yield (m^3 CH_4/kg VS	1.0	0.2	1.0	
added)	0.3	0.3	0.5	**1.0**
Methane Production Rate				
Total methane (m^3 CH_4)	0.3	0.1	0.5	
Methane production rate (m^3/day)	0.7	0.1	1.2	**2.0**

The total weight of material for each feedstock component was calculated based on data from the Ohio State University Extension (2006), including amount of waste generated by pigs and chickens daily, the dry material percentage of the waste, and the amount of VS in the TS. For Papua New Guinea, the ratio of feedstock consists of waste from 4 pigs, 10 chickens, and 2 sweet potato plants, each with 5 roots, for a total of 10 roots. The amount of TS in the entire batch must be calculated from the total amount of waste produced from the animals and crops, minus the water weight. According to the Ohio State University Extension, pig manure has a moisture content of 91% and chicken manure has a moisture content of 75% (2006). The moisture content was 26% for sweet potato (Aggie Horticulture, 2012).

The TS is calculated by multiplying the dry material percentages by the total weight of the material. Again it was assumed that the TS % of the batch was 10% due to processing equipment limitations. The batch size includes all material, bacteria, and water. Considering all feedstock components, the overall OLR for the system in Papua New Guinea is approximately 5.9 kg/day, slightly higher than in the system from Mozambique. More maintenance is required since the system is much smaller. Again, the biodegradability of manure is only 45%, whereas the biodegradability of food or crop waste is 82% (El-Mashad, 2010).

In Papua New Guinea, there is a harvest period in May, and then a second one from June to August. A small amount of sweet potato waste was added to the feedstock mixture. A village yield of sweet potatoes can range anywhere from 2 to 50 tons/hectare annually, so for calculations, it was assumed to be 30 tons/hectare (Bourke, 2005). In 2000, about 47% of total rural households, each consisting of six people on average, were engaged in some kind livestock and crop production. These four harvest months cover 123 days out of the year, but because they are consecutive, it is assumed that the annual waste from the crops is input into the initial batch of the digester.

The calculations for Table 5.10 were based on this assumption. It should not significantly impact the result since little crop waste is available for the digester system. Based on these conditions the daily methane production rate is 2.0 m^3, which meets the 2 m^3 of methane required for cooking fuel for a family of 5 to 6 people. Based on these calculations, the total methane yield for the system is 1.0 m^3 per kilogram of VS added to the system. In order to generate 2.0 m^3 of methane every day, the volume of the digester must be about 0.38 m^3. This requires a batch size of approximately 27.3 kilograms.

Pig manure does not have as high a C/N ratio as cow manure, and because of this the system in Papua New Guinea must rely substantially on sweet potato roots. Since pigs are the most prevalent animals, it is assumed that more pig waste is used than chicken waste. The initial loading amount is 27.3 kilograms, as determined in Table 5.10. From these results, the waste type, C/N ratio, and the amount of waste produced daily from each source helped determine the overall C/N of the feedstock mixture, as shown in Table 5.11.

Table 5.11. Initial Inputs for Digester Feedstock in Papua New Guinea

Waste Type	Waste (kg)	Total Batch (kg)	Waste % of Total Batch	C/N Ratio	Waste % x C/N Ratio
Pig	12.2	27.3	0.4	18	8.1
Chicken	3.0	27.3	0.1	10	1.1
Sweet Potato	12.1	27.3	0.4	40	17.7
Total					**26.9**

*Numbers based on calculations from the Ohio State University Extension (2006)

With a feedstock waste mixture containing these three materials, the overall C/N is 26.9, which falls within the optimal range of 20-30 (FAO, 1997). Since sweet potato has a C/N ratio more than twice the ratio for pig waste, as much sweet potato waste should be added as possible to increase the total C/N ratio. However, if a village has more animals, and little crop waste, animal waste may also alleviate this problem. Papua New Guinea has a significant amount of rainfall; so water may be added to the digester to help process the material, without lowering the energy content. Based on the results provided in Table 5.1, it is assumed that the waste produced from each pig equates to that produced by 5 chickens. Again, the calculation results in Table 5.11 verify a realistic distribution of waste for initial modeling conditions.

The assumptions and calculations provided in this chapter are crucial to the modeling portion of this thesis. The average annual solar insolation, batch size, and OLR are all direct inputs for the computer-based system dynamics model. In addition, the calculations provide an accurate representation of an anaerobic digestion system, and a baseline to later compare modeling results to those found in literature. Overall, the results of these initial calculations are promising; they show that predictive optimization models are versatile. This will allow the digester to adapt to a multitude of farming community contexts.

6 DEVELOPING THE MODEL

The previous chapter outlined two geographical contexts, Mozambique and Papua New Guinea, and defined the initial conditions and assumptions for each location. Using this as groundwork, the aim of this chapter is to define boundary conditions, make assumptions for the computer-based system dynamics model initially described in Chapter 4, and perform trial runs of the model for both a week and a year. This will serve as proof of concept for model verification, and facilitate redefinition of the overall scope and purpose of the thesis.

The model pictorially displays the interactions between the stock variables (squares), flow variables (double lined arrows), and converters (single lined curved arrows). The clouds going into or out of flow variables represent stocks that are outside the system boundary. The converters help describe the flows, while the flows directly influence the stock variables. Multiple converters can be used to describe each flow variable. Many of the converters in the model are used to convert units, so that the flows and stocks are consistent with one another.

This system dynamics model, as shown in Figure 6.1, evolved from four stock variables for the anaerobic digester system: waste, gas, bacteria, and temperature regulation. Initial input values for stock variables, rates, and conversion factors were based on literature review of previous experimental results and additional research on existing renewable energy systems. Before delving into the analysis of the context-specific geographical locations, it is necessary to verify proof of concept; that the interactions between system components make sense with expected trends, and are consistent with those seen in previously published works in this area, with a preliminary single waste stream model. Since anaerobic digestion is a context specific process, it is important that the interactions are consistent and accurate such that the final model provides realistic results.

The following initial assumptions were made:

1. There are 100 kg of animal and crop waste in digester
2. There are 50 m^3 of methane-rich biogas in digester
3. Each colony of bacteria consumes one kilogram of waste
4. Temperature inside digester is 28°C initially before use of solar component
5. Monthly average insolation incident measured on horizontal surface

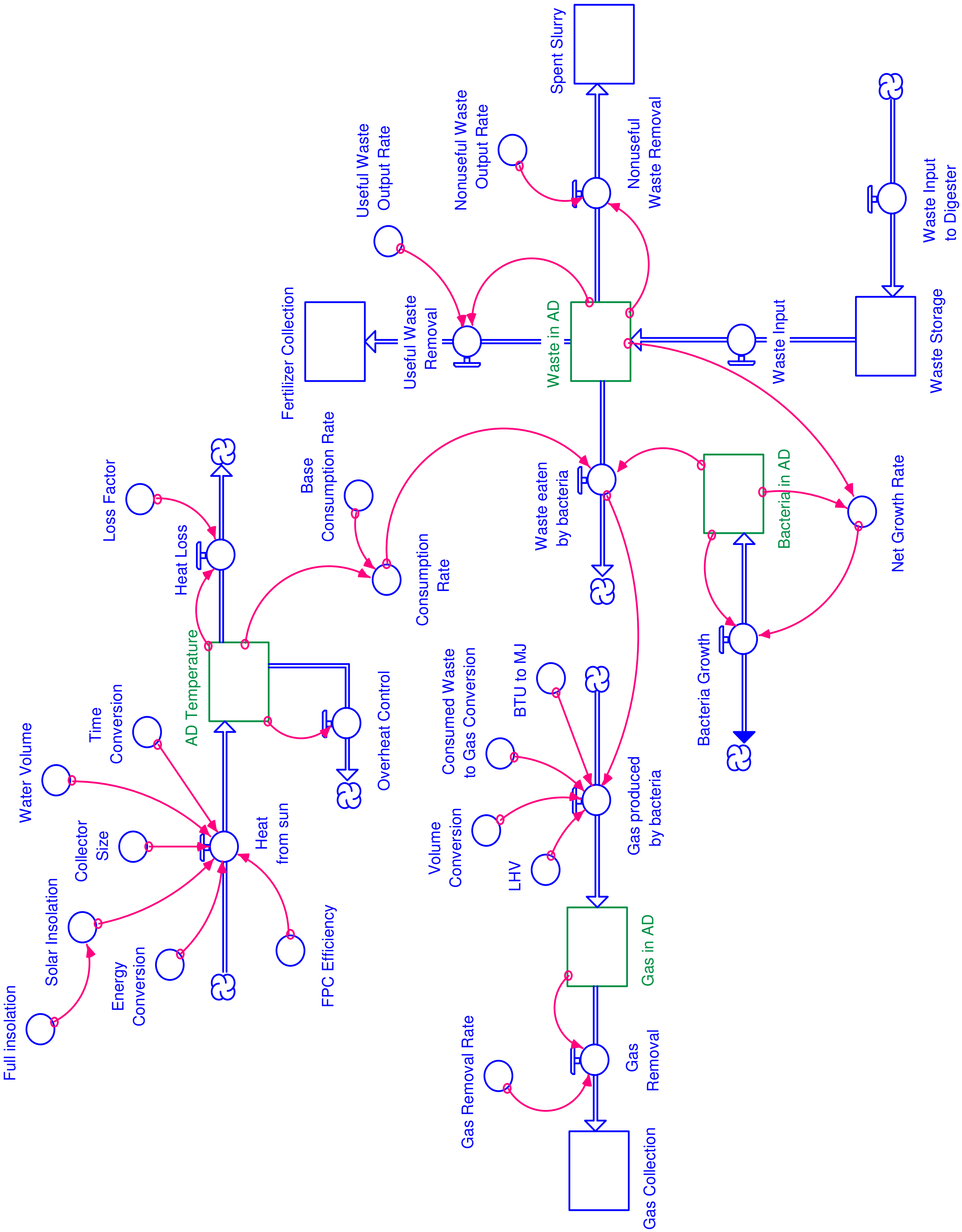


Figure 6.1. System dynamics model of anaerobic digester system generated by Stella

The model assumes that waste is previously collected, stored, and fed into the digester a set number of times during the course of a year, or 8,760 hours. The bacteria population is proportional to the amount of available waste, such that each colony of 100 bacteria consumes 1 kilogram of waste; the exact number of bacteria is not important, only the relative value with respect to available waste. Bacteria growth is dictated by the amount of bacteria present in the digester multiplied by a net growth rate. This rate is both positive and negative; it adjusts based on the ratio of bacteria to available waste. Therefore, if the bacteria population is higher than the amount of waste, the growth rate is negative, and if the population is lower than the amount of waste, the growth rate is positive. This rate captures the importance of space and nourishment for bacteria survival.

Tables 6.1 – 6.3 lists all of the variables in the system, as shown in Figure 6.1. The tables are split between stock variables, flow variables, and converters. Stock variables must have finite values and represent initial conditions, whereas flows and converters are defined mathematically. There are 37 total variables for the model, including 8 stocks, 11 flows, and 18 converters.

Table 6.1. Stock variable definitions

VARIABLE	DEFINITION	UNIT
AD Temperature	28	º C
Waste Storage	100	kg
Waste in AD	254.5 (Mozambique) 27.3 (Papua New Guinea)	kg
Fertilizer Collection	50	kg
Spent Slurry	0	kg
Bacteria in AD	254.5 (Mozambique) 27.3 (Papua New Guinea)	colonies
Gas in AD	50	m^3
Gas Collection	0	m^3

Table 6.2. Flow variable definitions

VARIABLE	DEFINITION	UNIT
Waste Input to Digester	10	kilograms
Waste Input	10	kg/hr
Heat from the Sun	(Solar_Insolation*Collector__Size*Time__Conversion*FPC_Efficiency) / (Energy__Conversion*Water_Volume)	
Heat Loss	Loss_Factor*AD_Temperature	
Overheat Control	IF(AD_Temperature>38)THEN(AD_Temperature-38)ELSE(0)	
Useful Waste Removal	IF(Waste_in_AD>5)THEN(Waste_in_AD*Useful_Waste__Output_Rate)ELSE(0)	
Non-useful Waste Removal	IF(Waste_in_AD>5)THEN(Waste_in_AD*Nonuseful_Waste__Output_Rate)ELSE(0)	
Waste Eaten by Bacteria	Bacteria_in_AD*Consumption__Rate	
Bacteria Growth	Bacteria_in_AD*Net_Growth_Rate	
Gas Produced by Bacteria	(Waste_eaten__by_bacteria*Volume__Conversion*LHV*BTU_to_MJ) / Consumed_Waste__to_Gas_Conversion	
Gas Removal	Gas_in_AD*Gas_Removal_Rate	

Table 6.3. Converter variable definitions

VARIABLE	DEFINITION	UNITS	COMMENT
Full Insolation	5.7 (Mozambique) 5.438 (Papua New Guinea)	kWh/m^2/day	Refer to Chapter 5
Collector Size	4.76	m^2	Adapted from Silicon Solar (2010)
Energy Conversion	4.184	cal → J	-
Flat Plate Collector (FPC) Efficiency	0.658	-	Adapted from Silicon Solar (2010)
Water Volume	4353.2	1000 g → 1 L	Adapted from Silicon Solar (2010)
Time Conversion	3600	s → d	-
Loss Factor	0.005	%	Adapted from Axapoulos (2000)
Base Consumption Rate	0.2	kg/hr	
Useful Waste Output Rate	0.01	kg/hr	Adapted from El-Mashad (2010)
Non-useful Waste Output Rate	0.01	kg/hr	Adapted from El-Mashad (2010)
Consumed Waste to Gas Conversion	0.714	kg/m^3	-
Volume Conversion	35.315	m^3 → ft^3	-
BTU to MJ	0.001055056	BTU → MJ	-
Low Heating Value (LHV)	983	BTU/ft^3	Adapted from Silicon Solar (2010)
Gas Removal Rate	0.1	m^3/hr	Adapted from Axapoulos (2000)
Solar Insolation	Full_insolation - Full_insolation*sin((PI/12)*(TIME-6)) + sin((PI/4380)*TIME)		
Consumption Rate	IF(AD_Temperature<25)THEN(0) ELSE(IF(AD_Temperature>40)THEN(0) ELSE(Base__Consumption_Rate)		
Net Growth Rate	0.2*(1 – (Bacteria in AD/Waste in AD))		

As shown in the comments column, several of the converter definitions were calculated based on literature results. These values were then adapted to fit this specific system based on initial conditions.

6.1 Weekly Trial Run Results

The following figures show results for the interactions of selected variables within the model, and how the solar component directly impacts gas production. Although the model will ultimately be concerned with anaerobic digester function and gas production for the entire year, it is important to see what is happening on a smaller scale; how the system behaves over the course of a week, or 168 hours. This will serve as verification of the system's reproducibility, and therefore increase its dependability as a prediction tool.

As shown in Figure 6.2, all four subsystems are sinusoidal. As the waste in the digester increases, the amount of bacteria in the digester increases. The gas follows this trend, but lags waste and bacteria slightly. Gas is produced as a result of waste consumption by the bacteria. When waste is no longer available, the system must be restocked. Waste that is not consumed and remains nutrient rich is removed as fertilizer; spent slurry is removed separately. A buildup of non-useful waste will eradicate the bacteria population, and subsequently decrease gas production.

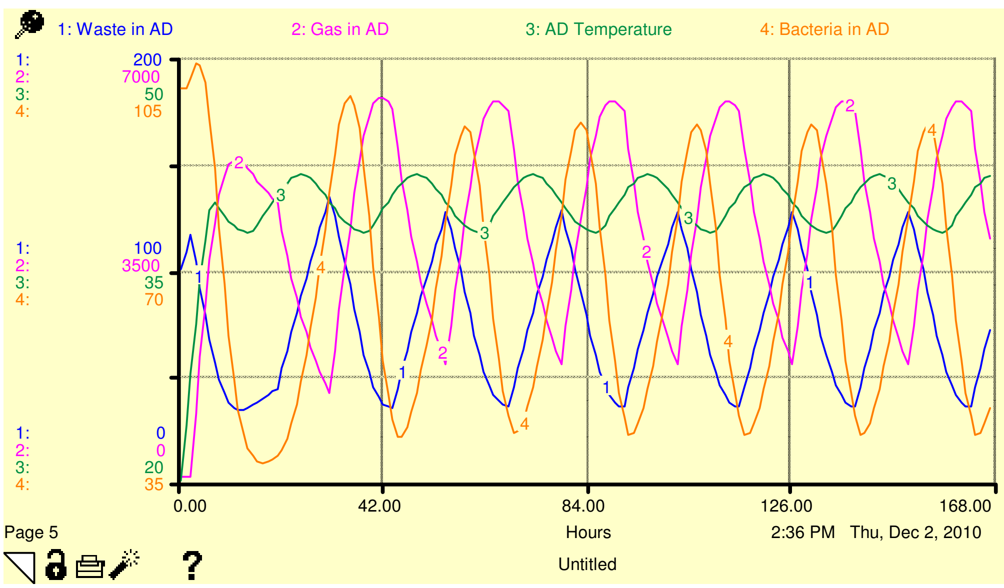


Figure 6.2. Weekly trends of four subsystems of anaerobic digester system

Temperature regulation is another crucial component to optimal bacteria activity. Based on the graph, the maximum bacteria population occurs when the temperature is approximately 38°C, at the high end of the mesophilic range. This temperature coincides with results found in literature for optimal digester performance. When the temperature reaches its maximum value, the bacteria population is low, only about half that at the optimal temperature. Since gas produced follows bacteria activity, when the temperature is at its maximum, the amount of gas in the digester is approximately 80% of that when temperature is optimal.

Figure 6.3 focuses on the solar component and its impact on the temperature within the digester. Again, the trends are sinusoidal, with the AD temperature, heat from the sun, and solar insolation almost perfectly in sync. Solar insolation data is based on temperatures for Rochester, NY. As defined previously in Table 6.2, the heat of the sun variable is influenced by solar insolation, and several constants: size, efficiency, and amount of water used by the collector. The peak temperature lags the peak solar insolation and heat from the sun minimally. The results are consistent with the expected results; more sun exposure produces more heat, and raises the temperature inside the digester.

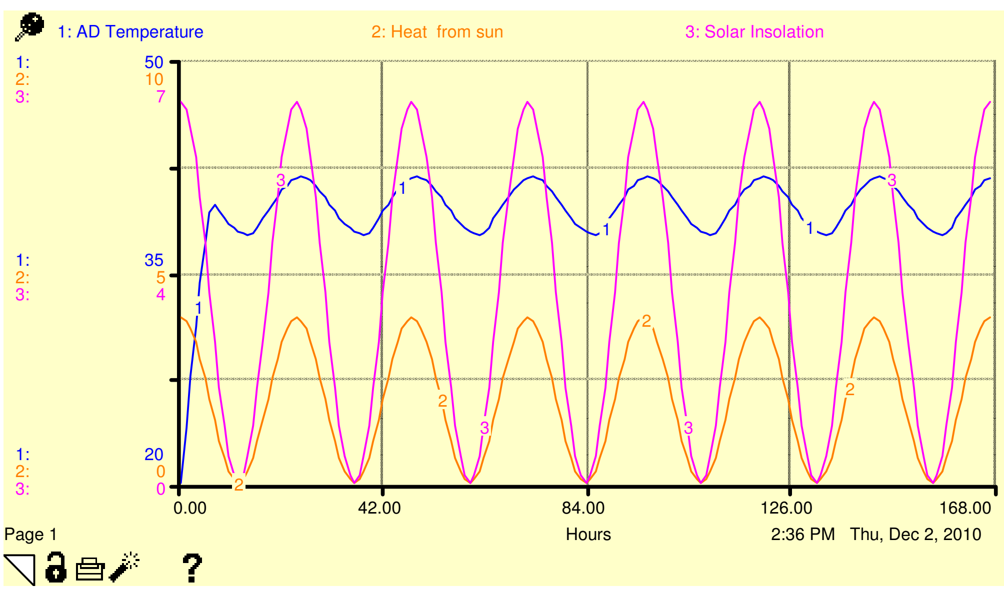


Figure 6.3. Weekly trends of solar component and AD temperature

Figure 6.4 shows the relationship between bacteria activity and gas production and storage. As defined in Table 6.2, the amount of gas produced by bacteria depends of the amount of waste eaten multiplied by the low heating value of methane at standard temperature and pressure, a conversion from BTUs to megajoules, and a volume conversion from cubic feet to cubic meters. This is then divided by the relative molar mass of methane. Depending of the digestive process, the methane content is generally between

55% and 80% (Jemmitt, 2006), so the model assumes that the gas produced is solely methane. In this equation, all variables are constants except for the amount of waste eaten by the bacteria. Therefore, these variables should be consistently in sync. When the waste eaten and gas produced reach maximum values, the amount of gas in the digester is about halfway to its maximum. The gas in the digester lags slightly because the biological process of waste consumption to gas produced takes time. When there is no more waste available, no more gas is produced, and all gas from the previous bacteria activity is in the digester. This gas is then removed at a linear rate.

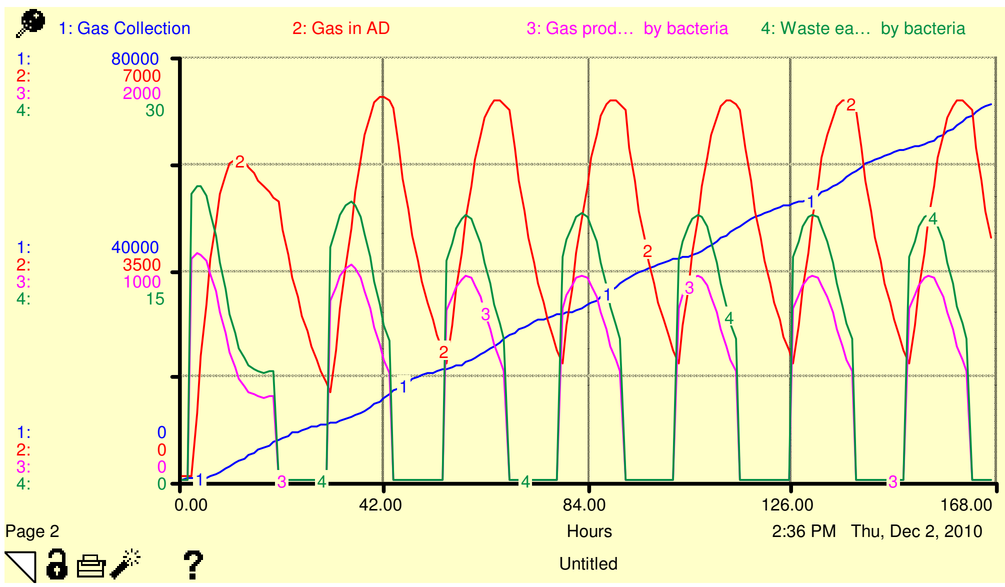


Figure 6.4. Weekly interaction between gas and bacteria population

Figure 6.5 shows the interaction between the size of the bacteria population, the amount of waste eaten by this population, and the rate at which the waste is consumed. The consumption rate is dependent on temperature, and is confined by a predetermined mesophilic temperature range between 25°C and 40°C. The boxed sinusoidal trend of the consumption rate shows that the bacteria population and amount of waste eaten by these bacteria are at a maximum when the temperature is approximately 38°C, as discussed in Figure 6.2.

