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Design of Small Scale Anaerobic Digesters for Application in Rural Developing Countries

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Design of Small Scale Anaerobic Digesters for Application in Rural Developing Countries

by

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Dedication

To Paul J. Notarianni – An amazing, courageous person and a great friend. One day, I will build a space ship powered by liquid methane produced from animal waste.

To Casey, Eleni, and Daragh – Admirable women of strength speaking truth.

To Kate – Whom I never knew. May we bring change to the Peace Corps in her memory and name.

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Table of Contents

List of Tables

List of Figures

List of Symbols

a = animal

kg = kilogram

m = meter

d = day

% = percent

Q = volumetric flow rate (m^3/d)

Q_0 = initial volumetric flow rate (m^3/d)

C = concentration

C_0 = initial concentration

kg VS = kilograms of volatile solids

µg = microgram

µm = micron; micrometer

L = liter

mg = milligram

mol = mole

θ_c = solids retention time (d)

X = cell concentration

Q_w = volumetric flow rate, out (m^3/d)

X_w = cell concentration, out

C_{VS} = concentration of volatile solids (kg VS/m^3)

$V_{reactor}$ = liquid and solids reactor volume

[ ] = concentration (mol/L)

ºC = degrees Celcius

atm = atmosphere

ρ = density (kg/m^3)

P = pressure

θ = hydraulic residence time (HRT) (d)

V = volume

log = logarithm base 10

(g) = gas

K_H = Henry's gas constant

% wt. = percent by weight basis

List of Acronyms

CH_4 = methane

CO_2 = carbon dioxide

H_2S = hydrogen sulfide

PFR = plug flow reactor

CSTR = continuous stirred tank reactor

SRT_{lim}^{min} = minimum solids retention time (d)

SF = safety factor

HRT = hydraulic retention time (d)

SRT = solids retention time (d)

OLR = organic loading rate (kg VS/(m^3*d))

HDI = human development index

LPG = liquid petroleum gas

MDG = Millennium Development Goals

DALY = Disability-Adjusted Life Year

U.S. EPA = United States Environmental Protection Agency

NH_3 = ammonia

GWP = Global Warming Potential

BOD = biochemical oxygen demand

BOD_u = ultimate biochemical oxygen demand

BOD_5 = 5-day biochemical oxygen demand

$CaCO_3$ = calcium carbonate; alkalinity

H_2 = hydrogen gas

COD = carbonaceous oxygen demand

H^+ = hydrogen proton

HCO_3^- = bicarbonate ion

CO_3^{2-} = carbonate ion

OH^- = hydroxide ion

pKa = logarithm of the Ka (activity coefficient)

alk. = alkalinity

bicarb. = bicarbonate

carbs = carbohydrates

temp. = temperature (ºC)

VFA = volatile fatty acids

TOC = total organic carbon

N/A = not applicable

TFE = tetrafluoroethylene; Teflon

Abstract

The high incidence of upper respiratory diseases, contamination of waterways due to pathogens and nutrients from human and animal wastes, unsustainable deforestation, gender disparities in burden of disease due to unequal exposure to indoor air pollutants, and carbon black emissions from the burning of solid fuels are interrelated problems in many developing countries. Small scale anaerobic digestion provides a means of alleviating these problems by treating livestock waste onsite to produce biogas (methane and carbon dioxide) in rural areas in developing countries. Fuel can then be used for cooking, lighting, and heating. Methane fuel is an alternative to traditional three-stone fires, improved cook stoves, and liquid petroleum gas. However, there is a lack of information available on design methods for these systems. The goal of this research was to develop a design tool that could be used for anaerobic digester sizing based on livestock waste availability. An Excel spreadsheet model was developed for sizing the bioreactor and the gas container based upon recommended values from a literature review. Needed monitoring parameters for operation of an anaerobic digester in the field were identified and standard methods of analysis were recommended. Sample preservation techniques were detailed. Guidelines for pathogen reduction in thermophilic anaerobic digestion were identified. Further study of pathogen reduction in low temperature reactors currently in use in developing countries was recommended. Three digester designs included in the Excel spreadsheet model were: the polyethylene tubular

digester, the floating drum digester, and the fixed dome digester. The design tool may be requested from Dr. Sarina Ergas, sergas(at)usf.edu. An organic loading rate of 1.0 kg VS/(m^3*d) was chosen for use in the design tool based upon a review of the literature. A semi-empirical kinetic model was developed for defining the SRT based on the temperature inputted by the user. Three case studies, based upon livestock waste availability in a rural community in the Dominican Republic, were analyzed using the sizing design tool. The case studies were conducted on three scales: one household, six households, and a village of 48 households. The specific biogas production rates were, for Case Studies one through three, respectively, 0.0076, 0.0069, and 0.010 m^3 biogas/kg Volatile Solids reduced. Additional future work included: characterization of human feces and guinea pig manure, laboratory and field testing of the Excel spreadsheet design tool, and promotion of anaerobic digesters by development workers, non-governmental organizations, and governments.

Chapter 1: Introduction

1.1 Problem Description

Small scale anaerobic digesters provide potential solutions to: 1.) poor indoor air quality and subsequent chronic health problems, 2.) unequal exposure to hazards by gender, 3.) the need for a cooking fuel, 4.) deforestation for fuel use, 5.) lack of treatment of animal waste, 6.) expensive inorganic fertilizers, 7.) mitigation of methane released into the atmosphere, and 8.) reduced amount of residuals for disposal, compared with aerobic treatment (Smith, 1993; Mihelcic et al., 2009; WHO, 1979; Smith et al., 1994; Niles et al., 2002; Katuwal & Bohara, 2009; Douglas & Simula, 2010; Tchobanoglous et al., 2003; World Health Organization, 2011; Jonsson et al., 2004; Mara & Cairncross, 1989). However, many small scale anaerobic digesters in developing countries fail for various reasons, including: design, high capital cost, construction, maintenance, user needs, operational problems, or availability of materials for maintenance (Ocwieja, 2010; van Nes & Nhete, 2007; GTZ / GIZ, 1999). Anaerobic digester designs must be implemented that are best suited to the end user and location, the process variables must be optimized to the extent possible, trained maintenance personnel must be available to the user, and government support must be present (Ocwieja, 2010). The current work addresses choosing and sizing designs that fit the end user and location and discusses optimization of process variables.

Gaps identified in the literature include:

- There are no long term operation studies on anaerobic digesters in developing countries.
- There are no design equations for sizing an anaerobic digester of a given design for small scale[2] anaerobic digesters in developing countries.
- There are no design criteria for maximizing pathogen reduction in anaerobic digesters typical of developing countries.

1.2 Introduction to Anaerobic Digestion

Anaerobic digestion is a biological treatment process that recovers valuable products, energy and nutrients, from organic waste streams in useable forms. Energy is recovered in the form of biogas, typically a mixture of 70 wt.% methane (CH_4), 29 wt.% carbon dioxide (CO_2), and a small percentage of hydrogen sulfide (H_2S) (Rittmann & McCarty, 2001). Nitrogen and phosphorus, valuable nutrients that may be used to augment crop growth as a fertilizer, are recovered in the form of liquid effluent from the digester. Nitrogen and phosphorus are also recovered in the form of biosolids, which may be applied to agricultural land if the pathogen level is low enough.

The anaerobic digestion process results in a net energy output and produces less biological sludge compared to aerobic treatment process. In addition, anaerobic treatment does not require aeration, which has the highest energy costs in wastewater treatment (McCarty, 1964). Small scale anaerobic digesters are currently in use in rural China, India, Nepal, Africa, and Latin America for treatment of animal waste and sometimes, household food scraps. Large scale anaerobic digesters for treatment of municipal waste

[2] Small scale anaerobic digesters are defined by the author as producing biogas which is used directly for cooking, lighting, or heating. If the biogas produced is used for electricity generation, the anaerobic digester is not small scale.

are currently in use in Germany, the United Kingdom, Europe, Brazil, and the United States.

1.3 Positive Community Impacts of Anaerobic Digestion

In the context of small scale anaerobic digestion in rural developing countries, there are many ways in which implementation can positively impact a community's or an individual family's quality of life. Anaerobic digestion addresses the following issues, detailed in Table 1.1:

- energy production in the form of methane, which can be used as a cooking fuel
- indoor air pollution
- unsustainable deforestation due to collection of wood for use as a biomass cooking fuel
- mitigation of methane and carbon black emissions into the atmosphere
- treatment of animal and/or human waste
- empowerment of women
- reduced amount of biosolids to be disposed
- produces nutrient-rich effluent that may be used as a fertilizer

These issues are discussed further in Sections 1.3.1 through 1.3.8.