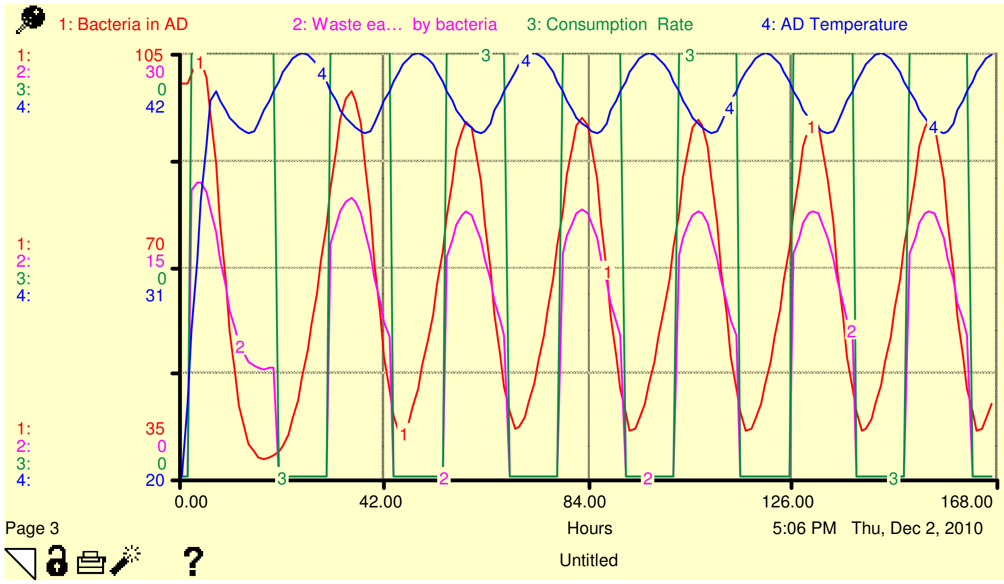


Figure 6.5. Weekly interaction between waste, bacteria, consumption rate, and temperature

Although these results provide a proof of concept of the proposed system, real system operation is contextually dependent on geographic location. Therefore, the inputs will later be altered to match the calculations and assumptions for Mozambique and Papua New Guinea. As stated in Chapter 4, the aim of this thesis can be divided into three areas: exploring how the addition of a solar component increases the robustness of the design, examining predicted biogas generation as a function of varying input conditions, and determining how best to configure such systems for use in varying developing world environments.

6.2 Annual Trial Run Results

In order to demonstrate proof of concept and confirm that all interactions of the model are communicating properly, the simulation was run with these initial assumptions and constraints. The simulation targeted the following areas inside the anaerobic digester:

1. Temperature regulation
2. Amount of waste
3. Bacteria population
4. Bacteria growth and death trends
5. Amount of gas

6.2.1 Temperature Regulation

As discussed in Chapter 2, the ideal conditions for bacteria activity and growth, and subsequent biogas production, fall within the upper mesophilic and lower thermophilic temperature range, between 36°C and 45°C. Following the trial simulation, hourly data points for temperature inside the digester were organized into bins, from the minimum startup temperature to the maximum temperature recorded during the year, and distributed in a histogram. As shown in Figure 6.6, the model heat loss control is working properly to maintain temperatures within the desired range, even with seasonal isolation variation.

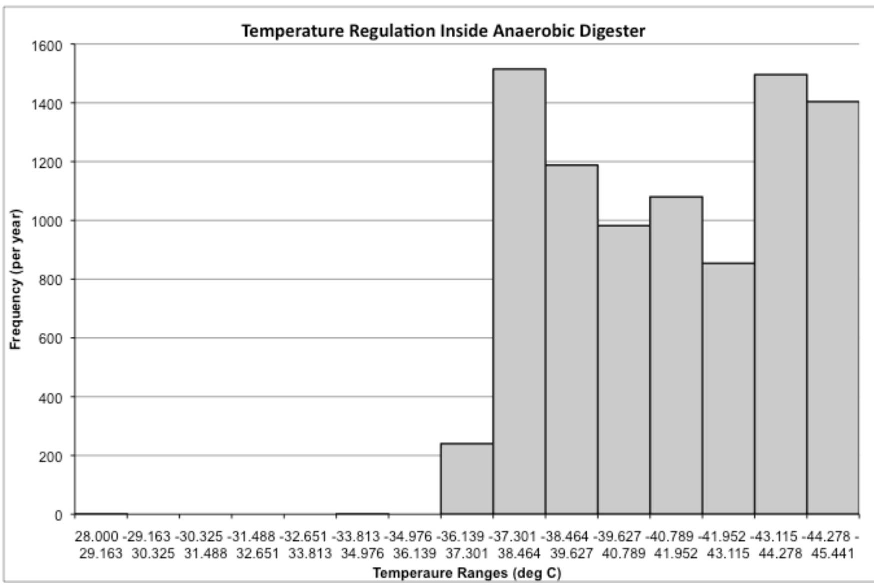


Figure 6.6. Histogram of temperature regulation inside digester for trial run

With the exception of the initial startup temperature, and one outlying point, data points fall within a temperature range of 37.301°C and 45.441°C, with a mean temperature of 41.279°C. The two ranges with the most frequently repeated temperatures were 37.301°C to 38.464°C and 43.115°C to 44.278°C. Therefore, it can be assumed that these two windows include the optimal temperatures for digester operation.

6.2.2 Amount of Waste

Assuming the system begins on the vernal equinox, annually at the end of March, and continues for 8,760 hours for the entire year, the amount of waste inside the digester should fluctuate with the seasons. This is because more feed material will be available during certain months than others. This sinusoidal wave can

be seen in Figure 6.7.

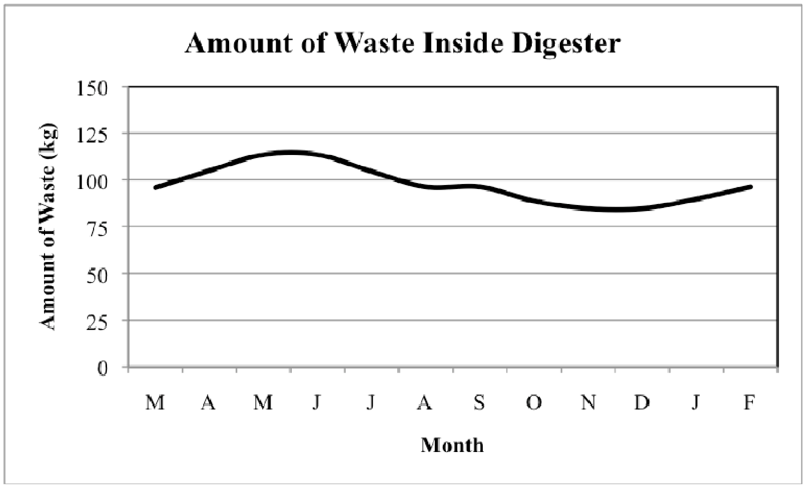


Figure 6.7. Amount of waste inside digester for trial run

As shown, there is the most waste in the digester during the months of May and June, and the least inside the digester during November and December. The placement of the sinusoidal wave will alter according to the agricultural harvesting seasons for each geographical context, but still retain the same general shape. As shown, the months of March, August, September, and February have similar amounts of waste, which demonstrates that this system is in fact cyclical in nature, and therefore, can be used as an accurate prediction tool for gas output. Farmers will be able to estimate the amount of methane produced each month based on the amount of waste input into the digester, without deviating from their regular agricultural practices.

6.2.3 Bacteria Population

Bacteria population is directly influenced by the amount of waste in the digester, the net growth rate of the colonies, and the amount of waste eaten. Therefore, given the curve for the amount of waste present in the digester, the bacteria population should mimic it precisely. Figure 6.8 shows the bacteria population inside the anaerobic digester over the course of a year.

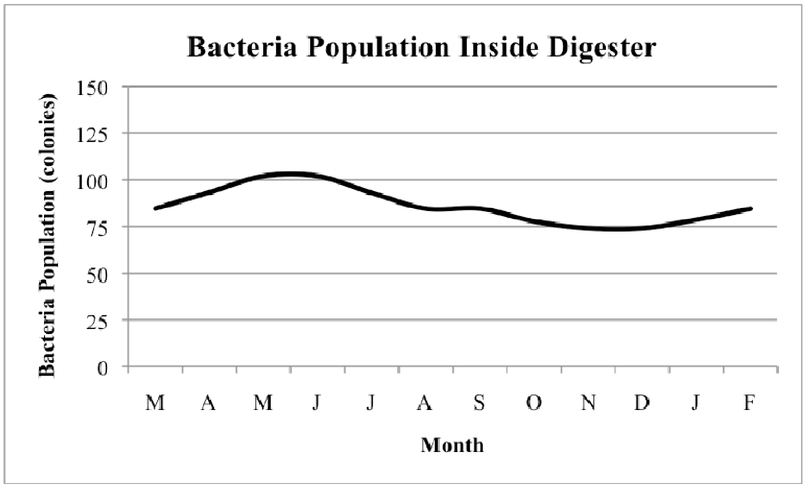


Figure 6.8. Bacteria population inside digester for trial run

As shown, the bacteria population curve does mimic that of the amount of waste present in the digester. This verifies the accuracy of the bacteria activity, to consume the available waste, as well as the relationship between the growth rate of the bacteria population and the inflow and outflow of waste to the system.

6.2.4 Bacteria Growth and Death Trends

Bacteria, as living organisms, need a stable environment in which to thrive. The growth and reduction of the population varies as a result of several chemical and physical factors such as temperature and pH regulation, availability of food, nutrients, and water, and prevention of toxins. All of these factors play a critical role in the productivity of the bacteria. Like any population, there is a saturation point for which the bacteria inside the system thrive. When more waste is available for consumption, the population increases. However, once the population reaches the point where the bacteria must compete for food, the population decreases. This check of natural selection keeps the entire system in equilibrium, and allows for a reliable source of methane production. Although the loading rates, mixing techniques, and retention times vary by system and context, the population of the bacteria will follow similar trends as long as the basic ideal environmental conditions exist. Figure 6.9 shows the growth and death trend of the bacteria population over the course of a year.

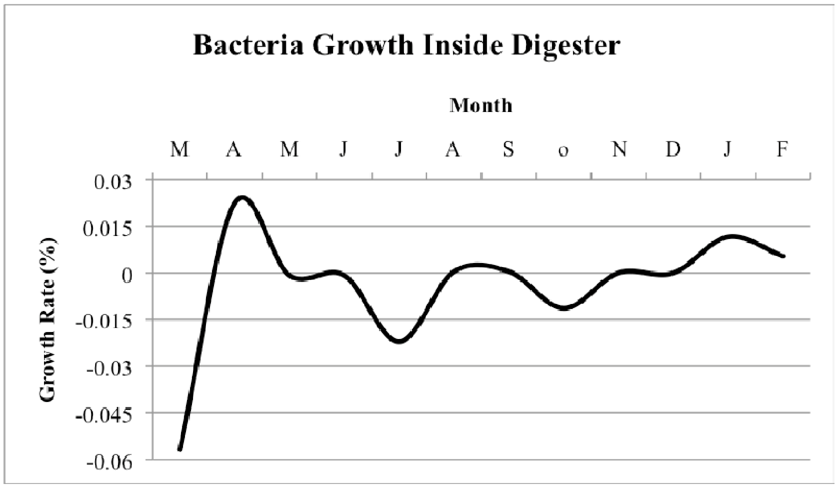


Figure 6.9. Bacteria growth and death trends inside digester for trial run

This graph is a good representation of ecological population behavior, which is concerned with the changes in population size and age distribution within a population as a consequence of interactions of organisms with the physical and chemical environments in which they exist, with individuals of their own species, and with organisms of other species. Although these trends are greatly stochastic and may seem chaotic at first glance, patterns are recognizable upon further analysis.

Upon initiation of the system, the population rises steadily, as shown in the month of March. But then in April, this population reaches a saturation point as the amount of available waste for consumption decreases. Even though the most nutrient-rich waste exists in the system between April and July, the bacteria population must find equilibrium. There is a decrease in overall population from April to May, until the waste in the system reaches a maximum, and the population stabilizes, and slightly increases temporarily. Once the influx of waste is consumed, the population decreases again from June to July, until it reaches a minimum for the system activity, and starts to grow from July to August. This growth and death trend continues over the course of the year, but as seen in the graph, the severity of the changes in population diminish over time, as the system finds a healthy and productive equilibrium. From October through February, the fluctuations in population growth and death are minimal in comparison to that at the system's inception.

6.2.5 Amount of Gas

As described previously, there is a significant amount of biological and chemical activity inside the digester. The waste added to the system is consumed by the bacteria population. Methane is produced as a

result of this consumption. Figure 6.10 shows the cyclic nature of the amount of gas inside the digester over the course of a year.

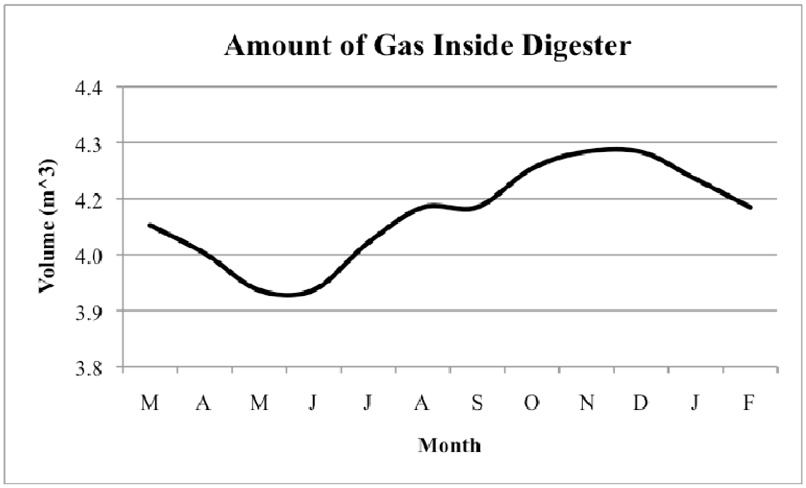


Figure 6.10. Amount of gas inside digester for trial run

As shown in the figure, the most amount of gas resides in the digester during the months with the least agricultural activity. The sinusoidal curve of the amount of gas opposes that for the amount of waste inside the digester. This reflects the activity of the bacteria population, because as the waste is consumed, gas is produced. Because the most waste is fed into the system between April and July, there is a slight lag in the gas production, giving the bacteria time to reproduce, and consume the food available. Therefore, the greatest volume of gas exists between the months of October and January.

7 MODEL ANALYSIS

Model development provides a base structure on which further analysis can build. Verification of proof of concept allows for the crucial next step: validation of the model. Once the model is reproducible, it needs to be flexed such that it behaves consistently; the overall structure should remain constant, both numerical and conceptual dimensions should be consistent, the system should respond appropriately when exposed to extreme conditions, and overall sensitivity analysis should yield realistic and useful results, that can be used to make future predictions in any context in which the system exists. These validation points were more thoroughly defined in Chapter 4.

Chapter 6 defined boundary conditions and performed trial runs of the model for both a week and a year. These tests confirm the structure assessment and dimensional consistency of the system dynamics model, the first steps in overall model validation. As mentioned in Chapter 4, models should be robust in extreme conditions. The following chapter analyzes the extreme conditions outlined previously for Mozambique and Papua New Guinea, given the initial conditions and environmental factors defined for each geographic location.

7.1 Mozambique Analysis

As defined in Chapter 5, for this context, it is assumed that the digester is located on a farm within the small holding category, the digester feedstock is a combination of animal and crop waste, and the crop waste calculations were based off of other uses and losses utilization, and will not displace animal feed. The initial amount of waste inside the digester is 254.5 kilograms. The average annual solar insolation is 5.7kWh/m^2/day.

7.1.1 Waste Input Ceases

The first extreme condition explores the cessation of waste input to the system. Although predictable, this verifies the reliability of the model to function as it would in a real context. Figure 7.1 compares the amount of waste input over time.

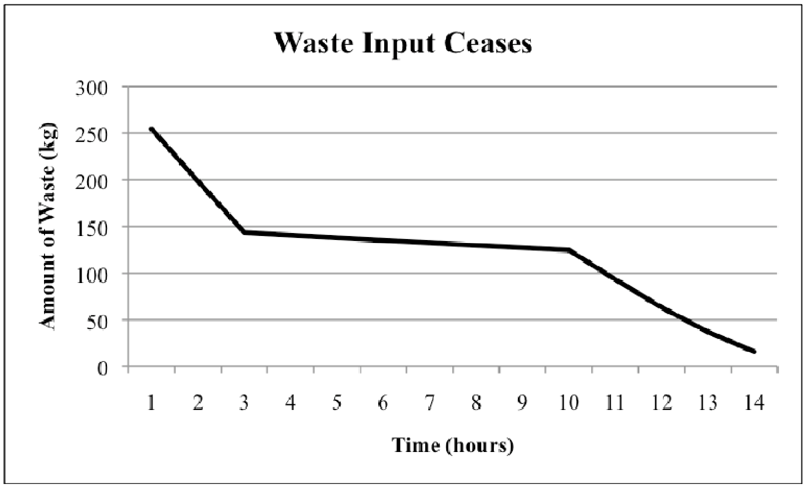


Figure 7.1. Impact of waste input cessation on digester

As shown, the model only runs for 14 hours before the waste inside the digester depletes completely. When the input stops, the model in Stella outputs an error message, as shown in Figure 7.2.

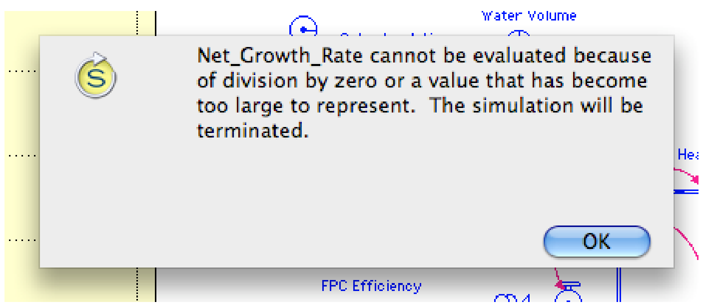


Figure 7.2. Error message generated by Stella upon waste input cessation

It explains that the net growth rate cannot be evaluated once waste input stops, because it cannot be divided by zero. The net growth rate is defined as: 0.2*(1-Bacteria_in_AD/Waste_in_AD), with the multiplying factor of 0.2 based on published experimental. Therefore, as the denominator goes to zero, the fraction becomes undefined. This makes sense, that if the system has no fuel, it cannot operate.

7.1.2 Initial Waste Amount Doubles, Triples, in Same Time Interval

The baseline model for Mozambique assumes the initial waste inside the digester to be 254.5 kilograms, with each kilogram of waste tied to one colony of 100 bacteria. In order to investigate the impact of this amount of waste on both bacteria population and gas produced, the waste was doubled, and then tripled. It is assumed that the base loading rate of 5.9 kg/day is constant.

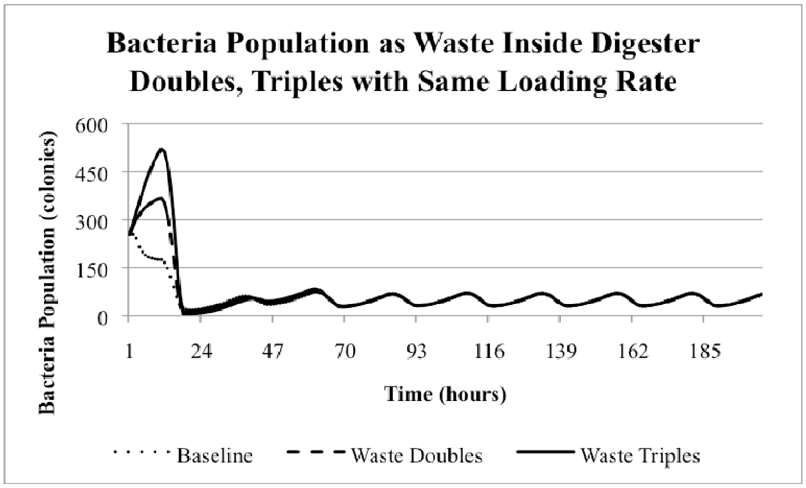


Figure 7.3. Effect of doubling, tripling waste inside digester on bacteria population

The first test analyzed the impact of doubling and tripling the initial amount of waste inside the digester on the overall bacteria population, as shown in Figure 7.3. There is only a brief period within the first day where there is a difference in bacteria population, as compared to the baseline. After this point, all three lines follow the same trend, as the system regains equilibrium. After 204 hours, or 8.5 days, all lines converge.

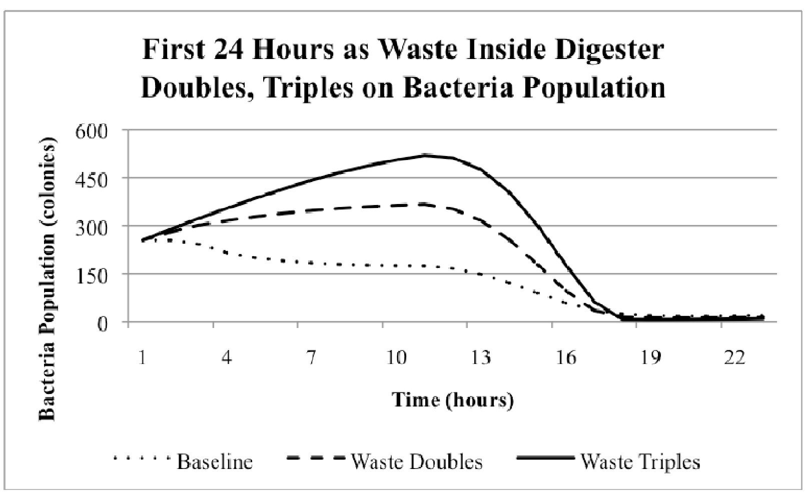


Figure 7.4. Effect of doubling, tripling waste inside digester within first 24 hours on bacteria population

Figure 7.4 provides a closer look at the first 24 hours as the waste inside the digester is doubled and tripled. As shown, in the baseline run, the waste decreases from the initial 254.5 kilograms steadily for the first 17 hours. At this point, the bacteria population reaches a minimum until the system is loaded with more waste. When the initial amount of waste in the digester doubles and triples, this trend changes slightly.

When the waste doubles, the ratio of waste available to bacteria population is 2:1, with about 437 kilograms inside the digester. As shown by the dashed line, the bacteria population increases slightly for the first 12 hours, from the initial 254.5 colonies to about 367 colonies. At 13 hours, the population starts to die off at a fast rate, until minimizing around 18 hours.

When the waste triples, the ratio of waste available to bacteria population is 3:1, with about 655.5 kilograms inside the digester. As shown by the solid line, the bacteria population increases steadily for the first 12 hours, from the initial 254.5 colonies to about 520 colonies. At 13 hours, the population starts to die off again, at an even faster rate than when the waste was doubled, until minimizing around 18 hours.

When the waste doubles, the bacteria population grows by about 44% and when the waste triples, the bacteria population grows by about 104% within the first 12 hours. During baseline conditions, the bacteria population at 12 hours is about 69% of its original amount. Therefore, the initial amount of waste in the digester proportionally increases bacteria population in order to consume the excess waste.

The surge of population increase only occurs within the first 12 hours, as indicated by Figure 7.3. After the first 8.5 days, the system reaches equilibrium and balances bacteria population with available waste.