Table 1.1: Benefits of Anaerobic Digestion in Developing Countries

Benefits of anaerobic digestion for developing country applications	Explanation	Reference
Improved indoor air quality	Combustion of solid biomass cooking fuels results in high levels of particulate matter in the indoor microenvironment. Particulate matter causes respiratory infections in children, adverse pregnancy outcomes, chronic lung diseases and heart diseases, and cancer.	(WHO, 1979; Mihelcic et al., 2009; Smith, 1993)
Energy production in the form of biogas, which can be used as a cooking fuel	Anaerobic digestion is a net-energy producing process. Biogas, similar to natural gas, produces very little air pollution when combusted.	(Mihelcic et al., 2009; Smith-Sivertsen et al., 2004)
Provides an alternative to unsustainable deforestation	One cause of deforestation is the use of wood fuel for cooking and lighting. Introduction of household anaerobic digesters and the use of biogas for cooking reduce wood fuel use and therefore reduce deforestation.	(Douglas & Simula, 2010; Katuwal & Bohara, 2009; Niles et al., 2002)
Provides treatment of human and/or animal waste	Prevents nutrient runoff into water basins which drain to ocean environments, creating environmental problems. Prevents possible diarrheal disease downstream.	(Antweiler et al., 1995; Tchobanoglous et al., 2003)
Empowers women	Women and girls typically spend more time indoors cooking, and therefore, have a disproportionate exposure to indoor air pollution from combustion of solid biomass fuels. They are more likely to develop chronic health problems related to exposure to particulate matter.	(Mihelcic et al., 2009; WHO, 2011)
The amount of biosolids to be disposed is smaller than the amount resulting from aerobic treatment processes	Most of the energy input into the anaerobic digester in the form of raw wastewater is converted to CH_4 and CO_2. Relatively little energy goes to cell growth.	(McCarty, 1964; Tchobanoglous et al., 2003)

Table 1.1, Continued

Nutrient- rich effluent may be used as a fertilizer for crops	Commercial fertilizers are expensive and the processes for making them are unsustainable. Nitrogen and phosphorus are nutrients excreted from the human body in the form of feces and urine. Effluent from anaerobic digestion contains nitrogen and phosphorus which may be used as a fertilizer for agricultural crops.	(Jonsson et al., 2004; Mara & Cairncross, 1989; Smil, 1999; Tchobanoglous et al., 2003)
Mitigation of methane and carbon black emissions into the atmosphere	Methane has a Global Warming Potential twenty-one times greater than carbon dioxide. Black carbon particles absorb radiation and cause warming of glaciers by reducing light reflection.	(WHO, 2011; Cakir & Stenstrom, 2005; Kandlikar, et al., n.d.; Edwards, et al., 2004)

1.3.1 Indoor Air Pollution

Indoor air pollution is a critical public health problem in developing countries. According to Smith (1993), there are four major microenvironments in developing countries (defined as having a Human Development Index (HDI) as less than or equal to 0.784 by the United Nations Development Programme, 2010). These four microenvironments are rural indoors, rural outdoors, urban indoors, and urban outdoors. Particulate matter is released by the burning of biomass (wood, coal, animal dung, hay, etc.) and is of primary public health concern because of its ability to afflict the upper airways of the respiratory system (Mihelcic et al., 2009). Environmental tobacco smoke, crop burning, municipal solid waste burning, and industry emissions, such as power plants, are also sources of particulate matter in less developed countries. Other pollutants of health concern are carbon monoxide and polyaromatic hydrocarbons, both released along with particulate matter when biomass is burned. The majority of air pollution research has been conducted in highly developed countries in urban outdoor environments. There is a lack of air pollution research in less developed countries in rural indoor and urban indoor environments. These two microenvironments are of particular public health interest because they are the microenvironments in which the greatest amounts of people in the world spend the majority of their time. According to Smith (1993), 77% of people in the world in 1990 were living in less developed countries. Three-fifths of these people's time was spent indoors. Additionally, four-fifths of the world population's (population was 5.28 billion in 1990) exposure to particulate matter occurred indoors in less developed countries. According to Bruce et al. (2002), up to 90%

of rural households in less developed countries cook or heat using unprocessed biomass fuels.

According to Smith (1993), particulate matter was found in average daily concentrations of 551 $\mu g/m^3$ in rural developing country indoor environments and 93 $\mu g/m^3$ in rural developing country outdoor environments. Particulate matter was found in average daily concentrations of 255 $\mu g/m^3$ in urban developing country indoor environments and 278 $\mu g/m^3$ in urban developing country outdoor environments. According to the World Health Organization (1979), it is recommended that a person be exposed to particulate matter less than 10 μm in diameter at mean daily concentrations of 150- 230 $\mu g/m^3$ for no more than 7 days per year. It is recommended that a person be exposed to particulate matter annual mean concentrations of less than 60- 90 $\mu g/m^3$. According to the World Health Organization (1979), 24-hour mean smoke concentrations of 500 $\mu g/m^3$ were reported in air pollution research to cause increases in mortality.

In rural indoor microenvironments of less developed countries, four major illnesses have been documented due to particulate matter exposure, including respiratory infections in children, adverse pregnancy outcomes, chronic lung diseases and heart diseases, and cancer (Smith, 1993). Acute respiratory infections in children (such as pneumonia) kill more than 4.3 million children per year. Acute respiratory infections kill 30% more children per year than diarrheal disease, which is the number two cause of mortality in children (Smith, 1993). Adverse pregnancy outcomes can include low birth weight of a child born to a mother exposed to indoor air pollution and stillbirth. Chronic lung diseases include Chronic Obstructive Pulmonary Disease (COPD) and chronic bronchitis. Cancer, possibly related to polyaromatic hydrocarbons, is not well-

documented because of its chronic nature and the difficulty associated with records of exposure over long periods of time (Smith, 1993). There is a dire need for technologies and sustainable implementation and operation of technologies to reduce indoor air pollution in less developed countries.

1.3.2 Energy Production and an Alternative Cooking Fuel: Methane

Energy produced from anaerobic digestion in the form of biogas may be used as a clean-burning, liquid cooking fuel. A concept known as "the energy ladder" dictates that fuel types that are less polluting to the indoor environment become more prevalent as household socioeconomic status increases (Smith et al., 1994). Additionally, manual labor associated with the technology decreases with these fuel types as cost increases. At the bottom of the energy ladder is dung, the most polluting of the fuel types on this ladder. Next follow crop residues, then wood, then charcoal, next kerosene and coal, liquid petroleum gas (LPG) and natural gas, and finally, electricity (Smith et al., 1994). Dung, crop residues, wood, and charcoal are all locally-producible fuel sources. LPG and natural gas require transportation. Electricity is often not reliable in less developed countries, and often does not come from sustainable sources. Not mentioned in this energy ladder is biogas, which is similar to LPG (Mihelcic et al., 2009).

1.3.3 Addresses Unsustainable Deforestation Caused by Wood Fuel Use

The main causes of deforestation worldwide are agricultural expansion and mechanization, the growth of grazing operations, mining, and fuel collection (Douglas & Simula, 2010). Anaerobic digestion addresses unsustainable deforestation by providing

an alternative cooking fuel, biogas, instead of traditional cooking fuel such as wood. In Nepal, wood fuel is the major energy source for cooking and lighting. Household anaerobic digesters have been introduced in many households with success. Wood fuel consumption was observed to decrease by 53%, with each household saving a calculated 250 kg of firewood per month and each household saving 3 tons of firewood per year (Katuwal & Bohara, 2009).

Three mitigation strategies for reducing atmospheric carbon emissions in developing countries are reforestation of deforested lands, introducing sustainable agricultural practices on existing agricultural lands, and slowing deforestation in the tropics (Niles et al., 2002). Of these mitigation strategies, only reforestation of deforested lands is eligible for financing by the rules of the Kyoto Protocol (Niles et al., 2002).

1.3.4 The Empowerment of Women

In many developing countries, women and girls do most of the cooking, and therefore, have a disproportionate exposure to indoor rural air pollution in comparison with men. According to Mihelcic et al. (2009), of the Chronic Obstructive Pulmonary Disease experienced by women in less developed countries, 40- 45% of this disease burden is caused by indoor air pollution from the use of biomass cooking fuel. One of the Millennium Development Goals (*MDG's*) is *to promote gender equality and empower women.* Anaerobic digestion technology can empower women by reducing the DALY's[3] women cooking with biomass solid fuels experience and by improving indoor air quality.