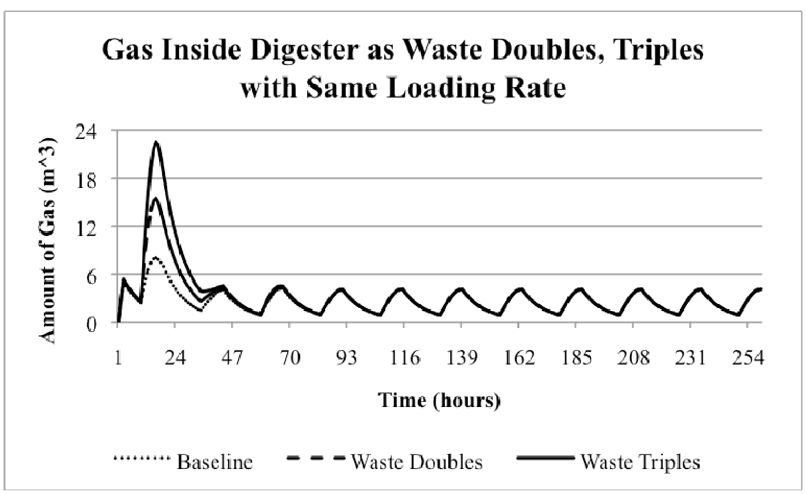


Figure 7.5. Effect of doubling, tripling waste inside digester on gas produced

The second test analyzed the impact of doubling and tripling the initial amount of waste inside the digester on the amount of gas produced, as shown in Figure 7.5. All three curves peak around 18 hours, and then follow the same trend, as the system reaches equilibrium. After 260 hours, or about 10.8 days, all lines converge.

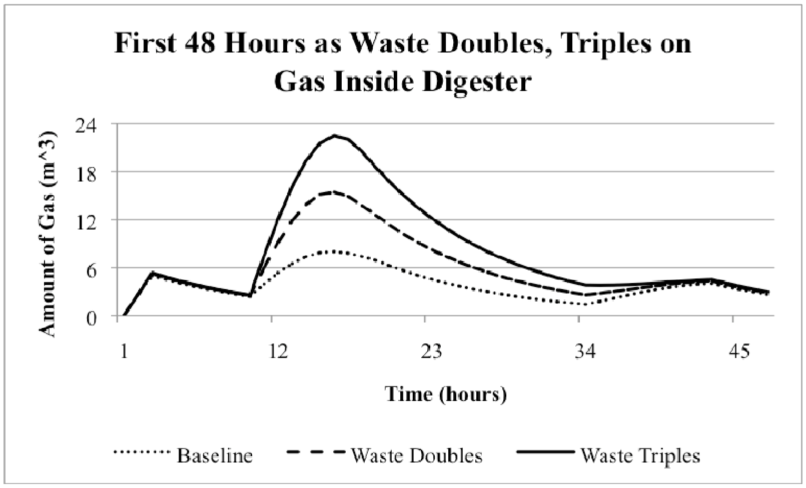


Figure 7.6. Effect of doubling, tripling waste inside digester within first 48 hours on gas production

Figure 7.6 provides a closer look at the first 48 hours as the waste inside the digester is doubled and tripled. All curves follow the same trend for the first 11 hours, and then split, and reconverge around 44 hours. All lines reach a minimum at about 35 hours of system operation. As shown, in the baseline run, the amount of gas produced inceases slightly from 11 hours to 17 hours, reaching a maximum of about 8 m^3. After this point, the bacteria population starts to die off and less gas is produced. When the initial amount of waste in the digester doubles and triples, the surge of gas production increases accordingly.

When the waste doubles, the amount of gas produced at its maximum approximately doubles as well, increasing to about 16 m^3. When the waste triples, the amount of gas produced at its maximum approximately triples, increasing to about 23 m^3. This makes sense because as more waste is available, the bacteria population increases proportionally, and produces gas accordingly. These results show that the model can be used to predict and control approximate biogas yield.

7.1.3 Severe Weather Patterns which Erratically Affect Solar Insolation

As discussed in Chapter 5, Mozambique has a wet season during the summer, between October and March and a dry season from April to September, with minimal temperature variation between seasons. The wet season brings the heaviest rain along the coast, along with cyclones and flooding. The level of vulnerability is aggravated due to its geographic location, limited resources to accurately forecast extreme weather, and a reduced capacity to adapt to natural disasters that strike.

The majority of cyclones hit between December and March. Besides damage from the storms themselves, cyclones result in severe flash flooding that directly impacts the food supply, as well as increases

susceptibility of disease. For example, the extended wet season brings high rates of malaria infections cholera outbreaks (Queface, 2004).

In order to capture the effect of an extreme weather pattern, the original curve controlling the system dynamics model was altered. Equation 7.1 represents the baseline for all analyses:

Equation 7.1. Baseline system operation equation

$$\text{Solar\_Insolation} = \text{Full\_insolation} - \text{Full\_insolation}((\sin((\frac{\pi}{12})(\text{TIME}-6)) + \sin((\frac{\pi}{4380})(\text{TIME})))$$

Where Full_insolation represents the average annual solar insolation for Mozambique, and TIME represents the period of time the model accounts for, in this case, 8,760 hours for one year. The equation assumes a sinusoidal curve to account for the seasons.

In order to account for the cyclones, which occur between December and March, this curve was shifted to delay the temperature pattern, as defined in Equation 7.2:

Equation 7.2. Extreme cyclones system operation equation

$$\text{Solar\_Insolation} = \text{Full\_insolation} - \text{Full\_insolation}((-\cos((\frac{\pi}{12})(\text{TIME}-6)) - \cos((\frac{\pi}{4380})(\text{TIME})))$$

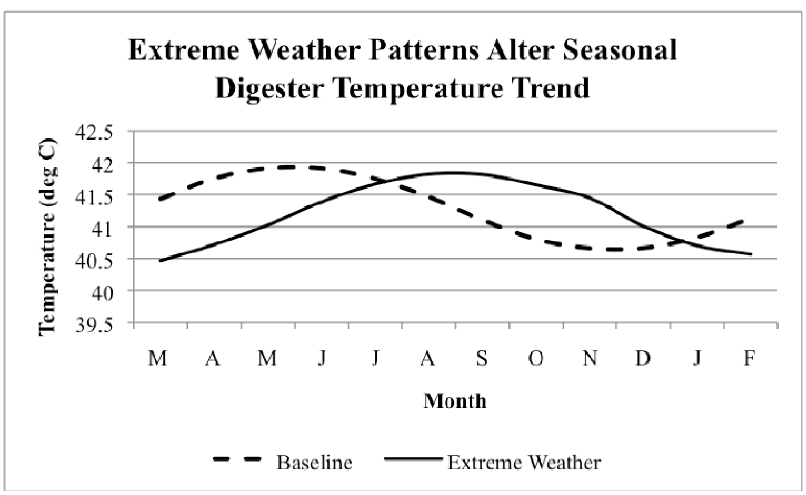


Figure 7.7. Effect of extreme weather on seasonal digester temperature trend

Figure 7.7 shows the impact of extreme weather, specifically tropical cyclones and flooding, has on the temperature inside the anaerobic digester. Average temperatures were taken monthly over the course of the year, and compared to the baseline conditions. As shown, when extreme weather occurs, the optimal operating temperature range shifts from November through January to February through April. The model assumes that the extreme weather delays the operation of the system, however, realistically it is likely that the system may be destroyed completely depending on the severity of flooding on the farm. In many cases, farmers are forced to leave their homes if they live near rivers or bodies of water.

From a functionality point of view, it is also important to look at how extreme weather affects the amount of gas produced, assuming the system operation is delayed and not stopped. Figure 7.8 shows how the gas production trend changes when severe weather occurs.

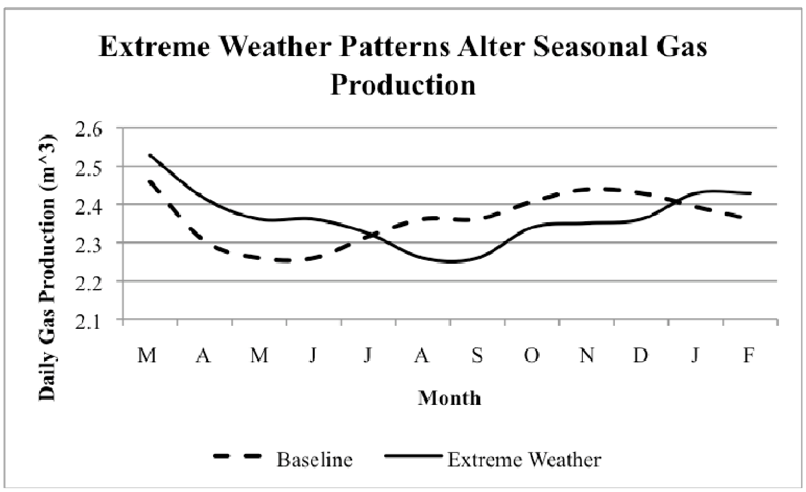


Figure 7.8. Effect of extreme weather patterns on gas production

Averaging the amount produced by month, it is evident that extreme weather severely effects gas production. Despite the shift in maximum production time, the curves are no longer the same. With the baseline conditions, the gas production follows a trend shifting with the seasons. With the extreme weather conditions, the curve assumes a concave parabolic shape, reaching a minimum between August and September. Although maximum gas production still occurs between February and April, the trend is not as predictable throughout the course of the year.

On the other hand, the maximum amount of gas produced under extreme conditions is about 2.46 m^3, whereas for the baseline conditions it only reaches about 2.53 m^3. Therefore, over the course of the entire year, the extreme conditions increase total gas production by about 0.07 m^3. Although not altered in the model, realistically this could be attributed to a higher water content of the waste input into the system,

along with a smaller temperature range window during operation. Due to the factors listed above, extreme weather will always be a factor. Therefore, these results show that despite the shift in operation temperature, slightly more gas is produced under realistic weather patterns.

7.1.4 No Solar Component

One of the aims of the thesis is to show that the addition of a solar component to the system design increases bacteria activity, and subsequent gas production. Therefore, this extreme condition flexes the model such that the solar collector is removed, and the temperature fluctuation is completely dependent on the biological processes of the bacteria population. Bacteria generate a small amount of heat as they consume the waste. However, this heat fluctuates with the growth and death of the population. Figure 7.9 shows the alterations to the temperature control portion of the system dynamics model.

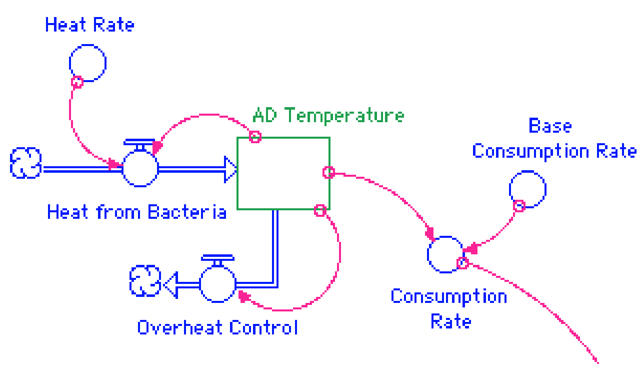


Figure 7.9. Model alterations for no solar component trial

Heat rate, the new converter variable, equals 0.005 based on previous literature findings for methanogenic bacteria activity. Heat from bacteria, the new flow variable = AD_Temperature*Heat_Rate, where the initial temperature inside the digester is 28°C. The base consumption rate remains 0.2. Table 7.1 shows the alterations for previously defined variables overheat control and consumption rate:

Table 7.1. Altered Stella model for no solar collector

VARIABLE	DEFINITION
Overheat Control (Original)	IF(AD_Temperature>38)THEN(AD_Temperature-38)ELSE(0)
Overheat Control (New)	IF(AD_Temperature>40)THEN(AD_Temperature-32)ELSE(0)
Consumption Rate (Original)	IF(AD_Temperature<25)THEN(0) ELSE(IF(AD_Temperature>40)THEN(0) ELSE(Base__Consumption_Rate)
Consumption Rate (New)	IF(AD_Temperature<27)THEN(0) ELSE(IF(AD_Temperature>35)THEN(0) ELSE(Base__Consumption_Rate)

The range of overheat control and consumption rate were tightened since the temperature fluctuation range is much smaller without solar insolation and seasonal influence. It is important that the temperature be kept directly within the optimal mesophilic range over the course of annual operation to maximize gas production from natural bacteria activity.

Based on these changes, it was important to see how much an influence the solar collector has on gas production. Figure 7.10 shows the trends for annual gas production for both conditions.

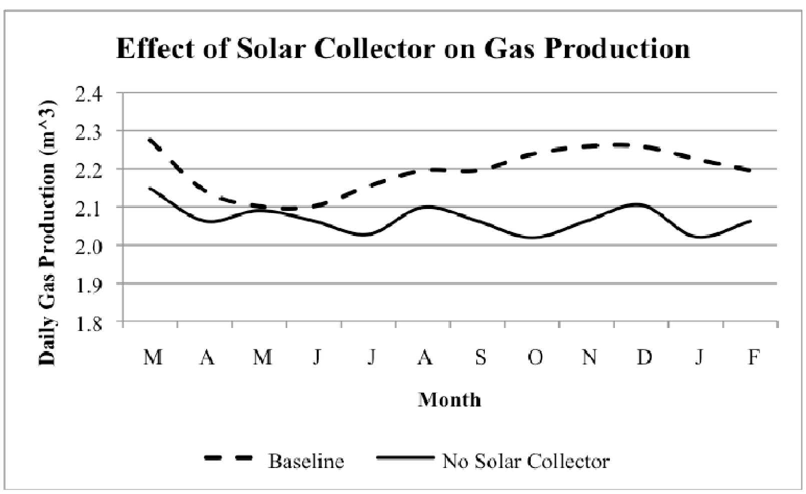


Figure 7.10. Effect of adding a solar component on system gas production

Two conclusions are evident from the results; first, the noticeable difference in trends of the two curves, and second, the amount of gas production for the baseline conditions far exceeds that of the system with no solar collector. The baseline curve follows a seasonal trend, with maximum gas production between November and February. The gas output in the system with no solar collector fluctuates more frequently,

but the range is limited between 3.8 and 4.0 m^3 for the year. In fact, the maximum average monthly amount of gas produced with no solar collector is about 4.067 m^3 in May, and the minimum average monthly amount of gas produced in under baseline conditions is about 3.965 m^3 in May. Therefore, there is only a difference of about 0.1 m^3 between the maximum of one curve and the minimum of the other, concluding that the solar component significantly increases overall gas production.

7.1.5 No Overheat Control

The current model utilizes an overheat control function to maintain the internal digester temperature within the optimal mesophilic range, and slightly into the thermophilic range. If this function is removed, there exist detrimental consequences to multiple components of the overall system. Figure 7.11 shows the general trend of the system without overheat control over the course of a year.

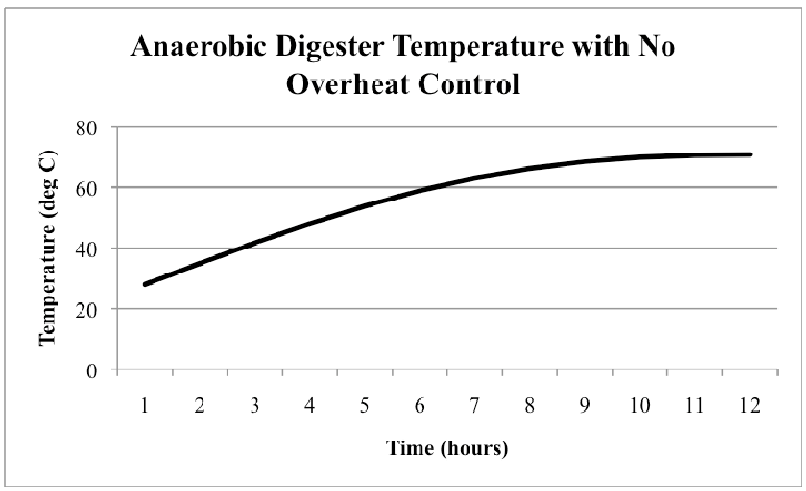


Figure 7.11. Anaerobic digester temperature with no overheat control

It takes only about 3 hours for the temperature to exceed the mesophilic range, to about 40°C, and about 6.5 hours to exceed the thermophilic range, above 60°C. The graph only shows the first 12 hours of operation, because beyond this point, all bacteria activity ceases. Even though some strains of methanogenic bacteria can survive in conditions up to 100°C, they will no longer be able to consume waste and produce gas for the system.

As stated previously, no overheat control disrupts many components of the system. The following figures show the most extreme cases, and the time period associated with the effect of rising temperature on system performance.

Assuming all other system constraints remain constant, as the temperature rises, there is a significant effect on the bacteria population, the waste it consumes, and the gas produced. Figure 7.12 shows the amount of waste inside the digester over a period of 511 hours, or approximately 21.3 days.

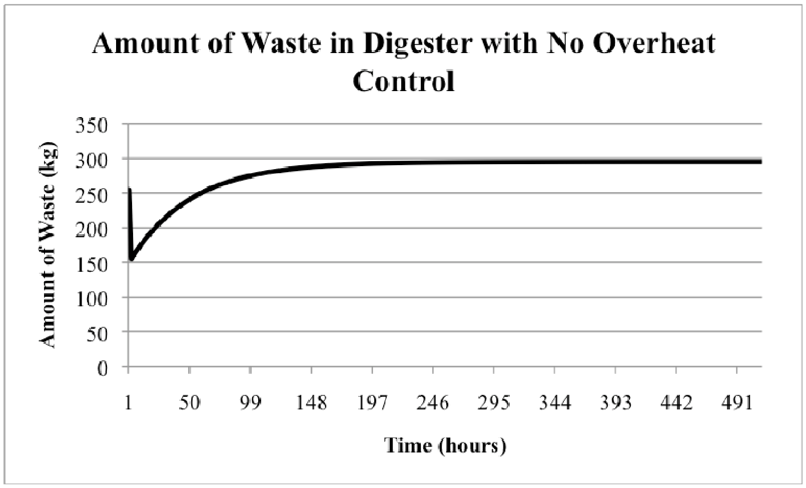


Figure 7.12. Effect of no overheat control on amount of waste in digester

The digester initially contains 254.5 kilograms of waste. As the temperature increases, a portion of the waste is consumed within the first 4 hours, depleting by about 39% of the original amount. After this point, the amount of waste increases because the bacteria population starts to die off. However, as shown, the amount of waste maxes out at 300 kilograms after about 200 hours, or approximately 8 days, since the loading rate remains unchanged.

After considering the amount of waste inside the digester, it is important to see what effect the rising temperature has on the bacteria population. Figure 7.13 shows the bacteria growth rate when there is no overheat control.

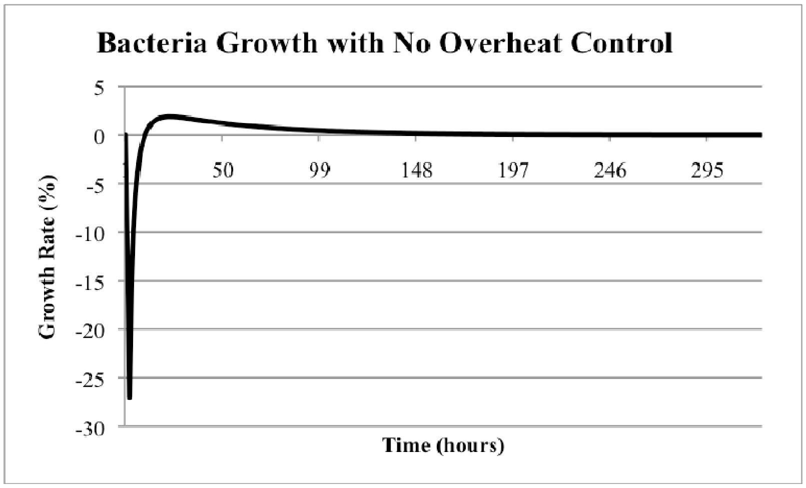


Figure 7.13. Effect of no overheat control on bacteria growth

As shown, the growth rate dips initially as the rising temperature inhibits the enzymatic behavior of the bacteria population. The death rate reaches about 27% within the first few hours. However, when the initial amount of waste is consumed, and the temperature continues to rise, after 24 hours, the growth rate reaches a maximum, and the bacteria must compete for the food source, as they experience extreme physiological conditions. After this point the rate decreases drastically until it falls below a 1% growth rate at 60 hours, or about 2.5 days, and ceases after 323 hours, or about 13.5 days. This shows that even though there remains a viable food source, methanogenic bacteria cannot survive with extreme hot temperatures. At 87 hours, the temperature inside the digester is about 208°C, which is approximately 4.5 times the high end of the optimal mesophilic range. This shows that although bacteria are quite robust, the temperature increase must be controlled in order for the system to function properly.

If the bacteria population dies off, gas production is inhibited. Figure 7.14 shows the gas production inside the digester without overheat control.

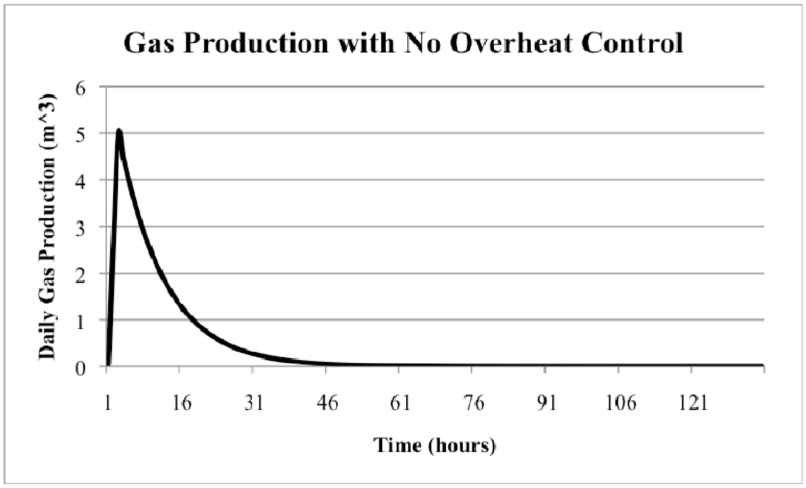


Figure 7.14. Effect of no overheat control on gas production

As shown, the gas production trend follows that of the bacteria growth rate. However, this spike occurs only after 4 hours, reaching a volume of about 5 m^3. After this point, the gas production exponentially decays for about 2 days until no more gas is produced. It only takes between 10 and 11 hours for the total volume of gas produced to deplete by half, and between 18 and 19 hours for the total volume to deplete to one-quarter of the maximum amount. It takes 136 hours, or about 5.7 days for gas production to cease. Therefore, even though some bacteria live for about 4 days, they are no longer healthy enough to produce gas.

7.1.6 Fertilizer Collection or Spent Slurry Removal Ceases

Spent slurry refers to the material that the bacteria can no longer use or reactivate for further gas production, whereas fertilizer is spent material that still has nutrients useful to other forms of bacteria. In the baseline model, this material is removed from the system on a regular basis, to prevent buildup of non-useful matter. Excess amounts of spent slurry or fertilizer in the system will not only take up space, but also inhibit the fresh material from proper exposure to the bacteria for consumption. In order to test the impact of this system component, both slurry removal and fertilizer collection were eliminated from the model, in different trials. However, because they are removed at the same rate, the results were combined. Figure 7.15 shows the effect of fertilizer collection or spent slurry removal cessation on the amount of waste inside the digester.