[3] DALY: Disability-Adjusted Life Year: "A time-based measure that combines years of life lost due to premature mortality and years of life lost due to time lived in states of less than full health" (World Health Organization, 2011).

Additionally, the use of biogas as a cooking fuel frees up time spent looking for firewood. Firewood collection, depending on the country, is a chore that may be the task of primarily women and children (Katuwal & Bohara, 2009).

1.3.5 Treatment of Animal and Human Waste

Runoff of animal waste into streams and other water bodies adversely affects surface water quality. Nutrients present in untreated animal waste create nutrient loading of streams which causes algal blooms, lower oxygen carrying capacity of the stream, and may create dead zones in the ocean environment where a large river discharges. For example, the Mississippi River Basin constitutes 1.25 million square miles and portions of thirty-one different states (Antweiler et al., 1995). Large agricultural areas, including corn and wheat belts, as well as large cities on the Mississippi River, add nutrients through agricultural runoff and wastewater treatment plant effluent. Every year, 1.65 million tons of nitrogen and 100,000 tons of phosphorus are discharged into the Gulf of Mexico from the Mississippi, creating a large hypoxic area known as the "Dead Zone" (Antweiler et al., 1995).

Additionally, pathogens present in animal wastes degrade the water quality of the receiving water. Pathogens present in municipal wastewater include bacteria, protozoa, helminths, and viruses. Bacteria of the genus *Salmonella* are one of the most common bacteria. Common protozoa include *Cryptosporidium parvum*, *Cyclospora*, and *Giardia Lamblia*. Helminths, commonly known as worms, include *Ascaris lumbricoides*, which is the cause of the majority of parasitic infections worldwide. Mesophilic anaerobic digestion does not sufficiently inactivate many helminth eggs. Enteric viruses are present

in the intestinal tract and excreted in the feces of infected humans or animals. The enteric viruses of primary concern to public health are the enteroviruses (including polio), Norwalk viruses, rotaviruses, reoviruses, calciviruses, adenoviruses, and hepatitis A virus (Tchobanoglous et al., 2003).

Animals such as cattle, horses, pigs, and chickens are often enclosed with streams because this requires less work than carrying water to the animals. There are both human and environmental costs associated with animal waste runoff into streams and water bodies. Animal waste runoff creates contamination problems for communities and cities downstream.

1.3.6 Anaerobic Digestion Generates Less Biosolids for Disposal

Anaerobic digestion produces less biological sludge than aerobic treatment produces. This is because most of the energy is converted to methane and carbon dioxide gas, while relatively little energy goes to cell growth, resulting in the accumulation of biosolids (McCarty, 1964; Tchobanoglous et al., 2003).

The United States Environmental Protection Agency (EPA) regulates pathogens in biosolids that may be applied for various uses. Class A Biosolids may be used by the public, applied to nurseries, gardens, and golf courses and are defined as biosolids which contain pathogens (including enteric viruses, pathogenic bacteria, and viable helminth ova) below the detectable level (US EPA, 2003). Class A Biosolids are produced from temperature- phased anaerobic digestion (Tchobanoglous et al., 2003). Stage 1 is thermophilic (50- 60˚C) and Stage 2 is mesophilic (30- 35˚C). High pathogen reduction is caused in Stage 1 (Han & Dague, 1997).

Class B Biosolids may be applied to agricultural land in the United States and are defined as biosolids which contain pathogens in amounts that will unlikely threaten public health and the environment when used as recommended (US EPA, 2003). Class B Biosolids are produced from anaerobic digestion, operated as a process to significantly reduce pathogens (PSRP). The operation criteria for thermophilic anaerobic digestion (35- 55˚C) is a Solids Retention Time (SRT) of 15 days and for mesophilic anaerobic digestion at 20˚C is 60 days (Tchobanoglous et al., 2003).

1.3.7 Nutrient – Rich Effluent as a Fertilizer

Anaerobic digestion produces nutrient-rich effluent that may be used as a fertilizer. The commercial fertilizer-producing process is called the Haber-Bosch process. The Haber-Bosch process is a high-energy consumptive process which takes nitrogen gas and transforms it into ammonia, NH_3. Commercial fertilizers use large quantities of energy to produce and are expensive. According to Smil (1999), an additional two billion people are alive today because of the invention of the Haber-Bosch process and 40% of the dietary protein in the world comes from synthetic fertilizers.

In contrast, the anaerobic digestion process is *energy- producing*. Anaerobic digestion additionally produces fertilizer in the form of liquid effluent. Instead of purchasing an energy-consumptive and costly fertilizer, farmers can produce their own fertilizer, through an energy-producing process.

There is a finite amount of phosphorus accessible for input into commercial fertilizers from conventional mining. Phosphorus and nitrogen are nutrients essential to biochemical processes in the human body, and are excreted from the body in both urine

and feces. According to Jonsson et al. (2004), research done in Sweden shows that 88% of nitrogen excreted from the human body and 67% of phosphorus excreted from the human body is found in urine. Research done in China shows that 70% of nitrogen and 25- 60% of phosphorus is found in urine (Jonsson et al., 2004). The remainder of nitrogen and phosphorus excreted is found in feces. Because there is a finite amount of phosphorus available from mining processes and because phosphorus is cycled through the human body, the field of wastewater treatment is concerned with recovering phosphorus from wastewater.

1.3.8 Mitigation of Methane Release and Carbon Black into the Atmosphere

Methane has a Global Warming Potential (GWP) twenty-one times greater than the GWP of carbon dioxide. Global Warming Potential means that over a period of 100 years, 1 tonne (1000 kg) of methane is the equivalent of 21 tonnes (21,000 kg) of carbon dioxide emissions (European Commission, 2001). Global Warming Potentials are referenced to carbon dioxide, which has a GWP of one.

Anaerobic treatment processes are more favorable than aerobic treatment processes in terms of greenhouse gas emissions at influent wastewater concentrations >300 mg/L BOD_u. At influent concentrations ≤ 300 mg/L BOD_u, aerobic processes are more favorable because they emit less greenhouse gases. In anaerobic treatment at low influent concentrations of BOD_u, small amounts of methane are produced and are present in the gas phase, while large amounts of nitrogen gas originally present in the liquid influent are present in the gas phase. Because the amounts of methane in the gas phase due to influent concentrations ≤ 300 mg/L BOD_u are small, it is difficult to collect and

utilize the methane for energy. When methane is present in larger amounts at higher concentrations of BOD_u, the energy from the combustion of methane may replace other fuel sources (Cakir & Stenstrom, 2005).

Burning of solid fuels also releases black carbon, a carbonaceous aerosol. Black carbon emissions are also a large concern in the warming of the planet, due to their ability to absorb solar radiation. Black carbon is responsible for 15% of excess radiative forcing globally. (Kandlikar, et al., n.d.). Additionally, black carbon has a seven-day residence time in the atmosphere; therefore, reduction in black carbon emissions will have more rapid effects than reduction in carbon dioxide emissions (Kandlikar, et al., n.d.). Inefficient combustion of solid fuels contributes to black carbon emissions, so there is an argument for building more efficient cook stoves, as well an argument for other alternative fuels, such as biogas (Edwards et al., 2004).

1.4 Disadvantages of Anaerobic Digestion

There are some disadvantages to the anaerobic digestion process. First, small scale anaerobic digestion requires the addition of water (Sharma & Pellizzi, 1991). This can be a hardship in some places during the dry season. Anaerobic digestion takes more time to start- up the process because methanogens have slower growth kinetics. High effluent BOD_5 concentrations prevent direct discharge into water bodies. Anaerobic digestion may require the addition of alkalinity (in the form of sodium bicarbonate) to reach levels of 2000- 3000 mg/L as $CaCO_3$ in order to maintain an optimal pH. Reaction rates in the anaerobic digestion processes are much more sensitive to changes in temperature (Tchobanoglous et al., 2003). For this reason, a stable operating temperature

is very important, and changes in temperature of less than 0.5˚C/day are recommended (Vesilind, 1998). Higher capital costs are associated with anaerobic digestion than with aerobic treatment because a larger reactor volume is required for anaerobic treatment and because of the additional infrastructure required for methane capture and energy use. Anaerobic digestion is much more vulnerable to upsets from toxic compounds found in the waste stream and there is a potential for the production of corrosive gases and odors (Tchobanoglous et al., 2003).