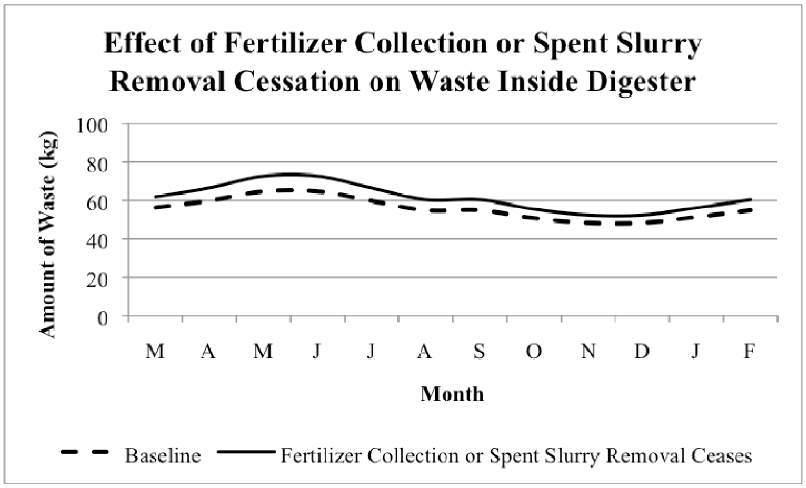


Figure 7.15. Effect of fertilizer collection or spent slurry removal cessation on amount of waste in digester

As shown, when fertilizer collection or spent slurry removal ceases, there is a buildup of waste inside the digester. Although the test curve and baseline curve have the same trend, this buildup of non-useful matter will severely inhibit system operation. The average maximum amount of waste for test conditions is about 73 kilograms, versus only about 65 kilograms for the baseline conditions, occuring between May and June. The average minimum amount of waste for test conditions is about 20 kilograms, versus only about 17 kilograms for the baseline conditions. Therefore, there is a smaller range of waste fluctuation inside the digester over the course of the year for baseline conditions than test conditions. In order to improve system operation, spent matter should be removed regularly such that the amount of waste in the digester is useful to bacteria.

Ceasing fertilizer collection or spent slurry removal from the system shows the biggest effect in the amount of the opposite spent matter, either fertilizer or slurry, depending, that accumulates. The model is set up to remove spent slurry (non-useful waste) and fertilizer (useful waste) at the same rate. Therefore, as one of these outputs stops, there should be a noticeable increase in the other.

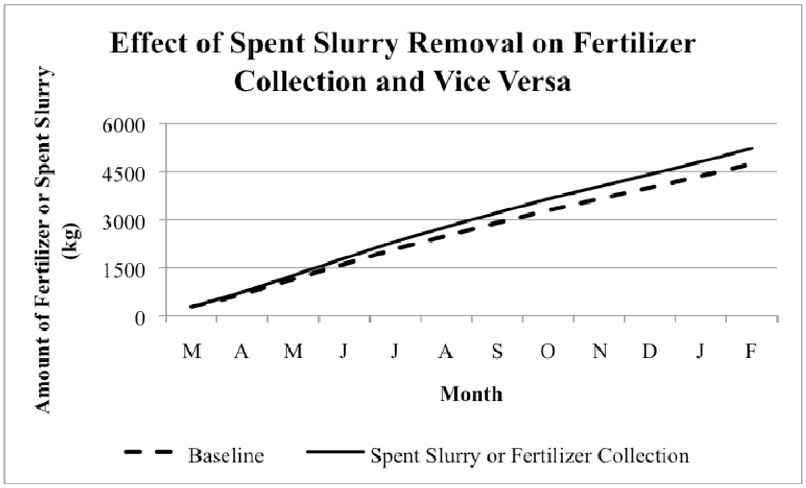


Figure 7.16. Relationship between fertilizer collection and spent slurry removal

As shown in Figure 7.16, the results match the expectation of the inverse relationship between spent slurry and fertilizer in the system. Over the course of the year, a system with no fertilizer collection or no spent slurry removal yields more of the opposite material than the baseline. This makes logical sense, although it does not say anything to the effect of the quality of the fertilizer. It is likely that when spent slurry is not removed from the system, more non-useful material is mixed in with the fertilizer that is collected.

7.1.7 Overpopulation of Bacteria in Digester

Given the initial loading conditions of the anaerobic digestion system in Mozambique, there exist 254.5 kilograms of waste inside, and 5.9 kilograms of feedstock input daily. For baseline conditions, each kilogram of waste is tied to one colony of 100 bacteria. In order to test the effect of disrupting this ratio, the amount of bacteria was doubled. The following graphs represent the effect of this overpopulation on the amount of waste and the volume of gas inside the digester.

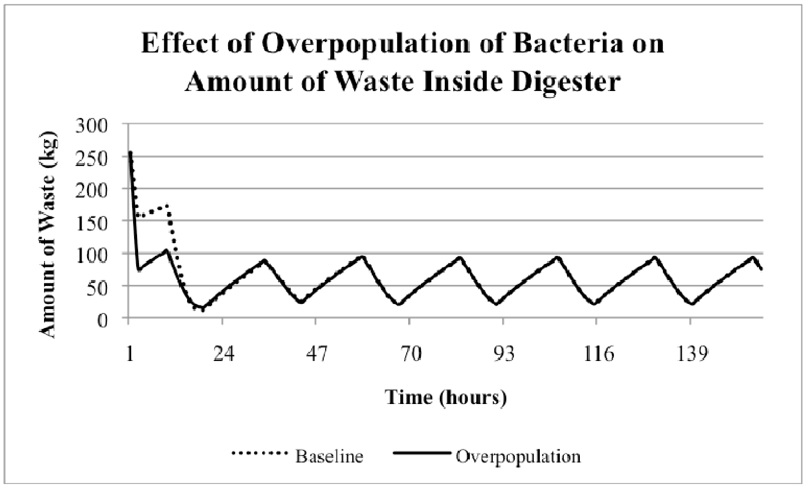


Figure 7.17. Effect of bacteria overpopulation on amount of waste in digester

As shown in Figure 7.17, it only takes only about 18 hours for the two lines to follow almost the same trend. After 157 hours, or about 6.5 days, the two lines converge completely. When there is an overpopulation of bacteria, about 70% of the waste is consumed immediately within the first few hours. This makes sense because if there is more bacteria in the system, they will consume more waste. However, after about 18 hours, the system reaches a balance between the ratio of waste to the bacteria, almost exactly the same as seen in the baseline trend. This shows that the system must reach a state of equilibirum to function properly over an extended period of time.

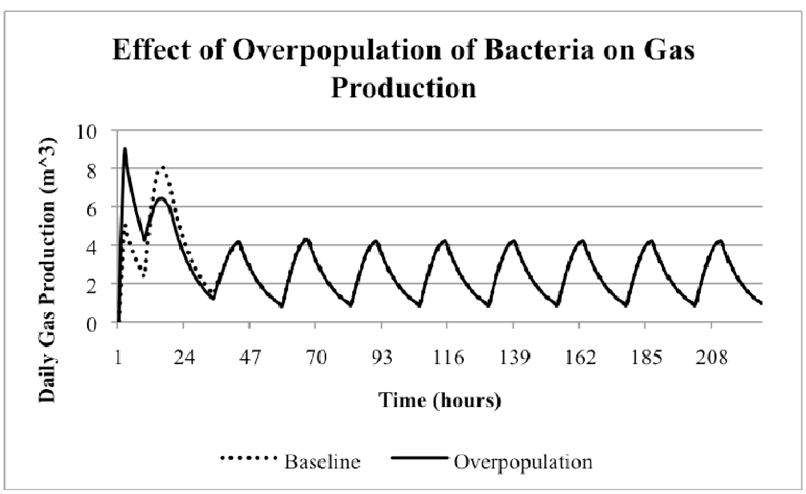


Figure 7.18. Effect of bacteria overpopulation on gas production

As shown in Figure 7.18, it takes about 38 hours for the two lines to quasi-converge. After about 226 hours, or about 9.5 days, the two lines converge completely. Since more bacteria are available to consume the waste, more gas is produced initially, as seen by the drastic spike in the first few hours of operation.

After this point however, the second peak around 22 hours is only about half the height of the first. As the waste depletes, and the bacteria must compete for a food source, less gas is produced. In the baseline trend, the gas production peaks initially, but has a larger peak around 22 hours. This is because in a balanced system there is no initial competition factor for available food. The bacteria exist in proportion to the amount of available waste. When time passes, bacteria competition increases with the diminishing food source. As the waste depletes, the bacteria consume what's left at a faster rate to make sure they have enough to eat, and there is an increase in gas production as a result. Again, the graph shows that the system must reach a state of equilibrium to function properly over an extended period of time.

7.1.8 Underpopulation of Bacteria in Digester

Given the initial loading conditions of the anaerobic digestion system for Mozambique, there exist 254.5 kilograms of waste inside, and 5.9 kilograms of feedstock input daily. As stated previously, for baseline conditions, each kilogram of waste is tied to one colony of 100 bacteria. In order to test the effect of disrupting this ratio, the amount of bacteria was halved. The following graphs represent the effect of this underpopulation on the amount of waste and the volume of gas inside the digester.

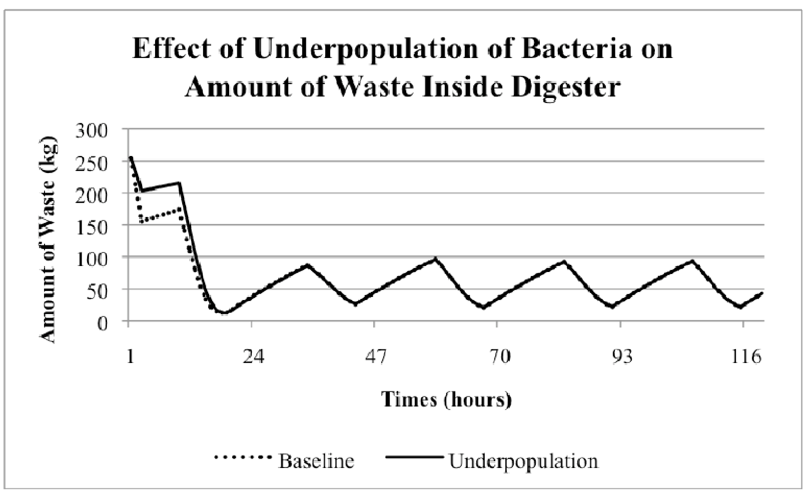


Figure 7.19. Effect of bacteria underpopulation on amount of waste in digester

As shown in Figure 7.19, it only takes only about 16 hours for the two lines to follow almost the same trend. After 120 hours, or about 5 days, the two lines converge completely. When there is an underpopulation of bacteria, about 20% of the waste is consumed immediately within the first few hours. This makes sense because if there is less bacteria in the system, they will consume less waste. However, after about 16 hours, the system reaches a balance between the ratio of waste to the bacteria. This shows that the system must reach a state of equilibirum to function properly over an extended period of time.

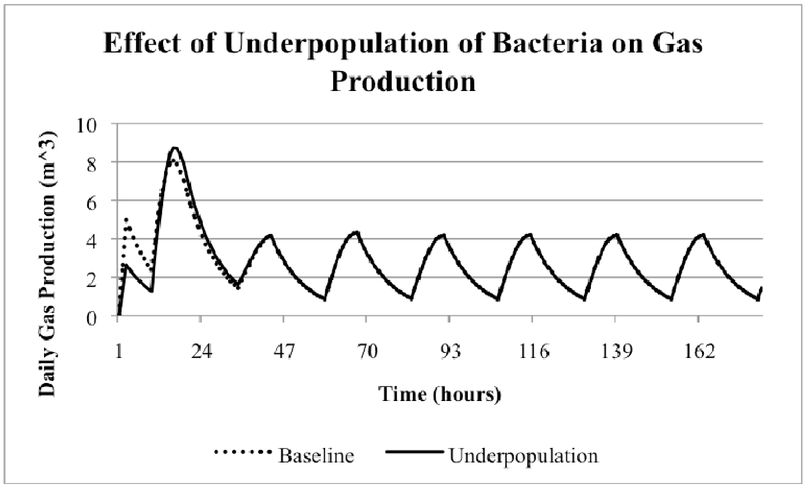


Figure 7.20. Effect of bacteria underpopulation on gas production

As shown in Figure 7.20, it takes about 24 hours for the two lines to quasi-converge. After about 180 hours, or about 7.5 days, the two lines converge completely. Since fewer bacteria are available to consume the waste, less gas is produced initially. Unlike the overpopulation trends, the baseline and underpopulation lines follow the same pattern throughout operation. In order to get a closer look at the difference between the lines, the first 24 hours was evaluated separately, as shown in Figure 7.21.

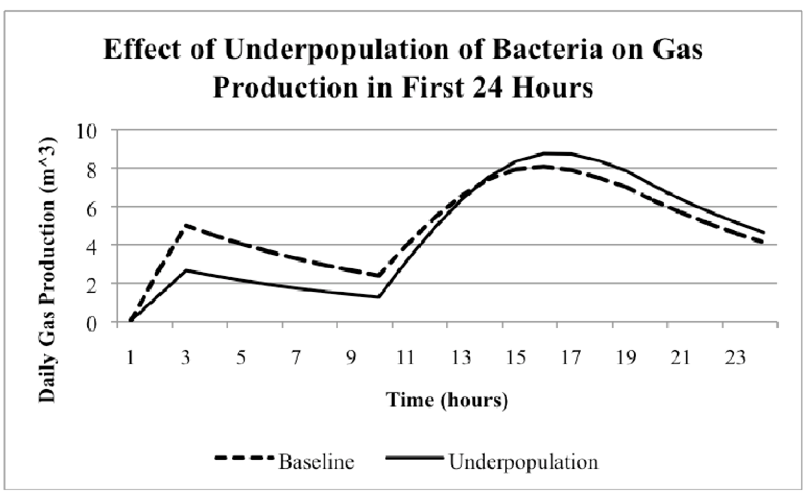


Figure 7.21. Effect of bacteria underpopulation on first 24 hours of gas production

Since the trend of the baseline and underpopulation are so close to one another, it is important to take a closer look at the effect on the volume of gas inside the digester during the first 24 hours. This is where the greatest difference in behavior exists. As shown in Figure 7.21 above, the baseline initially peaks between 3 and 4 hours at about twice the amount as the underpopulation line. These lines cross at around 15 hours, and the underpopulation line remains slightly above the baseline until the two lines merge after

about 9 days. Since the waste is depleting at a slower rate, there is less competition amongst the bacteria population, which explains the lower initial gas production. It takes about 15 hours for the bacteria to compete for available food. Again, the graph shows that the system must reach a state of equilibrium to function properly over an extended period of time. In comparison to an overpopulation of bacteria is the system, an underpopulation has less of an overall impact on the general trend and balance.

7.2 Papua New Guinea Analysis

As defined in Chapter 5, for this context, it is assumed that the digester is located on the farm of a villager, and the digester feedstock is a combination of predominantly animal waste, and minimal crop waste. Unlike Mozambique, Papua New Guinea does not tend to produce as much crop waste, as almost all crops are used directly for consumption. The initial amount of waste inside the digester is 27.3 kilograms. The average annual solar insolation is 5.438kWh/m^2/day.

7.2.1 Waste Input Ceases

Again, the first extreme condition explores the cessation of waste input to the system. Although predictable, this verifies the reliability of the model to function as it would in a real context. Figure 7.22 compares the amount of waste input over time.

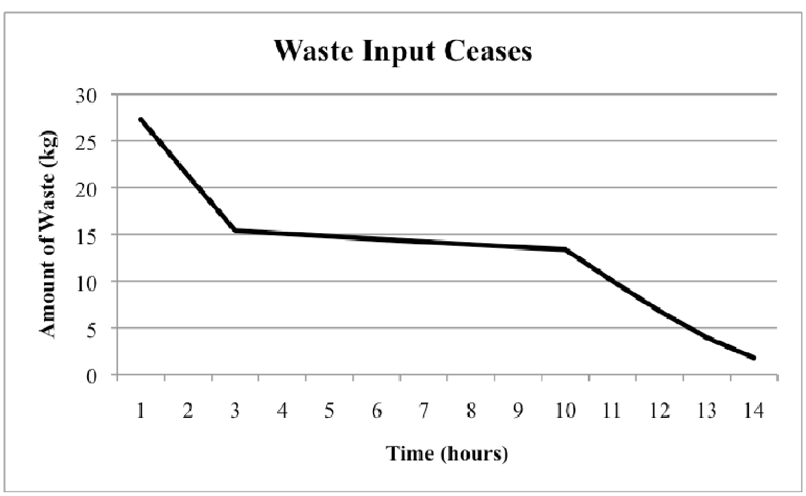


Figure 7.22. Impact of waste input cessation on digester

As shown, the model only runs for 14 hours before the waste inside the digester depletes completely. When the input stops, the model in Stella outputs the same error message generated before for Mozambique analysis, as shown in Figure 7.2. Once again, it explains that the net growth rate cannot be evaluated once waste input stops, because it cannot be divided by zero.

7.2.2 Initial Waste Amount Doubles, Triples, in Same Time Interval

The baseline model for Papua New Guinea assumes the initial waste inside the digester to be 27.3 kilograms, with each kilogram of waste is tied to one colony of 100 bacteria. In order to investigate the impact of this amount of waste on both bacteria population and gas produced, the waste was doubled, and then tripled. It is assumed that the baseline organic loading rate of 5.3 kg/day is constant.

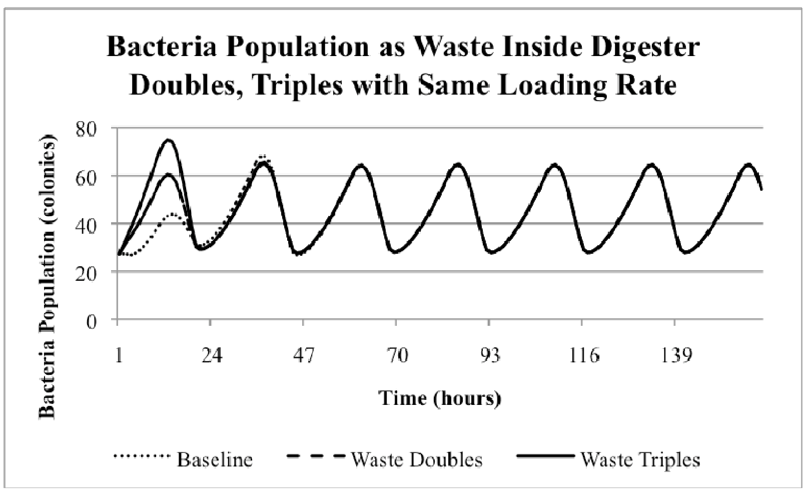


Figure 7.23. Effect of doubling, tripling waste inside digester on bacteria population for PNG

The first test analyzed the impact of doubling and tripling the amount of waste inside the digester on the overall bacteria population, as shown in Figure 7.23. Just like the Mozambique trends, there is only a brief period within the first day where there is a difference in bacteria population, as compared to the baseline. After this point, all three lines follow the same trend, as the system regains equilibrium. After 161 hours, or 6.7 days, all lines converge. Therefore, the system in Papua New Guinea reaches equilibrium about half a day faster than in Mozambique.

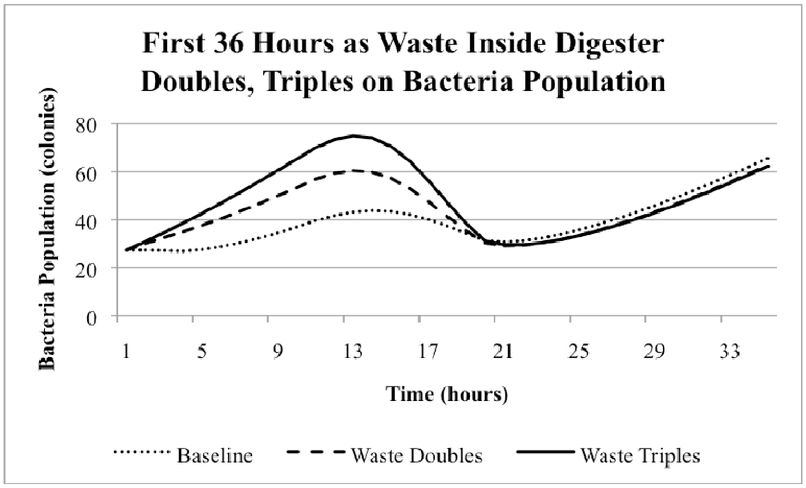


Figure 7.24. Effect of doubling, tripling waste inside digester within first 36 hours on bacteria population for PNG

Figure 7.24 provides a closer look at the first 36 hours as the waste inside the digester is doubled and tripled. As shown, in the baseline run, the waste decreases from the initial 27.3 kilograms steadily for the first 8 hours, then increase slightly before decreasing more rapidly until 22 hours. This dip in bacteria population does not occur in the Mozambique analysis, and is most likely due to the fact that there is less initial waste in the system to allow for population fluctuation. The population relatively stabalizes for the first 12 hours, until the waste depletes. When the initial amount of waste in the digester doubles and triples, this trend changes slightly.

When the waste doubles, the ratio of waste available to bacteria population is 2:1, with about 54.6 kilograms inside the digester. As shown by the dashed line, the bacteria population increases slightly for the first 14 hours, from the initial 27.3 colonies to about 60.4 colonies. At 15 hours, the population starts to die off at a fast rate, until minimizing around 22 hours.

When the waste triples, the ratio of waste available to bacteria population is 3:1, with about 81.9 kilograms inside the digester. As shown by the solid line, the bacteria population increases steadily for the first 14 hours, from the initial 27.3 colonies to about 74.9 colonies. At 15 hours, the population starts to die off again, at an even faster rate than when the waste was doubled, until minimizing around 22 hours.

When the waste doubles, the bacteria population grows by about 40% and when the waste triples, the bacteria population grows by about 74% within the first 14 hours. During baseline conditions, the bacteria population at 12 hours is about 58% more than its original amount. When the waste triples the peak for maximum bacteria population is one hour later than when waste doubles. In comparison to Mozambique,

the baseline bacteria population does not deplete as quickly in the first 14 hours of system operation. Again, tripling the amount of waste initially in the system significantly increases bacteria population..

The surge of population increase only occurs within the first 14 hours. After the first 6.7 days, the system reaches equilibrium and balances the bacteria population to the waste available.

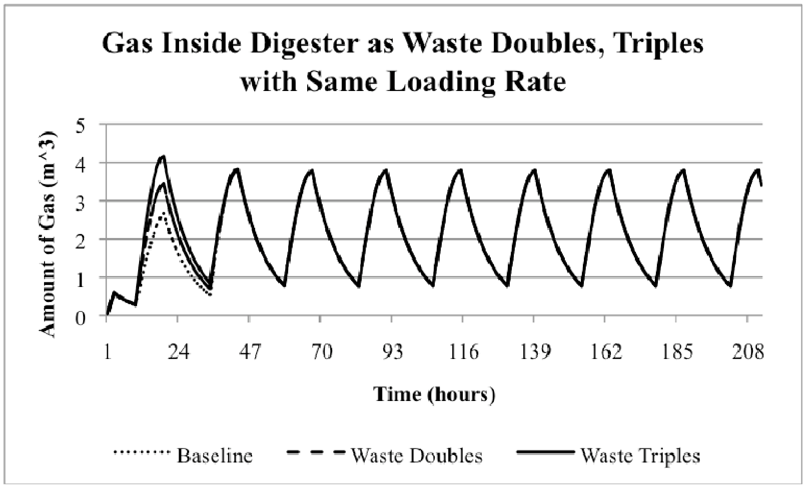


Figure 7.25. Effect of doubling, tripling waste inside digester on gas produced for PNG

The second test analyzed the impact of doubling and tripling the amount of waste inside the digester on the amount of gas produced, as shown in Figure 7.25. All three lines peak at 20 hours. After this point, all three lines follow the same trend, as the system reaches equilibrium. After 213, or about 8.9 days, all lines converge.

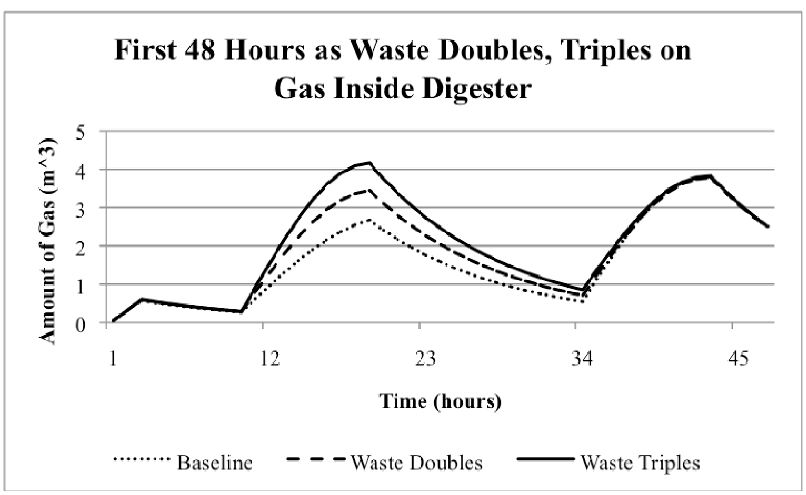


Figure 7.26. Effect of doubling, tripling waste inside digester within first 48 hours on gas production for PNG

Figure 7.26 provides a closer look at the first 48 hours as the waste inside the digester is doubled and tripled. All curves follow the same trend for the first 11 hours, and then split, and reconverge around 44 hours. Again, all lines reach a minimum at about 35 hours of system operation. As shown, in the baseline run, the amount of gas produced inceases slightly from 11 hours to 19 hours, reaching a maximum of about 3.8 m^3. After this point, the bacteria population starts to die off and less gas is produced. When the initial amount of waste in the digester doubles and triples, the surge of gas production increases accordingly.

When the waste doubles in the first 24 hours, the amount of gas produced at its maximum approximately increases by 1.3 times the baseline amount, to about 3.5 m^3. When the waste triples, the amount of gas produced at its maximum approximately increase by 1.6 times the baseline amount, to about 4.2 m^3. These results differ from that of Mozambique, where the gas amounts doubles and tripled as waste did. Due to the lower bacteria population and waste amount in the system, the proportions are not as accurate, making it more difficult to predict and control approximate biogas yield.

7.2.3 Severe Weather Patterns which Erratically Affect Solar Insolation

As discussed in Chapter 5, Papua New Guinea has a tropical climate, with monsoons from the northwest coming between December and March, and from the southeast between May and October. In addition, the country experiences periods of uncharacteristically low rainfall due to the El Niño Southern Oscillation phenomenon.

El Niño is a temporary change in the climate of the Pacific Ocean around the equator whereby the ocean surface warms, causing trade winds to slacken and thunderstorms to move eastward into the center of the pacific, away from Papua New Guinea, causing droughts. Since the frequency and intensity of these events have increased significantly in the last century in conjunction with increases in global temperatures, Papua New Guinea is extremely vulnerable. Papua New Guinea's National Agricultural Research Institute (NARI) responded to this crisis with a World Bank funded research project and developed a series of drought-coping strategies for rural communities. It is recommended that farmers plant drought tolerant crops, most of which are staple foods, every year (Anzu, 2012). These crops include sweet potato, banana, and cassava varieties. Initial model assumptions include sweet potato content in the digester feedstock. Based on these conditions, the model will ignore the monsoons and focus on periods of severe drought.

This analysis used the same baseline conditions as in the analysis for Mozambique, using Equation 7.3:

Equation 7.3. Baseline system operation equation

$$\text{Solar\_Insolation} = \text{Full\_insolation} - \text{Full\_insolation}((\sin((\frac{\pi}{12})(\text{TIME} - 6)) + \sin((\frac{\pi}{4380})(\text{TIME})))$$

Where Full_insolation represents the average annual solar insolation for Papua New Guinea, and TIME represents the period of time the model accounts for, in this case, 8,760 hours for one year. The equation assumes a sinusoidal curve to account for the seasons.

In order to account for severe drought, it was assumed that there was less fluctuation in annual temperatures, or less distinction between seasons. In order to capture this effect in the model, the second sinusoidal curve was extended from 4,380 hours, or half a year, to 6,570 hours, or three-quarters of a year. Equation 7.4 yields the modified curve:

Equation 7.4. Extreme drought system operation equation

$$\text{Solar\_Insolation} = \text{Full\_insolation} - \text{Full\_insolation}((\sin((\frac{\pi}{12})(\text{TIME} - 6)) + \sin((\frac{\pi}{6570})(\text{TIME})))$$

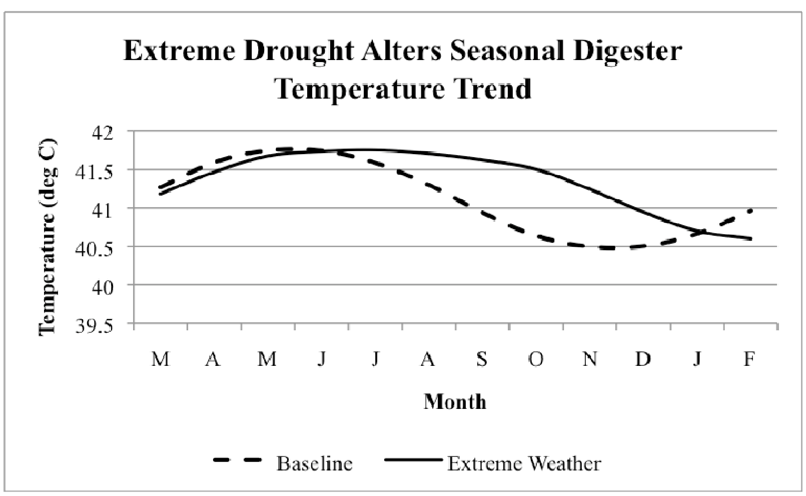


Figure 7.27. Effect of extreme weather on seasonal digester temperature trend

Figure 7.27 shows the impact severe drought has on the temperature inside the anaerobic digester. Average temperatures were taken bi-monthly over the course of the year, and compared to the baseline conditions. As shown, when extreme weather occurs, the optimal operating temperature range shifts from

the four months between November and February to less than a month between January and February. The model assumes that the drought inhibits the seasonal harvest, and consequently the optimal range for bacteria activity. Although minimizing temperature fluctuations could be ideal in terms of system stability, the temperature in the extreme conditions is slightly too high, and therefore will hurt the bacteria population. In addition, both the decreased amount and quality of waste feedstock would significantly diminish system operation.

From a functionality point of view, it is also important to look at how extreme drought affects the amount of gas produced, assuming the system operation is delayed and not stopped. Figure 7.28 shows how the gas production trend changes when sever weather occurs.

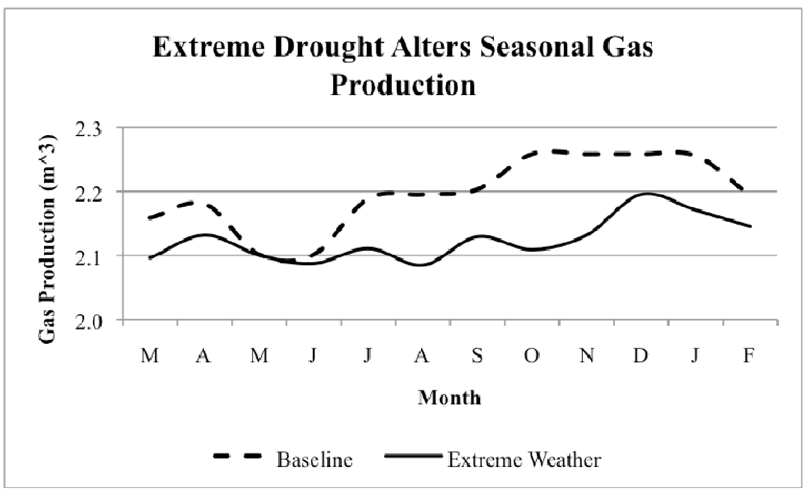


Figure 7.28. Effect of extreme weather patterns on gas production

Averaging the amount produced monthly, it is evident that extreme weather severely effects gas production. Over the course of the year, overall gas production is much lower due to the lack in optimal temperature. With the extreme weather conditions, the curve is more linear, reaching a minimum between July and August. Although maximum gas production occurs between January and March, the trend is not as predictable throughout the course of the year, because there is no way of telling how severe the drought may be, and how long it will last.

Maximum gas production only differs by about 0.06 m^3 over the course of the year between baseline and extreme conditions. However, on average, less gas is produced each month under extreme drought conditions, with the biggest discrepancy between July and November. This falls directly around the second harvest period. Therefore, extreme drought plays a large role in the overall system operation and dependency as a fuel source.

7.2.4 No Solar Component

The same model and variable alterations for removing the solar component as shown in Figure 7.9 for Mozambique were applied the Papua New Guinea analysis.

Since Mozambique and Papua New Guinea have different average annual solar insolation inputs in the baseline model, it is interesting to see the difference in gas production when the solar component is removed. The results are shown in Figure 7.29.

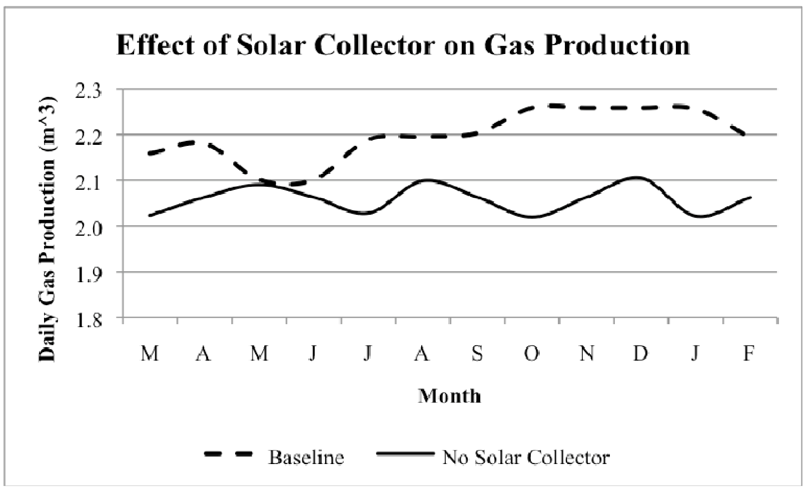


Figure 7.29. Effect of adding a solar component on system gas production

Although the seasonal trend of the baseline curve is not as defined as in Mozambique analysis, it still exists in contrast to the fluctuating test curve with no solar collector. However, it is apparent that once again, the amount of gas production for the baseline conditions exceeds that of the system with no solar component. The gas output in the system with no solar collector fluctuates more frequently, but again the range in limited between 2.0 and 2.2 m^3 for the year. The maximum average monthly amount of gas produced with no solar collector is about 2.1 m^3 in May, and the minimum average monthly amount of gas produced in under baseline conditions is about 2.3 m^3 in May. There is inconsequent difference of about 0.15 m^3 between the maximum of one curve and the minimum of the other. Therefore, with a lower average annual solar insolation, the solar component is critical for a system in Papua New Guinea.

7.2.5 No Overheat Control

As described in the analysis for Mozambique, the baseline model utilizes an overheat control function to maintain the internal digester temperature within the optimal mesophilic range. Figure 7.30 shows the

general trend of the system in Papua New Guinea without overheat control over the course of a year.

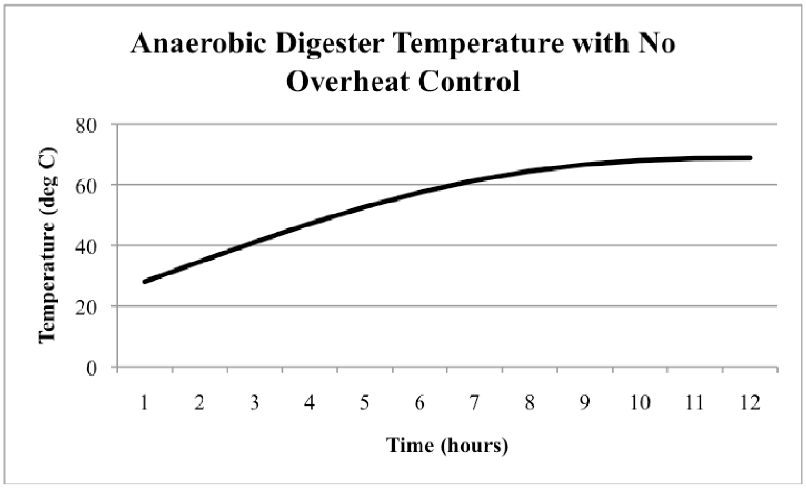


Figure 7.30. Anaerobic digester temperature with no overheat control for PNG

Again, it takes only about 3 hours for the temperature to exceed the mesophilic range, to about 40°C, and about 7 hours the exceed the thermophilic range, above 60°C. Therefore, the smaller system size and lower solar insolation allows for the system to withstand extreme temperatures slightly longer than the system in Mozambique. The graph only shows the first 12 hours of operation, because beyond this point, all bacteria activity ceases. Even though some strains of methanogenic bacteria can survive in conditions up to 100°C, they will no longer be able to consume waste and produce gas for the system. Again, it is obvious that without the overheat control this system is unusable.

The following figures show the most extreme cases of how no overheat control affects the entire digester system, and the time period associated with the effect of rising temperature on system performance.

Assuming all other system constraints remain constant, as the temperature rises, there is a significant effect on the bacteria population, the waste it consumes, and the gas produced. Figure 7.31 shows the amount of waste inside the digester over a period of 538 hours, or approximately 22.4 days. This is almost exactly the same timeframe as in Mozambique analysis. Therefore, despite differences in solar insolation and the initial amount of waste in the digester, no overheat control has the same effect on the system for both locations.

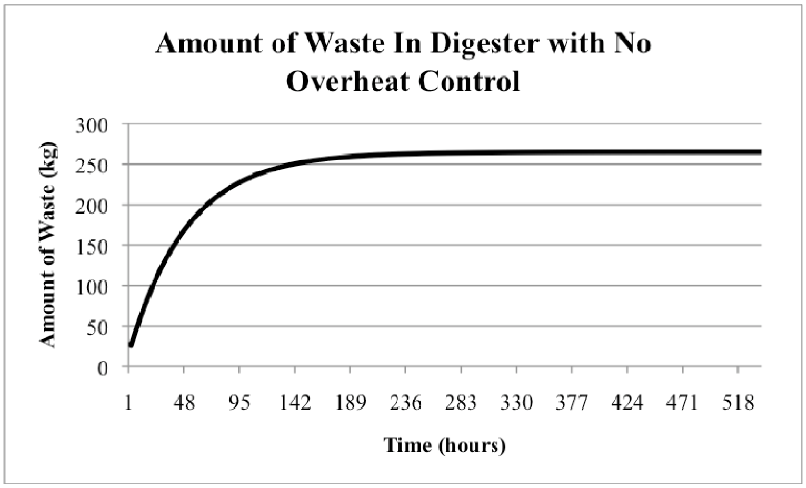


Figure 7.31. Effect of no overheat control on amount of waste in digester for PNG

The digester initially contains 27.3 kilograms of waste. As the temperature increases, a portion of the waste is consumed within the first 3 hours, depleting by about 5% of the original amount. This is not as drastic a change as in Mozambique when more waste is available for consumption. After this point, the amount of waste increases because the bacteria population starts to die off. However, as shown, the amount of waste maxes out at 265 kilograms after about 200 hours, or approximately 8 days. Therefore, it takes about a week for the bacteria population to die off completely.

After considering the amount of waste inside the digester, it is important to see what effect the rising temperature has on the bacteria population. Figure 7.32 shows the bacteria growth rate when there is no overheat control.

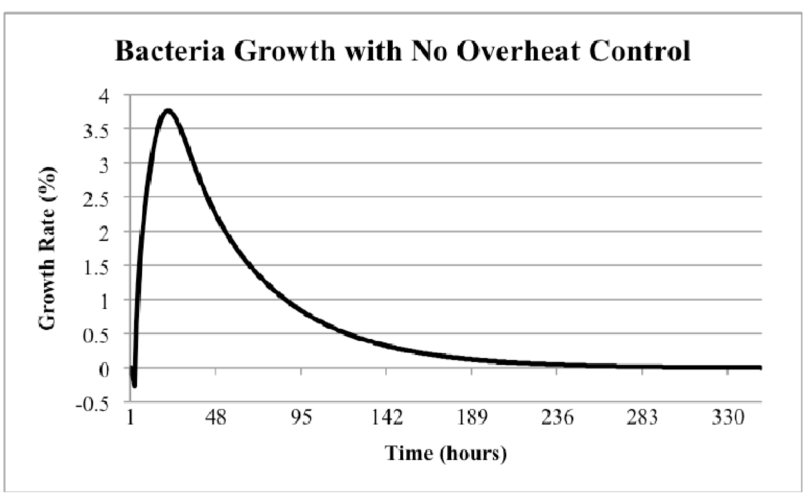


Figure 7.32. Effect of no overheat control on bacteria growth for PNG

The growth rate dips initially as the rising temperature inhibits the enzymatic behavior of the bacteria population. Again, when the initial amount of waste is consumed, and the temperature continues to rise, after 24 hours, the growth rate reaches a maximum, and the bacteria must compete for the food source, as they experience extreme physiological conditions. After this point the rate decreases drastically until it falls below a 1% growth rate at 95 hours, or about 4 days, and ceases after 349 hours, or about 14.5 days. At 95 hours, the temperature inside the digester is about 261°C, which is approximately 7.5 times the high end of the optimal mesophilic range. Therefore, even though the bacteria population in the system in Papua New Guinea survives a day longer than in the Mozambique system, when comparing the systems when they fall below the 1% growth rate, Papua New Guinea exceeds the mesophilic range by more. However, despite this difference, the fact that the population survives longer means that the bacteria in the system in Papua New Guinea are slightly more robust.

If the bacteria population dies off, gas production is inhibited. Figure 7.33 shows the gas production inside the digester without overheat control.

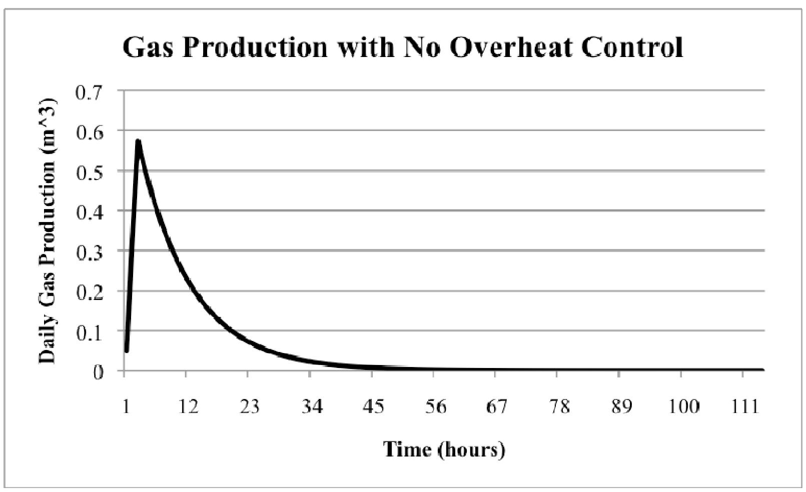


Figure 7.33. Effect of no overheat control on gas production for PNG

As shown, the gas production trend follows that of the bacteria growth rate. However, this spike occurs only after 3 hours, reaching a volume of about 0.6 m^3. After this point, the gas production exponentially decays for about 2 days until no more gas is produced, just like in the analysis for Mozambique. It only takes between 9 and 10 hours for the total volume of gas produced to deplete by half, and between 16 and 17 hours for the total volume to deplete to one-quarter of the maximum amount. It takes 115 hours, or about 4.8 days for gas production to cease.

7.2.6 Fertilizer Collection or Spent Slurry Removal Ceases

Figure 7.34 shows the effect of fertilizer collection or spent slurry removal cessation on the amount of waste inside the digester for Papua New Guinea.

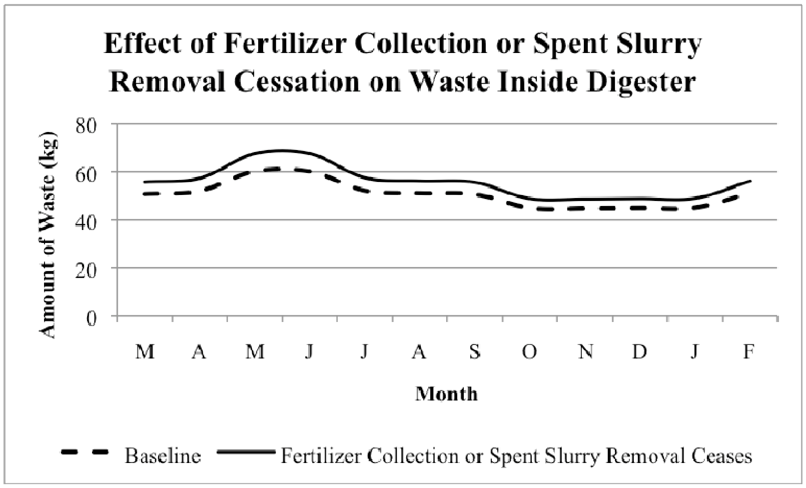


Figure 7.34. Effect of fertilizer collection or spent slurry removal cessation on waste in digester for PNG

Again, when fertilizer collection or spent slurry removal ceases, there is a buildup of waste inside the digester. The average maximum amount of waste for test conditions is about 67.6 kilograms, versus only about 60.2 kilograms for the baseline conditions, occuring between May and June. The average minimum amount of waste for test conditions is about 48.6 kilograms, versus only about 44.7 kilograms for the baseline conditions. These results are almost identical to the results from Mozambique. Again, there is a smaller range of waste fluctuation inside the digester for baseline conditions than test conditions.

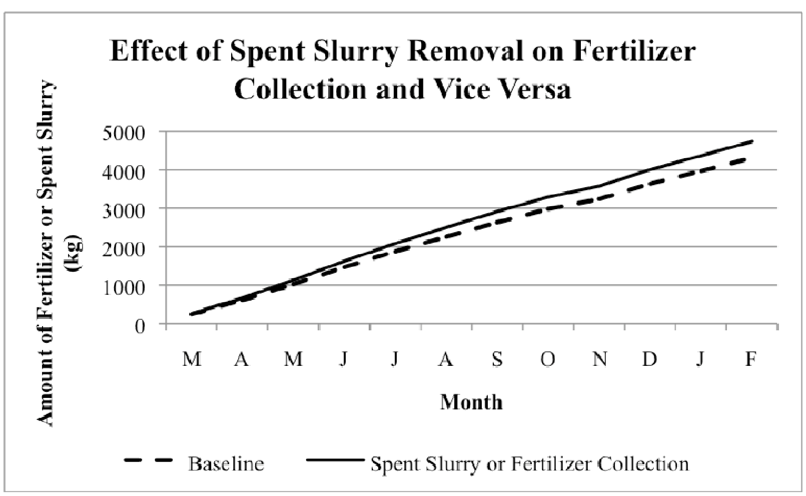


Figure 7.35. Relationship between fertilizer collection and spent slurry removal for PNG

As shown in Figure 7.35, the results match the expectation of the inverse relationship between spent slurry and fertilizer in the system. Over the course of the year, a system with no fertilizer collection or no spent slurry removal yields more of the opposite material than the baseline. In the case of Papua New Guinea, about 430 kilgrams more non-useful material is collected than in baseline coniditions, versus about 486 for Mozambique. Since there is less waste in the Papua New Guinea system, it makes sense that there is less discrepancy between overall accumulation over the course of the year.

7.2.7 Overpopulation of Bacteria in Digester

Given the initial loading conditions of the anaerobic digestion system in Papua New Guinea, there exist 27.3 kilograms of waste inside. For baseline conditions, each kilogram of waste is tied to one colony of 100 bacteria. In order to test the effect of disrupting this ratio, the amount of bacteria was doubled. The following graphs represent the effect of this overpopulation on the amount of waste and the volume of gas inside the digester.

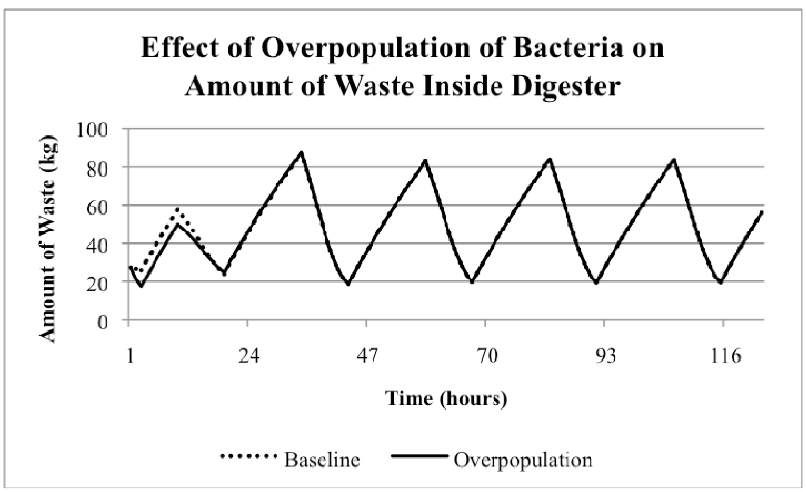


Figure 7.36. Effect of bacteria overpopulation on amount of waste in digester for PNG

As shown in Figure 7.36, it takes only about 16 hours for the two lines to follow almost the same trend. After 124 hours, or about 5.2 days, the two lines converge completely. When there is an overpopulation of bacteria, about 63% of the waste is consumed immediately within the first few hours. Since there is less waste overall in this system as compared to Mozambique, this percentage is not as drastic. After about 16 hours, the system reaches a balance between the ratio of waste the bacteria, almost exactly the same as seen in the baseline trend, about two days shorter than for Mozambique. The smaller system can adapt better to extreme bacteria overpopulation.

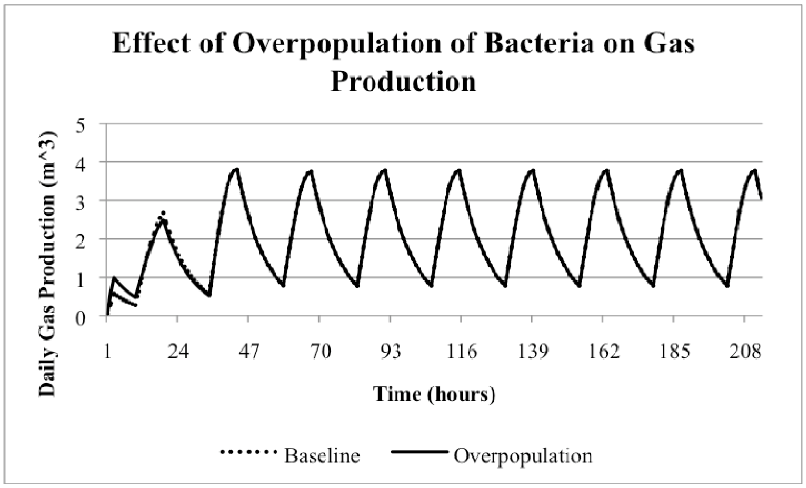


Figure 7.37. Effect of bacteria overpopulation on gas production for PNG

As shown in Figure 7.37, it takes about 37 hours for the two lines to quasi-converge. After about 214 hours, or about 9 days, the two lines converge completely. This is about 4 days longer than in Mozambique. Even though the lines start to converge around the same time, it takes longer for the system to reach complete equilibrium. Again, there is a drastic spike in the first few hours of operation, due to the increased bacteria population. After this point, the second peak around 22 hours is slightly more than the height of the first. This shows that the increased bacteria population has little to no effect on the amount of gas produced. This differs from the system in Mozambique where there is a noticeable drop in gas production after the first few hours. Whereas there is slightly more gas produced initially in the Mozambique analysis, the maximum amount produced in Papua New Guinea is the same for both baseline and test conditions.

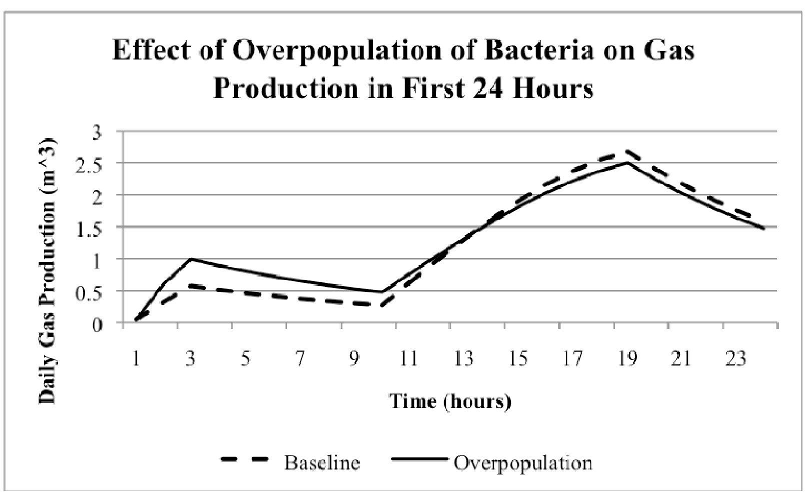


Figure 7.38. Effect of bacteria overpopulation on first 24 hours of gas production for PNG

Figure 7.38 shows a closer look at gas production during the first 24 hours of operation. The lines show the same trend, with the only significant difference being the rate at which gas production increases for the second peak, with the increase starting around 10 hours. The slope of the baseline curve is about two times steeper than in test conditions. This is because the initial gas production is about two times greater for the overpopulation model, reaching close the the system maximum in the first few hours, and establishing system equilibrium at a faster rate.

7.2.8 Underpopulation of Bacteria in Digester

Given the initial loading conditions of the anaerobic digestion system for Papua New Guinea, there exist 27.3 kilograms of waste inside. In order to test the effect of disrupting the ratio of bacteria to waste, the bacteria population was halved. The following graphs represent the effect of this underpopulation on the amount of waste and the volume of gas inside the digester.

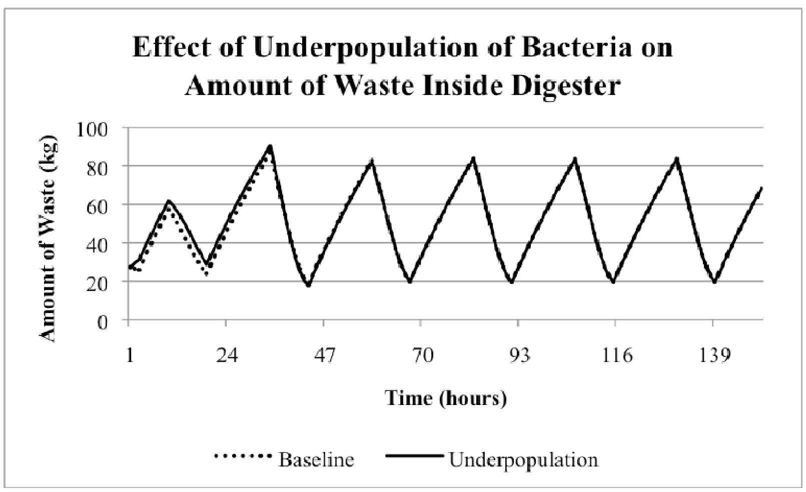


Figure 7.39. Effect of bacteria underpopulation on amount of waste in digester for PNG

As shown in Figure 7.39, it only takes about 36 hours for the two lines to follow almost the same trend. After 151 hours, or about 6.3 days, the two lines converge completely. The is no intial decrease in the amount of waste in the system since there are so few bacteria.

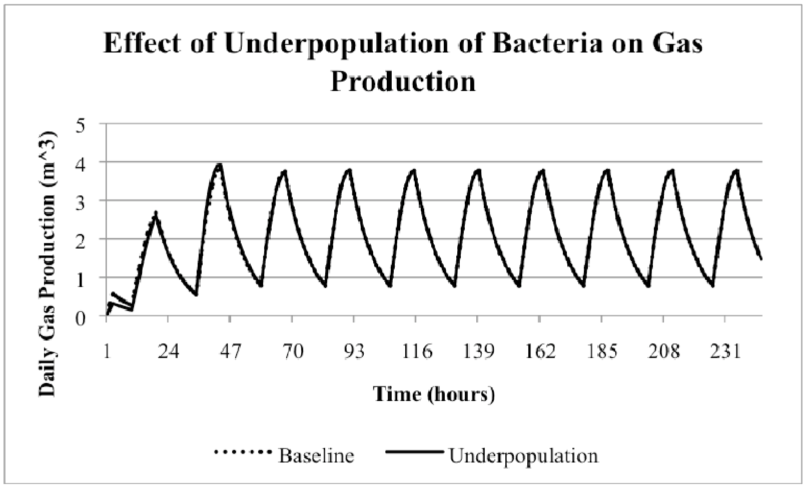


Figure 7.40. Effect of bacteria underpopulation on gas production for PNG

As shown in Figure 7.40, it takes about 16 hours for the two lines to quasi-converge. After about 245 hours, or about 10.2 days, the two lines converge completely. Since even fewer bacteria are available to consume the waste than in the Mozambique system, even less gas is produced initially. In order to get a closer look at the difference between the lines, the first 24 hours was evaluated separately.

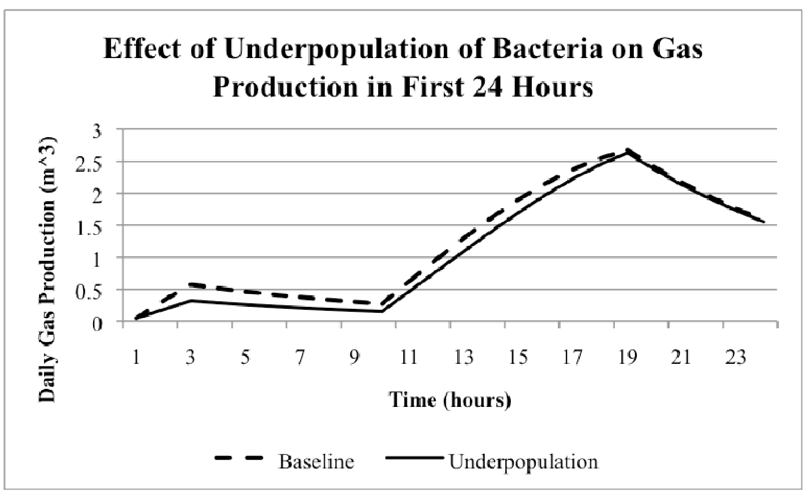


Figure 7.41. Effect of bacteria underpopulation on first 24 hours of gas production for PNG

The greatest difference between the baseline and test conditions exists in the first 24 hours of operation. As stated in Figure 7.41 above, the baseline initially peaks after 3 hours at a little less than twice the amount as the underpopulation line. These lines cross at 19 hours, and the underpopulation line remains slightly above the baseline until the two lines merge after about 11 days. The waste is depleting at even a slower rate than in Mozambique.

7.3 Sensitivity Analysis and Overall Conclusions

As stated in Chapter 4, sensitivity analysis is a tool to assess whether conclusions change in ways important to the purpose of the model, when assumptions vary over the plausible range of uncertainty. The previous extreme condition analyses for the two locations addressed both numerical and behavior mode sensitivity, such that it considered the sensitivity of results to assumptions about the boundary of the model, changes in the level of aggregation, and changes in the way decisions are made within the human-natural system interface.

Given the limited time and resources of the scope of this thesis, sensitivity analysis focused on the relationships and parameters suspected to be both highly uncertain and likely to be influential. A brief description of these results is given in the subsequent paragraphs; however, a more thorough comparison will be discussed in the following chapter, and related to similar experiments found in literature.

Table 7.2 summarizes the modeling results for each extreme condition trial for both locations, and also rates the level of severity (LOS) the condition has on the system as a whole. From these results, it will be possible to identify the ideal operating conditions for the anaerobic digester system in a specific context.

Table 7.2. Summary of modeling results

Extreme Condition	Mozambique	LOS	Papua New Guinea (PNG)	LOS
Waste Input Ceases	System runs for only 14 hours	**High**	System runs for only 14 hours	**High**
Initial Waste Amount Doubles, Triples in Same Time Interval	- Waste converges after 8.5 days - Gas converges after 10.8 days - Waste doubles → bacteria population grows by 44% - Waste triples → bacteria population grows by 104%	Medium	- Waste converges after 6.7 days - Gas converges after 8.9 days - Waste doubles → bacteria population grows by 40% - Waste triples → bacteria population grows by 74% - Gas production not proportional to waste increases	Medium
Severe Weather Patterns that Erratically Affect Solar Insolation	More gas produced under extreme conditions	Medium	Extreme weather minimizes temperature fluctuations, but holds temperature above optimal range → less gas produced each month	**Medium- High**
No Solar Component	Less gas produced with no solar collector	**High**	Less gas produced with no solar collector	**High**
No Overheat Control	- System temperature rises above optimal range after 3 hours - 27% death rate in first hours - Takes 2.5 days to fall below 1% bacteria growth rate - Waste maxes out after 8 days - Gas peaks at 4 hours - After 5.7 days, gas ceases	**High**	- System temperature rises above optimal range after 3 hours - Minimal death rate in few hours - Takes 4 days to fall below 1% bacteria growth rate - Waste maxes out after 8 days - Gas peaks at 3 hours - After 4.8 days, gas ceases	**High**
Fertilizer Collection or Spent Slurry Removal Ceases	Smaller waste fluctuation for baseline conditions	Low	Smaller waste fluctuation for baseline conditions	Low
Overpopulation of Bacteria in Digester	- Waste converges after 5.5 days - 70% waste consumed initially - Gas converges after 9.5 days - Overpopulation peaks initially, second peak only half of first peak at 22 hours	Medium	- Waste converges after 5.2 days - 63% waste consumed initially - Gas converges after 9 days - Overpopulation peaks slightly above baseline, but no significant difference	Low
Underpopulation of Bacteria in Digester	- Waste converges after 5 days - 20% waste consumed initially - Gas converges after 7.5 days - Lines cross at 15 hours, and underpopulation curve produces more gas for first day	Low	- Waste converges after 6.3 days - Gas converges after 10.2 days - Lines cross at 19 hours, and underpopulation curve produces more gas for first day	Low

7.3.1 Mozambique Summary

As indicated by the bold faced font in Table 7.1, conditions 1, 4, and 5 have the largest impact on the system as a whole. When no waste is input into the system, no biogas can be produced. Removing the solar collector from the system severely inhibits overall gas production. Given the higher solar average annual solar insolation for Mozambique, when the system has no overheat control, the bacteria growth rate is severely inhibited within the first few hours of operation. A death rate of 27% shows that the system cannot adapt quickly to extreme changes in internal system temperature. Therefore, the system needs a steady input of feedstock and to stay within the optimal temperature range for the methanogenic bacteria in order to function.

Beyond this point, conditions 2, 3, and 6 had a medium level of severity rating. When the initial amount of waste doubles or triples, it takes a little over a week for the system to regain equilibrium, and about a week and a half for gas production to reach equilibrium. When the amount of waste doubles the bacteria population grows by 44%, which indicates that the increased food source increase reproductive behavior of the bacteria. When the amount of waste triples the bacteria population grows by 104%, which indicates that adding more waste initially, disproportionately increases bacteria population. However, in a real system, even though there is a greater amount of food available for the bacteria, other physiological factors affect the rate of bacteria growth, such that the system maintains the proper balance to promote gas production.

When the system accounted for extreme weather patterns, namely cyclones, the curve shifted such that the harvest period was delayed. By doing this, the system actually produced more biogas over the course of the year than during baseline conditions. Although not added to the model, in a real system, this could be attributed to increased water content of the feedstock, which helps break down the material on a cellular level, and increases surface area. As explained in the background information in Chapter 2, moisture is required for all bacteria activity. Very wet waste feedstock can be used without loss of energy consumed. By decreasing the size of the material, the bacteria are able to consume more material in a shorter period of time.

When there is an overpopulation of bacteria, it takes about a week for the waste in the system to regain equilibrium. With more bacteria available, 70% of the waste is consumed in the first few hours. Gas production takes a little longer than a week to regain equilibrium, which makes sense as the bacteria need time to consume, and process the waste in order to produce gas. In terms of gas production, the

overpopulation curve peaks initially, but its second peak, around 22 hours, is only half the height of the initial peak, in terms of gas production, whereas the baseline curve has a smaller initial peak, and doubles around 22 hours. With overpopulation, as the waste depletes, the bacteria must compete for a food source, and less gas is produced as a result. In the baseline trend, which represents a balanced system, there is no initial competition factor for available food. The bacteria exist in proportion to the amount of available waste. When time passes, bacteria competition increases with the diminishing food source. As the waste depletes, the bacteria consume what's left at a faster rate to make sure they have enough to eat, and there is an increase in gas production as a result.

Lastly, conditions 5 and 7 had a low level of severity rating, which indicates minimal impact on the entire system. When fertilizer collection or spent slurry removal stops, there is minimal change in the amount of waste inside the digester, indicated by a smaller fluctuation of waste under baseline conditions. More non-useful material inhibits proper operation, but the system can still function. In order to maximize gas production, internal balance of useful and non-useful materials must be maintained.

With an underpopulation of bacteria, it takes a little less than a week for the amount of waste to reach equilibrium. In comparison to the 70% of waste consumed in the first few hours with overpopulation, only 20% is consumed with an underpopulation. If fewer bacteria exist in the system, they will consume less waste. Gas production takes a little more than a week to converge. Unlike the overpopulation trends, the baseline and underpopulation lines follow the same pattern throughout operation. The baseline initially peaks at 3 hours at about twice the amount as the underpopulation line. These lines cross at around 15 hours, and the underpopulation line remains slightly above the baseline until the two lines merge after about 7.5 days. Since the waste is depleting at a slower rate, there is less competition amongst the bacteria population, which explains the lower initial gas production.

Therefore, for optimal operating conditions for a system in Mozambique, there must be a steady stream of waste input and the temperature must stay in the lower to middle mesophilic range given the higher average annual solar insolation and the solar component. Doubling and tripling the amount of waste will significantly increase bacteria population and subsequent gas production. This means that any additional waste that can be spared for the digester will help produce more useable fuel source. The natural weather patterns that exist in Mozambique are assumed to increase gas production by adding moisture to feedstock content and minimizing the surface area of feedstock material. Adding more bacteria to the system will increase gas production initially, but there needs to be a balance between the amount of waste available and this population because gas production will be difficult to control if the system does not find

equilibrium. Bacteria population can have a positive or negative effect, depending on the level of monitoring taken by the operator. The more spent slurry that is removed from the system, the better it will operate. Again, overall attention to system health and maintenance will improve operation and gas production.

7.3.2 Papua New Guinea Summary

As indicated by the bold faced font in Table 7.1, conditions 1, 3, 4 and 5 have the largest impact on the system as a whole. When no waste is input into the system, no biogas can be produced. Without a solar collector, the annual gas production suffers. Even though the average annual solar insolation is slightly lower in Papua New Guinea than Mozambique, when the system has no overheat control, the bacteria growth rate is inhibited within the first few hours of operation. There is a minimal death rate, which shows that the system can adapt quickly to extreme changes in internal system temperature, and much quicker than the system in Mozambique. In the case of Papua New Guinea's climate, extreme weather patterns in the form of severe drought have a medium to high impact on the system as a whole. Even though extreme weather minimizes temperature fluctuation over the course of the year, the temperature stays above the optimal range for the bacteria. The lower solar insolation and lack of moisture in the digester is not enough to counter this impact. Again, the system needs a steady input of feedstock and to be kept within the optimal temperature range for the methanogenic bacteria in order to function.

Condition 2 is the only one rated at a medium level of severity. When the initial amount of waste doubles or triples, it takes about a week for the system to regain equilibrium, and about a week and a half for gas production to reach equilibrium. When the amount of waste doubles the bacteria population grows by 40%, which indicates that the increased food source increase reproductive behavior of the bacteria, but not as much as in the Mozambique system. When the amount of waste triples the bacteria population grows by 74%, which is even more of an extreme growth rate compared to the system in Mozambique. However, the gas production is not as proportional to the waste increases as it was in Mozambique, which makes it much more difficult to predict biogas yield.

Lastly, conditions 5, 6, and 7 had a low level of severity rating. When fertilizer collection or spent slurry removal stops, there is minimal change in the amount of waste inside the digester, indicated by a smaller fluctuation of waste under baseline conditions, just like in Mozambique.

When there is an overpopulation of bacteria, it takes about a week for the waste in the system to regain equilibrium. With more bacteria available, 63% of the waste is consumed in the first few hours. Gas production takes about a week and a half to regain equilibrium. In terms of gas production, the overpopulation curve peaks increase each cycle for three peaks, and then match the trend of the baseline conditions. Since the system has less waste available than the system in Mozambique, overpopulation does not have as great an effect. The system does not adjust to the overpopulation as quickly, but then can increase gas production for a longer period of time before establishing a balance.

With an underpopulation of bacteria, it takes almost exactly a week for the amount of waste to reach equilibrium. In comparison to the 63% of waste consumed in the first few hours with overpopulation, no extra waste is consumed with an underpopulation. This is even less than in Mozambique, due to the fact that the entire system in Papua New Guinea is smaller. Gas production takes about a week and a half to converge. Just like the overpopulation trends, there is minimal difference between the test and baseline conditions.

Therefore, for optimal operating conditions for a system in Papua New Guinea, there must be a steady stream of waste input, a solar collector, and the temperature must stay in the lower mesophilic range given the impact of severe drought and minimal water content for feedstock material. Doubling and tripling the amount of waste will significantly increase bacteria population and subsequent gas production. This means that any additional waste that can be spared for the digester will help produce more useable fuel source, but the yield will not be as easy to predict because the proportion of waste to gas production is not as accurate as in the system in Mozambique. Although it is important to remove non-useful waste from the digester, there is little change in system performance when these actions stop. Increasing or decreasing the bacteria population has minimal effect on the system. Unlike the system in Mozambique, it takes longer for the system in Papua New Guinea to regain equilibrium. This means the system would require even more maintenance and monitoring on a consistent basis. Therefore, it may be more difficult for a system in Papua New Guinea to thrive given the initial context, unpredictable weather patterns, and relatively inflexible operating conditions.

8 DISCUSSION

Given the results from Mozambique and Papua New Guinea in Chapter 7 analysis, it is now important to compare and contrast how the system dynamics model relates to real-world experimental findings. The following paragraphs describe various studies using anaerobic digesters. Since the system modeled in this thesis differs from any existing system, none of the studies exactly match all assumptions, constraints, and variables. However, the purpose of this discussion is to pull general trends from the experimental results, and compare them to the thesis model behavior, to verify that the proposed system operates realistically. Each section describes the initial conditions and results of the study, followed by a summary of how the thesis model results relate to the experimental results. To avoid confusion, the results from real-world experiments will be referred to as studies, and the thesis results will be referred to as the model.

8.1 Study 1 - Greece

A study in Greece involved a plug-flow swine manure digester having a useful volume of 45 m^3 constructed below ground level and a fixed cover made of flat plate collectors, like those used in the model. A simulation was run over a period of ten days in September with an average ambient temperature between of 25ºC, an average manure temperature of 33.5ºC, and an average biogas temperature of 27.1ºC. The volume of manure was 26.2 m^3 and the volumetric flow rate of waste into the digester was 7.5 m^3/day. Figure 8.1 shows the results of both the predicted and measured daily methane production rate for these ten days of the study (Axaopoulos, 2000).

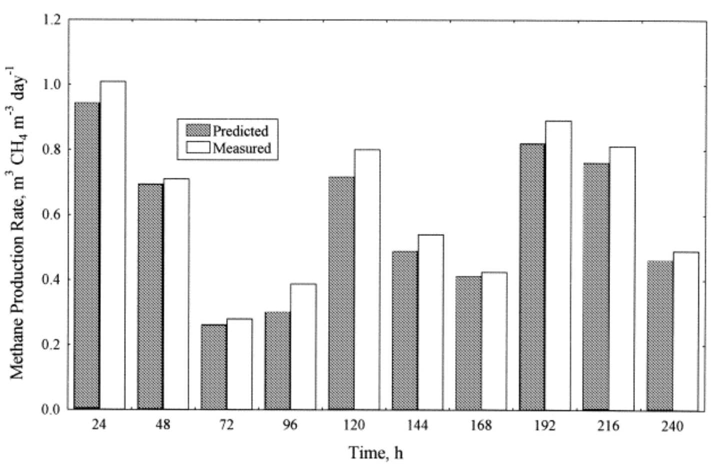


Figure 8.1. Predicted and measured daily methane production rate for 10 September days

Overall, the amount of methane measured over the 10 days surpassed the amount predicted in the study. The measured average daily methane production rate was 6.4 m^3/m^3 of the digester (Axaopoulos, 2000). The degradation of a portion of the volatile solids, represented by the fluctuating bar graph heights, can be explained by the following two reasons; the first is the dilution of manure with water inside the unit, and the second is the significant time needed between the excretion and the introduction of the manure into the digester. Important conclusions can be drawn from this experiment. First, the use of solar collectors as a cover for the gas chamber reduced the digester thermal losses. In addition, the back heat losses from the solar collectors positively affected the heat balance of the digester. Second, because the digester was not continuously stirred, the time and quantity of the incoming manure influenced the fluctuation of manure temperatures, and subsequent degradation of volatile solids.

These results confirm the behavior of the thesis model. As shown in the previous chapter, when there is no overheat control, the temperature fluctuation exceeds the optimal range for the bacteria, and gas production ceases. The flat plate solar collector is advantageous because it adds a consistent source of heat, but without the overheat control, it inhibits the system. Therefore, it is important to find the optimal temperature range and operate the system accordingly. Also, the modeling results for the fluctuation in methane production by not removing spent slurry from the system is realistic, as confirmed by the erratic fluctuations shown in Figure 8.1 of the study. Without proper system maintenance, methane is still produced, but the output is inconsistent.

8.2 Study 2 - Italy

A study using an inclined plug flow digester installed at the ENEA Research Center Trisaia in Italy performed a set of experiments using semi-solid wastes available from wholesale fruit and vegetable markets mixed together with different portions of sewage sludge to establish an efficient and reliable anaerobic treatment process (Sharma, 2000). This system has no solar component. The major problem of the anaerobic treatment process is that a considerably long start-up period is required for establishing a balanced microbial population. To shorten the start-up phase, pig manure was added to the system.

This study determined that successful operation of waste treatment depends on both the composition of the substrate and the developed population of anaerobic bacteria. The temperature during these experiments was 37±4°C, with the inclined design providing some gravitational axial mixing. During the start-up period, the loading rate was 20 kg/day, and the steady state loading rate increased to 40 kg/day. The experiments covered a start-up trial with a HRT of 33.7 days, a steady state trial with a HRT of 33.7

days, and a steady state trial with a HRT of 22.5 days (Sharma, 2000). The following figures provide experimental results regarding the gas production during these trials.

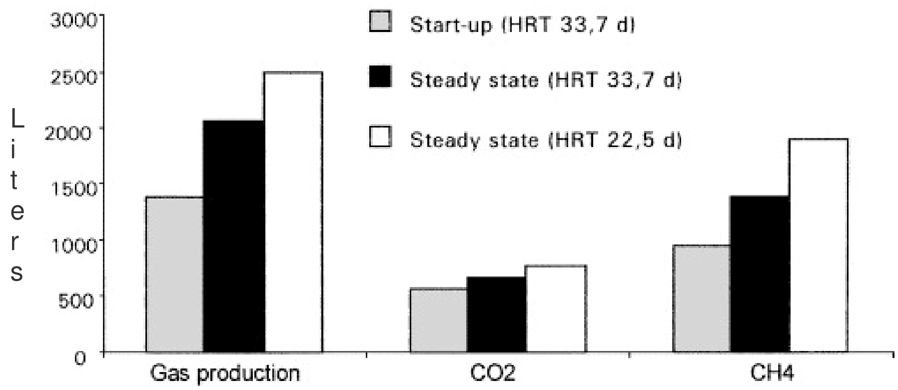


Figure 8.2. Mean values for daily biogas production during different experimental conditions

The bar graph in Figure 8.2 shows similar trends for total gas production, CO_2 production, and CH_4 production. All results are measured in liters of gas. The set of total gas production columns are the sum of the CO_2 and CH_4 production column sets. According to the results, less rise for CO_2 daily production was observed compared with that for CH_4 when related to the start-up trial at the same HRT. This enhanced performance was most likely due to the addition of the methanogenic bacteria.

By shortening the HRT, the daily methane and biogas production increased. However, this parameter was limited by the quantity of substrate fed into the digester every day. In order to determine the value of HRT at which the digester processing such as a substrate reaches maximum gas production, further investigations are needed, but shorter a shorter HRT than 22.5 days would result in lower gas production because the process would become time limited.

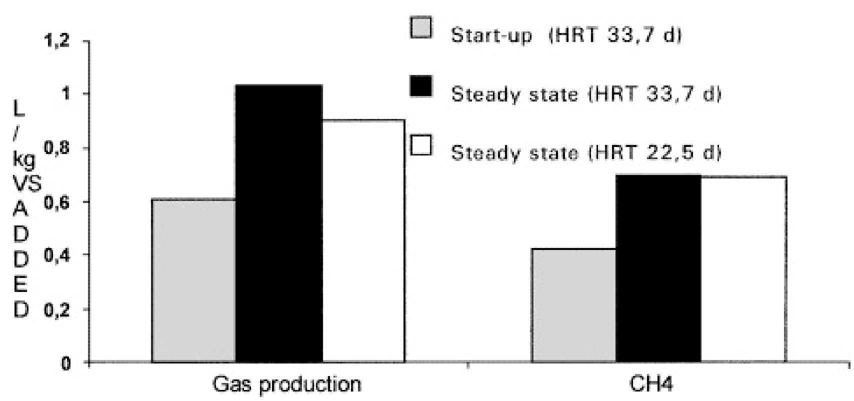


Figure 8.3. Mean values of methane and gas production per kg of VS added during different experimental conditions

As shown in Figure 8.3, at the longer retention time, total biogas production per unit mass of volatile solids fed into the digester was higher than that for the shorter HRT. However, the methane yield did not decrease. If such preliminary results are confirmed by further experimentation, it can be concluded that for the purpose of energy recovery of methane production, the digester can be operated with a shorter retention time, thus significantly reducing its overall dimensions, and subsequently the overall cost (Sharma, 2000).

This study provides a similar biological and chemical context to the thesis model because the feedstock consists of a mixture of food waste and manure, and operates within the mesophilic temperature range. However, whereas the loading rate for the model was only 5.3 kg/day for Mozambique, and 5.9 kg/day for Papua New Guinea, this study used loading rates of 20 and 40 kg/day. The results from ENEA are consistent with the model such that the daily methane production is greatest with a shorter HRT. This suggests that for optimal operation in Mozambique and Papua New Guinea, users should expect the batch system to run for about a month with optimal performance. Beyond this point, gas production will diminish due to bacteria death and useful feedstock depletion attributed to HRT and nutrient-rich material. Therefore, once a month, the system should be emptied and reloaded, or multiple batch reactors should be configured in series to prevent gaps in a steady fuel source.

8.3 Study 3 - Iran

Although thesis model utilizes a batch design, it is important to compare model results to those presented by other operating systems. A study at the Department of Chemical Engineering at Tehran University in Iran, modeled the dynamic behavior of cyclic batch and continuously stirred reactors (CSTR) with periodical feeds and extractions, that are often used in cattle manure anaerobic digestion. The study evaluated the effects of HRT, organic loading rate, reactant concentrations, feeding interval, and initial conditions such as pH and ammonia concentration on process performance. The motivation for this study was to explore the important factors responsible for expansion of anaerobic digestion technology in developing as well as developed countries, such as environmental conservation, irregular increase of wastes resulting from human activities, correct use of available natural resources, repaid depletion of vital sources, air pollution resulting from wood and fossil fuel combustion, and the vital requirement to use renewable energy resources (Keshtkar, 2001).

The system was maintained in the mesophilic temperature of 35°C throughout experimentation. Several assumptions were made about the gas phase: biogas contains methane, carbon dioxide, and water, biogas

follows ideal behavior, temperature and volume are assumed constant, water vapor in the biogas stream is at saturation state, and methane has low solubility in the liquid phase (Keshtkar, 2001).

The following figures resulted from a series of experiments for anaerobic digestion of cow manure in one liter complete-mix continuous reactors, based on the gas phase assumptions listed above. The predictive results generated from the study were compared to an experimental study performed in Spain (Bjora, 1994). Figure 8.4 compares the predicted versus experimental methane production rate as a function of HRT, measured in milliliters per day.

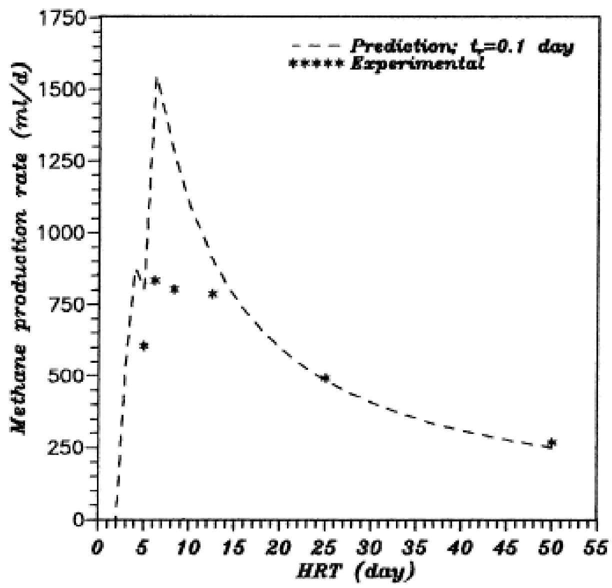


Figure 8.4. Comparison between experimental and prediction of methane production rate as a function of HRT

As shown, the maximum values for the methane production rate for the optimum HRT range fall between 5 and 15 days. The decrease in the methane production rate for HRTs higher than the optimum is due to a decrease in the organic loading rate, whereas for HRTs lower than the optimum, this decrease is due to the cell wash out and the accumulation of volatile fatty acids.

Since this study utilizes a CSTR system, the methane production period exceeds that in the thesis model. In the study, the maximum methane production for the optimum HRT falls between 5 and 15 days, whereas in the model systems in Mozambique and Papua New Guinea, maximum gas production occurs in the first day or two. Therefore, these results confirm the importance of consistent system maintenance; with continuous stirring, the bacteria are able to more actively consume nutrient-rich waste and produce

more gas over a longer period of time. The stirring extends the HRT by increasing available surface area of the feedstock material, and maintaining optimal moisture content.

8.4 Study 4 – United States

A study conducted at the University of Illinois, monitored the anaerobic digestion of cattle waste at mesophilic and thermophilic temperatures using stirred, bench-top fermentors fed on a semi-continuous basis each with a working volume of 3 liters (Mackie, 1995). Figure 8.5 compares the experimental values from this study and the prediction of gas production rate as a function of organic loading rate at a temperature of 40°C from Keshtkar.

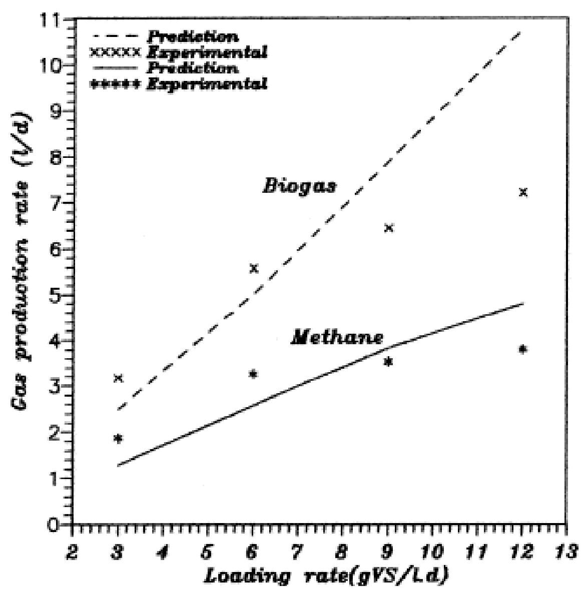


Figure 8.5. Comparison between experimental and prediction of gas production rate as a function of organic loading rate at a temperature of 40°C

As shown, the gas production rate is measured in liters per day, and as the loading rate increased, the gas production rate increased. However, there is a discrepancy between the predicted and experimental values of the study such that the predicted curves seem to increase at a faster rate than what was actually observed during experimentation. The accumulation of fatty acids curbed the production rate, especially at the high loading rates. Therefore, for optimal digester performance, fatty acids must be removed.

Prediction of optimum HRT is important for design engineers. In Figure 8.6, the ability of the model for prediction of optimum HRT is shown for a daily cyclic batch reactor under different feed total chemical oxygen demand (COD) concentrations. Chemical oxygen demand is commonly used to indirectly

measure the amount of organic compounds in water, as a test for water quality. It is expressed in grams per liter, which indicates the mass of oxygen consumed per liter of solution (Keshtkar, 2001).

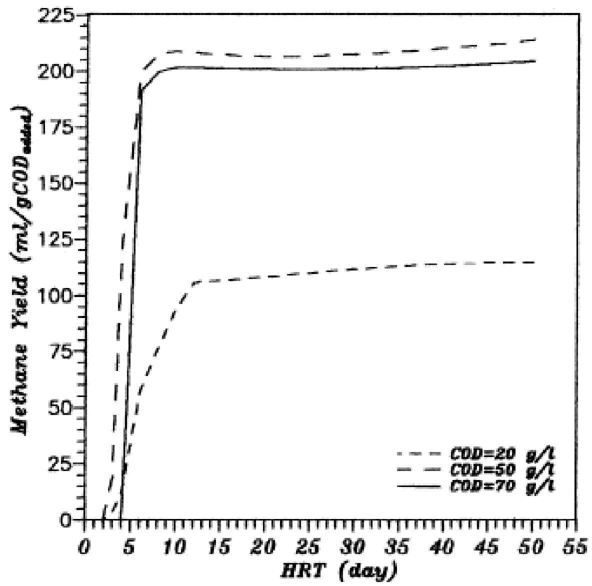


Figure 8.6. Model prediction for methane yield as a function of HRT at t_r=1 day and various COD concentrations of feed

As shown, the optimum HRT for the three substrate concentrations varies from 10 to 15 days. Since for HRTs greater than the optimum, the methane yield is nearly constant while for HRTs smaller then the optimum, the yield decreases sharply and the process is unstable. Therefore, increasing organic loading rate to the reactor without having unstable effects can be carried out by increasing influent substrate concentration instead of decreasing HRT.

Although the thesis model did not focus on the biochemical content of the feedstock material, Chapter 5 explained the assumed composition of the feedstock for each location, give local crop and animal waste available, as well as the proper C/N ratio for optimal system performance. Therefore, the results of this study verify the important of a balanced system in terms of waste content and a consistent loading rate. It makes sense that as more material is added per day, more gas is produced. However, as shown in both the study and model results, there are limits to both the ratio of waste to bacteria population, and the quality of the waste input into the digester. When the waste doubled and tripled, more gas was produced initially, but once the system regained equilibrium, gas production returned to the output given during baseline conditions. This surplus, although advantageous, is unlikely for a system in the developing world.

The effect of the time interval of feeding on the gas production as a function of time was evaluated. In Figure 8.7, the dynamic simulation of methane generation for cyclic batch reactors is compared to a continuous stirred tank reactor (CSTR) simulated by taking t_r = 0.1 day.

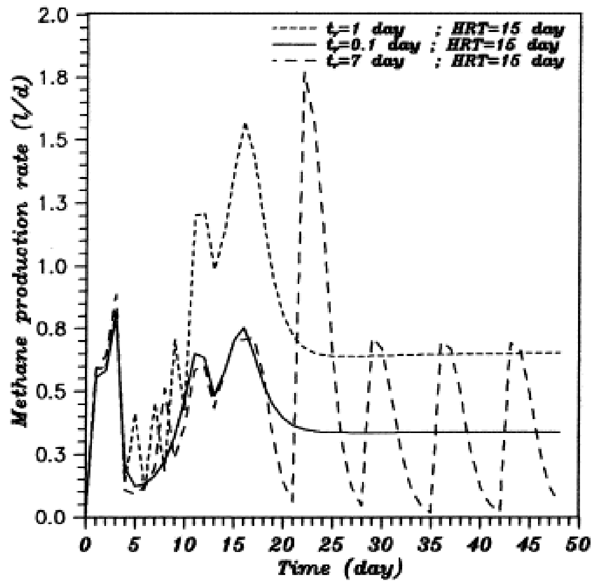


Figure 8.7. Comparison between dynamic modeling of methane generation at different feeding time intervals

As shown, the performance of a reactor fed on a daily basis is better than one fed weekly. In this experimental study, at steady state conditions the daily methane production for a CSTR is less than for a daily cyclic batch reactor, but greater than for a weekly cyclic batch reactor (Keshtkar, 2001). At the beginning of the process, methogenic bacteria quickly consume the acetate existing in the reactor. This fact explains a short peak in methane production observed during the early days of the process. The height of this peak allows for evaluation of the concentration of methanogenic bacteria in the reactor. Since the initial acetate and methanogenic bacteria concentrations have been chosen equal for all three cases, the height of the peak is observed equal for all three curves.

This study states that more biogas is produced given a daily loading rate instead of a weekly loading rate. The thesis model assumes a loading rate of 5.3 kg/day for Mozambique, and 5.9 kg/day for Papua New Guinea. Model results showing increased gas production in the first day or two confirms that it is an accurate representation of a batch system.

8.5 Study 5 – United States

In a study conducted in the Biological and Agricultural Department at the University of California, food waste collected in the City of San Francisco, California, was characterized for its potential for use as a feedstock for anaerobic digestions processes. The daily and weekly variations of food waste composition over a two-month period were measured. The anaerobic digestibility and biogas and methane yields of the food waste were evaluated using batch anaerobic digestion tests performed as 50°C.

The objectives of this study were to characterize the food waste collected from commercial restaurants for assessing their potential as a feedstock for a thermophilic anaerobic digester and to determine the overall variability and consistency of this material over time. Since the food waste collected from original sources contained considerable impurities, such as wood, metal, cardboard, glass, and plastics, a screening and grinding operation previously developed by a waste management company was used to prepare the food waste for anaerobic digestion.

In the experimental study, the composite samples were digester in four 1-L batch digesters at two initial volatile solid (VS) loadings, each in duplicate, and at a thermophilic temperature (50 ± 2°C). The effective volume of each digester was 0.5 L. At the beginning of the digestion tests, in each digester, 150 mL of bacterial inocula was mixed with food waste at an amount determined from the initial VS loading and the VS content of the food waste (Zhang, 2007).

The methane yield (mL/g VS) and methane production rate (mL/L-d) during the digestion of food waste are shown in Figures 8.8 and 8.9, respectively.

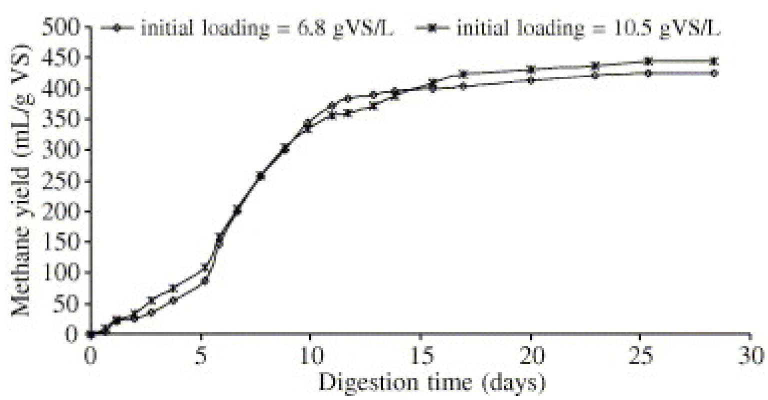


Figure 8.7. Methane yield of food waste during anaerobic digestion at 50 °C at two different initial loadings

Methane production increased until day 16, and then remained almost constant at a low level until the end of the experiment (28 days). The average level of methane yield from the digesters with 6.8 and 10.5 g VS/L initial loadings after 28 days of digestion was approximately 425 and 445 mL/g VS added, respectively, with their average being 435 mL/g VS. Essentially, there was no significant difference in the methane yield between the two different initial loadings. Approximately 80% of the methane yield was obtained after the first 10 days of digestion.

The thesis model was constrained to the mesophilic temperature range, but in order to compare results to this study using a thermophilic temperature range, the results from the extreme weather patterns for Papua New Guinea were used. Under the conditions defined by the thesis model, the temperature range was held at approximately 41°C, which is below the 50°C used in the study, but greater than the model baseline. The 10.5 gVS/L loading rate results from Figure 8.7 above show that more gas is produced with a high loading rate, which matches the thesis model results. However, because the digester is held above the optimal temperature range for the system in Papua New Guinea, less gas is produced each month. The different results between this study and the model show how important it is to consider the overall context of the system, including feedstock material, loading rate, and solar insolation. Therefore, a system dynamics approach is an accurate and effective method of generating realistic results.

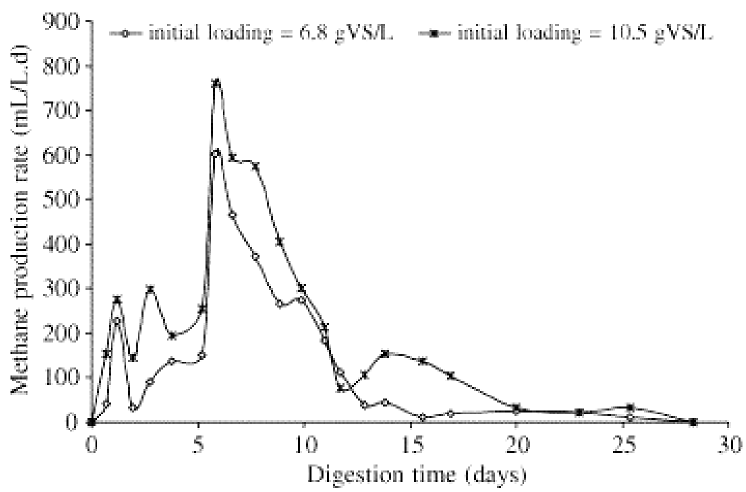


Figure 8.8. Daily methane production during digestion of food waste at two different initial loadings

As shown in Figure 8.9 from the study at the University of California, the methane production rate was relatively low during the first five days of digestion, increased to reach a peak at the sixth day of digestion, and then declined again. The maximum methane production rates of about 602 and 762 mL/L-d could be achieved for the digesters started at 6.8 g VS/L and 10.5 g VS/L initial loadings, respectively.

However, during the increasing period (day 2 to day 11), the average methane production rate per gram of VS was almost the same for both starting initial loadings. The calculated average methane rate during this period was 31 mL/L-d for both loadings. This may suggest that the anaerobic sludge used in the experiments had a high methanogenic activity.

The delay in gas production peak in this study verifies that there is a lag between bacteria consumption, and subsequent gas production. These results are apparent in the thesis model as well. The trends in Figure 8.9 match those in the thesis model throughout the analysis for Mozambique and Papua New Guinea, where there is an initial lag in gas production, a peak, and then the system reaches equilibrium. This reaffirms the importance of consistent loading rate in order to predict gas production, to use as a reliable fuel source.

8.6 Study 6 – Egypt and United States

In a research study conducted jointly between the Department of Agricultural Engineering at Mansoura University in Egypt, and the Biological and Agricultural Engineering Department at the University of California, evaluated the effect of screening on biogas yield of dairy manure and assessed the energy benefit gained from co-digesting dairy manure and food waste as compared to digesting dairy manure and food waste separately. Another objective was to develop a simple first-order kinetics simulation model to predict the methane yield from batch digestion of different mixtures of food waste and dairy manure (El-Mashad, 2010). The effect of manure screening on the biogas yield of dairy manure was evaluated in batch digesters under mesophilic conditions (35°C).

Figure 8.10 shows the biogas yield from unscreened manure, manure's fine and coarse fraction, food waste and two mixtures of food waste and unscreened manure. Each data point is the average of the measurements of two reactors.

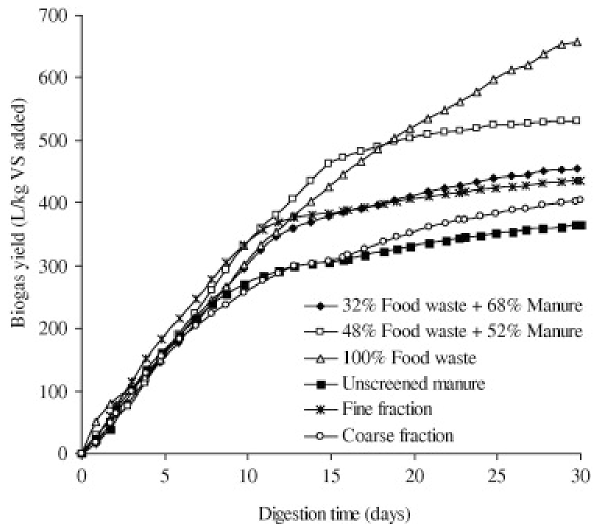


Figure 8.10. Biogas yield based on effect of screening and co-digesting feedstock

The fine fraction of screened manure had the highest biogas yield, compared with the coarse fraction and the unscreened manure. After 30 days of digestion, biogas yield was calculated to be 436, 404, and 366 L/kgVS for the fine and coarse fraction, and the unscreened manure, respectively. The statistical analysis showed that the biogas yield of fine or coarse fraction is significantly different from the yield of unscreened manure; however, there is no significant difference between fine and coarse fractions (El-Mashad, 2010). The higher biogas yield of the coarse fraction as compared to the unscreened manure may be attributed to the presence of spilled feed such as corn silage and grains. The mixture or food waste and manure, as well as the digestion of only food waste produced the most biogas. This indicates that the addition of food waste increases the biogas output in a mesophilic batch reactor.

Figure 8.11 shows the daily biogas production rates (L/L kgVS day) from unscreened manure, manure's fine and coarse fraction, food waste and two mixtures of food waste and unscreened manure. Again, each data point is the average of the measurements of two reactors.

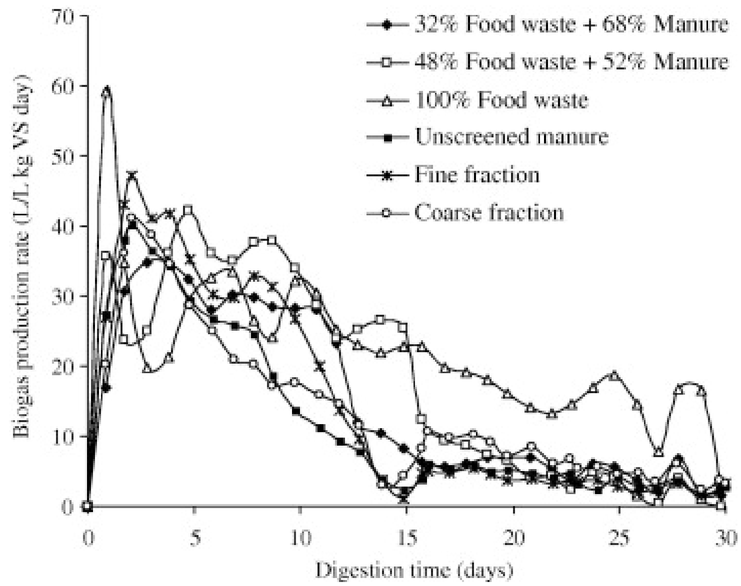


Figure 8.11. Daily biogas production rates based on effect of screening and co-digesting feedstock

For all manure types, a peak biogas production rate was observed after the second day of digestion. The maximum values of biogas production rate were 47, 40, and 41 L/L kgVS day for the fine and coarse fraction, and the unscreened manure, respectively (El-Mashad, 2010). The higher biogas production rate from the fine fraction may be attributed to the smaller particle sizes of this fraction and the presence of easily biodegradable organics compared with both the coarse fraction and the unscreened manure.

The results from this study match those from the thesis model, and confirm the importance of the mixture of food and crop waste, as discussed thoroughly in Chapter 5. Although the trends for food waste alone yield the greatest initial peak in biogas, this is unrealistic for the agricultural contexts of Mozambique and Papua New Guinea. As discussed in thesis model analysis, surface area plays a significant role in the amount of biogas produced, as the fine fraction trends are considerably higher than those for the coarse fraction.

The experimental figures and results from the studies in this chapter provide support from literature to the accuracy of the production of methane using a plug-flow anaerobic digestion system. Table 8.1 provides a summary of the key factors from each study, aims and results from each study, and a comparison of the study and Stella model results. Although the design and operating parameters for these systems vary from the proposed design modeled in this thesis, the trends remain constant. Consistency with previously published experimental data verifies the robustness, reproducibility, and overall performance of the system dynamics model. Any gaps can be attributed to differences in initial assumptions and constraints.

Table 8.1. Summary of key factors from studies and comparison to model results

STUDY	KEY FACTORS	AIMS / RESULTS OF STUDY	COMPARISON OF STUDY AND MODEL RESULTS
1	- Mesophilic temperature range - Plug-flow design - Solar component - System volume – 45 m^3 - Loading rate – 7.5 kg/day - HRT – 10 days	- Developed mathematical model for simulating solar-heated anaerobic digester - Experimentally investigated performance of the system and results indicate that use of solar collectors as a cover reduces thermal losses and positively affects the heat balance of the digester - Proposed model accurately predicts thermal behavior of the solar-heated digester compared to measured data	- When no overheat control, temperature fluctuation exceeds optimal range bacteria, and gas production ceases - Flat plate solar collector is advantageous because it adds a consistent source of heat, but without the overheat control, it inhibits the system - Fluctuation in methane production caused by not removing spent slurry from Stella system is realistic, as confirmed by erratic fluctuations shown in study - Without proper system maintenance, methane still produced, but output inconsistent
2	- Mesophilic temperature range - Inclined plug-flow design - No solar component - Start-up loading rate – 20 kg/day - Steady state loading rate – 40 kg/day - Start-up HRT – 33.7 days - Steady state HRT – 33.7 days - Steady state HRT – 22.5 days	- Performed set of experiments using semi-solid wastes available from wholesale fruit and vegetable markets mixed together with different portions of sewage sludge to establish an efficient and reliable anaerobic treatment process - Determined that successful operation of waste treatment depends on both composition of substrate and developed population of anaerobic bacteria - If preliminary results are confirmed by further experimentation, it can be concluded that for purpose of energy recovery of methane production, digester can be operated with shorter HRT, which significantly reduces overall dimensions and cost	- Study provides similar biological and chemical context to Stella model - Stella model loading rate was much lower, only about 5.5 kg/day - Both results show daily methane production is greatest with shorter HRT - Batch system should run for about a month with optimal performance; beyond this point, gas production diminishes due to bacteria death and useful feedstock depletion attributed to HRT and nutrient-rich material

3	- Mesophilic temperature range - Continuously stirred tank reactor (CSTR) design - No solar component	- Motivation was to explore important factors responsible for expansion of anaerobic digestion technology in developing and developed countries - Modeled dynamic behavior of CSTRs with periodic feeds and extractions - Evaluated effects of HRT, organic loading rate, reactant concentrations, feeding interval, and initial conditions (pH and ammonia concentration) on process performance	- CSTR system methane production period exceeds that in Stella model - Maximum methane production for optimum HRT falls between 5 and 15 days in study, whereas in Stella model, maximum gas production occurs in few days - Results confirm importance of consistent system maintenance; continuous stirring allows bacteria to more actively consume nutrient-rich waste and produce more gas over longer period of time - Stirring extends HRT by increasing available surface area of feedstock material, and maintaining optimal moisture content
4	- Mesophilic temperature range - Thermophilic temperature range - Semi-continuous stirring design - No solar component - System volume – 3 L	- Methane production was 84.5% higher in thermophilic digester than mesophilic digester - Methane production decreased with each increase in loading rate and decrease in HRT - Amount of methane was 49% less at highest compared to lowest loading rate in mesophilic digester; 16% less in thermophilic digester	- Stella model did not focus on biochemical content of feedstock material, but system constraints were based on composition of feedstock for each location, given local crop and animal waste available, as well as proper C/N ratio for optimal system performance - Study results verify importance of balanced system in terms of waste content and consistent loading rate - Both results show there are limits to ratio of waste to bacteria population, and quality of waste input into digester - When waste doubled and tripled, more gas produced initially, but once system regains equilibrium, gas production returns to baseline output - Study states that more biogas is produced given daily loading rate > weekly loading rate; confirmed by model results showing increased gas production in first couple days

5	- Thermophilic temperature range - Plug-flow design - No solar component - System volume – 0.5 L - Loading rate – 6.8 g VS/L - Loading rate – 10.5 g VS/L - HRT – 2 months - 150 mL bacteria added	- Objectives were to characterize food waste collected from commercial restaurants for assessing their potential as feedstock for a thermophilic anaerobic digester, and determine overall variability and consistency of this material over time - Used screening and grinding operation previously developed by waste management company to prepare waste for digestion	- Used extreme weather pattern results for PNG to compare results from study using thermophilic temperature range - Stella temperature range lower than in study - Both results show more gas is produced with higher loading rate, given plug-flow design - Delay in gas production peak in study verifies lag between bacteria consumption, and subsequent gas production - These trends match those in Stella model throughout analysis where there is initial lag in gas production, a peak, and then system reaches equilibrium - Results verify need for consistent loading rate
6	- Mesophilic temperature range - Plug-flow design - No solar component - System volume – 1 L - HRT – 30 days - 100 mL bacteria added	- Main objective was to evaluate the effect of screening on biogas yield of dairy manure, and to assess energy benefit gained from co-digesting dairy manure and food waste as compared to digesting dairy manure and food waste separately - Developed a first-order kinetics model to calculate methane yield from different mixtures of food waste and unscreened dairy manure - Predicted results from model showed that adding food waste into manure digester at levels up to 60% of initial volatile solids significantly increased methane yield for 20 days of digestion	- Study results confirm importance of mixture of food and crop waste - Although trends for food waste alone yield greatest initial peak in biogas, this is unrealistic for agricultural contexts in developing world - Results indicate importance surface area plays on amount of biogas produced, as fine fraction trends are considerably higher than those for coarse fraction in study

9 CONCLUSIONS AND FUTURE WORK

9.1 Conclusions

Much of the developing world lacks access to a constant supply of useful energy. Because of this, people turn to local, natural resources to meet their daily needs. However, these resources provide only a short-term solution. The use of firewood depletes natural resources. Cooking over an open stove creates hazardous health effects through inhalation of particles. Since agricultural practices are easily linked to energy production, anaerobic digestion provides a cheap and effective solution to meet daily energy needs. This process produces methane, which is comparable to natural gas, which can be used directly for cooking, heating, and lighting. In addition, anaerobic digestion is an existing technology, which allows for flexibility in system size, design complexity, and cost.

Anaerobic digestion is a sustainable technology that turns waste into energy. It provides energy close to the sources in need, such as homes, schools, and hospitals. The process replaces a dependence on firewood as a source of fuel which slows deforestation and soil erosion, decreases hazardous health effects, and increases safety of everyday activities. Environmentally, anaerobic digestion captures uncontrolled methane emissions, reducing release of a potent green house gas into the atmosphere.

Since much of the developing world lies close to the equator, adding a solar component is beneficial to digester performance. Heats acts as a catalyst for biological processes and increases the activity of methane-producing bacteria. A solar component allows for better overall system temperature regulation, which is important for optimal bacteria performance in terms of gas production. In addition, any excess heat can be dumped into a hot water storage tank and used for cooking and sanitation.

After review of several patents, digester designs, models, and experiments, no previous work has used a dynamic feedback model incorporating a solar component. A tool with this capability would allow end users to determine potential biogas output for various locations, given initial conditions and input parameters. Therefore, a computer-based system dynamics model allows for the analysis of sensitivity of outcomes based on changes in stated assumptions. The assumptions given the most attention depend on the dominant behavior, cost elements, and components of greatest uncertainty in design. In the model presented in this work, there components were solar insolation trends, loading rate, bacteria population and consumption rates, waste feedstock, and biogas production.

Two developing world countries, Mozambique and Papua New Guinea, were selected based on the fact that they are both agriculture-based societies, have a high number deaths attributed to hazardous levels of indoor air pollution, and have geographic locations, climate, and weather patterns that favor mesophilic anaerobic digestion.

The work presented in this thesis shows that it is possible to use system dynamics to accurately model the behavior of a solar-heated anaerobic digester. Taking into account the biological and chemical factors of the system, geographical location, and societal practices, this tool can evaluate the energy needs of both the developed and developing world.

According to the formal problem statement in Chapter 4, the purpose of this work was to focus on the development and validation of a computer-based model that combines the most important elements of the anaerobic digestion process in order to predict methane output; and following validation, to flex the model to:

1. Explore how addition of a solar component increases robustness and performance of the design
2. Examine predicted biogas generation as a function of varying input conditions, and
3. Determine how best to configure such systems for use in varying developing world environments

Through preceding model analysis and discussion, the system dynamics model for the proposed anaerobic digestion system achieves all three of these aims.

According to the modeling results discussed in Chapter 7, for optimal operating conditions for a system in Mozambique, there must be a steady stream of waste input and the temperature must stay in the lower to middle mesophilic range given the higher average annual solar insolation and solar component. Doubling and tripling the amount of waste significantly increases bacteria population and subsequent gas production. Adding more bacteria to the system increases gas production initially, but there must be a balance between the amount of waste available and this population because gas production will be difficult to control if the system does not find equilibrium. Bacteria population can have a positive or negative effect, depending on the level of monitoring taken by the operator. Finally, the more spent slurry that is removed from the system, the better it operates.

For optimal operating conditions for a system in Papua New Guinea, there must be a steady stream of waste input, a solar collector, and the temperature must stay in the lower mesophilic range given the

impact of severe drought and minimal water content for feedstock material. Doubling and tripling the amount of waste significantly increases bacteria population and subsequent gas production. Although it is important to remove non-useful waste from the digester, there is little change in system performance when these actions stop. Increasing or decreasing the bacteria population has minimal effect on the system. Unlike the system in Mozambique, it takes longer for the system in Papua New Guinea to regain equilibrium. This means the system would require additional maintenance and monitoring on a consistent basis. Therefore, it may be more difficult for a system in Papua New Guinea to thrive given the initial context, unpredictable weather patterns, and relatively inflexible operating conditions.

When compared to modeling and experimental studies discussed in Chapter 8, the thesis Stella model results held up. Based on the summary of results from all of the studies, the most important factors are temperature range, loading rate, hydraulic retention time, feedstock mixture and content, and particle size. Only two of these factors were controlled in the thesis model, which leaves much room for future modeling work. There factors, as well as many other areas of future work will be discussed later in this chapter.

Therefore, based on overall modeling results and analyses, it can be concluded that a computer-based model is capable of realistically following the behavior of a batch system, with the addition of a solar component. Anaerobic digestion is a sustainable technology which provides an economical and sustainable solution to help improve quality of life, and simultaneously, replace harmful methods of energy production.

9.2 Future Work

The work in this thesis provides an excellent baseline for the potential of a sustainable technology to make a significant impact on the quality of life in the developing world. However, there exist many areas of improvement associated with the complexity and capability of the system dynamics model in the future. The following paragraphs discuss some of the more apparent improvements to the system, based on limitations from the current model.

9.2.1 Multiple Waste Streams

The current model uses a single waste stream, but this is not accurate for real world application. As discussed in Chapter 5, each geographical location has unique livestock, crop waste, and agricultural

practices that all impact the function and maintenance of an anaerobic digester. The calculations were based on available components, specifically monitoring the C/N ratio of the mixture, to allow for optimal gas production.

In a future model, the system should allow for multiple waste streams, and consider the mixing process. It is likely that the biological content of the feedstock will vary with weather and seasonal patterns, versus having the exact same C/N ratio with each loaded batch. Therefore, there would be more fluctuations in biogas output, and possibly quality over the course of the year. However, once an optimal mixture is determined, it can be a powerful tool in terms of predicting the biogas output for longer periods of time, and allow for both storage and distribution planning.

9.2.2 Bacteria

As the feedstock mixture becomes more complex, so does the bacteria population. Multiple types of waste input will generate multiple types of bacteria. The current model associates a bacteria colony with an amount of waste, such that each colony is responsible for consuming a specific amount of waste in the digester, and therefore responsible for producing a specific fraction of the biogas. However, with multiple types of waste, these biological and chemical interactions become increasingly more complex. The degradation and consumption rates of the waste vary with biochemical makeup of each substance. This means that as each new type of waste is added to the system, a new type of bacteria will emerge to consume it.

In a future model, the system should allow for multiple types of bacteria with multiple birth, death, and consumption rates, as well as the interactions between these various types. It is likely that one type of bacteria can consume multiple types of waste material, creating competition between bacteria types for available food. With a steady input, these interactions should reach a state of balance, but as each new batch with varying content is introduced to the system, there will be fluctuations that will be visible in terms of gas output, and sludge within the digester. Therefore, it will be important to note the changes in behavior and in order to account for adjustments in loading rate, retention time, and waste removal from the system on a regular basis.

9.2.3 Pre-treatment of Waste

There have been multiple experimental studies involving anaerobic digesters that explore pre-treating the waste feedstock, to increase system performance, some of which have been cited in this thesis. As discussed, the biological composition of feedstock materials, as well as the entire mixture of waste, is extremely important. Depending on the type of system, water, particle size, and hydraulic retention time are all important factors. In a batch system, as proposed in this thesis, the window for optimal gas output is much smaller and more erratic than in a continuous stirred tank reactor (CSTR), for example. This means that pre-treatment of the feedstock waste to fit the ideal environmental conditions of the digester is necessary to have a predictable and reliable system. It becomes even more important with varying feedstock input mixtures based on weather or seasonal changes, since the mixture would not be consistent from one loading period to the next. Therefore, pre-treatment of the feedstock should be accounted for in a future model, even if it is listed as an initial system assumption.

9.2.4 Internal Digester Factors

As discussed in background information in Chapter 2, two of the most important factors for anaerobic digester success are the pH and presence of toxic materials. For methanogenic bacteria, the optimum pH ranges from 6.4 to 7.6, whereas non-methanogenic bacteria are not nearly as sensitive, and can function in a pH range from 5.0 to 8.5 (Price, 1981). Since pH is a function of the retention time, it is important to add this constraint to the model. For example, as the model accounts for the specific type of waste input, it should be able to calculate the overall pH of the system. If the pH goes outside the optimal range, the system should shut down, or generate an error message, in order to notify users of the problem.

The same should apply to the presence of toxic materials in the system. The model should accurately monitor the organic loading and biological solids retention time, in order to prevent any stress on overall performance. If any material is introduced into the system that poses a toxic effect, the system should shut down, or generate an error message. It is likely that there will always be some level of potentially toxic material in the system, as the feedstock mixture varies, so the model should set constraints to keep the level within an optimal range.

9.2.5 Filtering, Purification, and Storage of Biogas

Recent technologies to purify biogas having about 50-65% methane have been found to increase its caloric value yielding about 70-85% methane or more. Biogas cannot be stored easily as it does not liquefy easily under pressure and at ambient temperature. Raw biogas contains impurities comprising about 30-45% CO_2 which specifically hinders its compression into cylinders; traces of H_2S and water vapor which facilitate corrosion in generator parts and other storage devices.

In a study in the Department of Energy Systems Engineering at Koforidua Polytechnic in Ghana, three common methods of purifying biogas, absorption in water, absorption using chemicals, and biological methods were considered. Water scrubbing is the absorption of CO_2 and H_2S in biogas using water at high pressure. After analysis of all three methods, the capital costs associated with water scrubbing were lower than chemical absorption, and operational and maintenance costs were lower than chemical absorption and the biological method (Ofori-Boateng, 2009). It is also revealed in previous studies that chemical absorption releases some dangerous gases into the environment. This contributes significantly to the green house effect, which violates the benefit of biogas. Water scrubbing is found to be eco-friendly compared to the other methods.

Therefore, the model should incorporate filtering, purification, and storage options based on the composition of the output gas. In conjunction with the overall system constraints, the composition will help determine how much of the gas should be used directly from production, or if it should be stored. The filtration and purification processes should be utilized regardless, to increase the caloric value of the biogas.

9.2.6 Incorporating Economic Analysis

Economic analysis is one of the most important components to any alternative energy solution. The current model focuses more on system prediction and function, rather than a marketing tool. Since the digester is meant for the developing world, an interesting comparison in a future model will be not only the costs and benefits associated with system installation and maintenance of an individual inhabitance, but how the addition of an anaerobic digester will alter the costs associated with energy in the community.

It is assumed that the purpose of the system is to provide methane for everyday activities, not to make a profit. However, depending on the results from the model, it is possible that an excess of methane may be

produced. Therefore, an economic analysis would provide insight as to how the surplus gas is stored or distributed, and possibly suggest how the biogas should be networked, based on system performance. In addition, taking into account economic demographics will allow for adjustments on the type and size of the implemented system, and confirm the best fit for the potential household or community.

9.2.7 Environmental Factors

Although the current model takes into consideration the solar insolation for a specific geographic location, there is no input for varying weather patterns or seasonal anomalies. It is difficult to predict severe storms, but it is important to be able to alter the input factors of the model in case a disruption in the normal behavior occurs. For example, if a severe drought diminishes the production of a certain crop, it is likely that not as much or none of that material will be used as feedstock material. This in turn will upset the biochemical composition of the waste stream, all internal factors within the digester, and ultimately the biogas output and composition. Therefore, a future model should be able to incorporate the possibility of unpredicted environmental factors that will directly impact system performance.

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