Safety should be the primary concern in operation of an anaerobic digester. Gas storage must be available for the liquid volume change in anaerobic digestion. Kocak-Enturk et al. (2007) recommended the volume in the reactor for gas storage space should be 1/5 the volume of the solid and liquid volume in the reactor. Biogas storage containers should be durable and resistant to corrosion. If methane gas is released uncontrolled, methane and air can form an explosive mixture that can spontaneously combust at high temperatures (Tchobanoglous et al., 2003). Flames, such as matches, lighters, and cigarettes should not be lighted in the same room as the gas storage container. Biogas should be stored away from the biogas stove in order to minimize the explosion hazard. Methane and carbon dioxide are odorless gases. Hydrogen sulfide gas smells like rotten eggs, but scrubbing the biogas by passing it through iron oxide in the form of steel wool (GTZ/EnvDev, 2010) makes it likely that the biogas will not have any odor. This is dangerous because it reduces the likelihood of a leak in the storage container or gas line being detected quickly and because methane at high concentrations causes asphyxiation.

1.5 Summary of Potential for Anaerobic Digesters for Application in Rural Developing Countries

In summary, anaerobic digestion is a valuable technology to less developed countries and to individual households which currently use solid biomass cooking and heating fuels. The advantages of anaerobic digestion in developing countries include: reduced indoor air pollution, sustainability and local-producibility of cooking fuel, reduction in unsustainable deforestation, treatment of animal and/or human waste, empowerment of women, reduced amount of biosolids to be disposed, and the production of useable nutrient-rich effluent that may be used as a fertilizer.

1.6 Objectives

There are four main objectives to this Master's Thesis:

- Perform a critical literature review of different designs of small-scale anaerobic digesters that would be appropriate for implementation in rural developing countries;
- Identify traditional and field laboratory measurements that can be used in evaluating the performance of anaerobic digesters in rural developing countries;
- Develop a spreadsheet model to be used for sizing of bioreactor and biogas storage container based on human and livestock waste availability;
- Provide guidelines for residuals disposal (biosolids and liquid centrate) to prevent nutrient and pathogen contamination of waterways and drinking water resources;

1.7 Scope of Work

First, Chapter 2, Sections 2.1–2.6 review literature about different designs of small-scale anaerobic digesters. Important design parameters to consider are simplicity of the design, ease of operation and maintenance, ease of construction, local availability of construction and maintenance materials, low cost, volume of animal waste required, volume of water required, volume of biogas produced, volume of effluent produced, durability, location of the digester (temperature), cultural acceptance, cooking time and space needs, and pathogen reduction in both the centrate slurry and the biosolids.

In Chapter 2, Section 2.7, parameters and laboratory methods were identified for monitoring small scale anaerobic digesters. The appropriateness for use in rural areas of developing countries or the need for partnership with a laboratory in country was evaluated. Access to rural sites where there is dire need for alternative cooking technologies such as anaerobic digesters may be difficult and time-consuming. Therefore, when performing monitoring studies in rural areas, it is important to be able to preserve

samples for measurement in a partner laboratory. Samples may need to be stored for periods of time before measurement.

In Chapter 3, the Excel spreadsheet design tool for use in sizing small scale anaerobic digesters will be elaborated. Model inputs, internal calculations, and outputs will be outlined. Development workers in the field would benefit from a spreadsheet model used for sizing of the bioreactor and biogas storage unit based on waste availability. In the field, development workers often lack the time and the access to valuable digester design resources. Many small-scale anaerobic digesters implemented in rural areas in developing countries fail because of failure in the design, operation, or maintenance phases. Therefore, it is important to design a model for bioreactor sizing design in order to maximize digester efficiency.

Chapter 4, Section 4.5 evaluates the lack of literature on pathogen reduction in small scale anaerobic digesters operated with no mixing and no heating. Guidelines for biosolids and centrate slurry use or disposal are important future work because local waterways and drinking water resources can be contaminated with pathogens and/or eutrophication can become a problem if proper measures are not followed. Guidelines should include dilution of effluent for use as fertilizer, proper times for fertilization (throughout the year and before a rain event), proper disposal of biosolids, and distance away from waterways and drinking water resources that fertilizers may be applied.

Chapter 2 Literature Review

2.1 Microbiology of Anaerobic Digestion

Three major microbiological processes take place in anaerobic digestion: fermentation, acidogenesis, and methanogenesis. A visual process diagram for anaerobic digestion is shown in Figure 2.1. The anaerobic process begins with a group of fermentative bacteria that excrete enzymes that break down macromolecules in the reactor. Macromolecules in anaerobic digestion include proteins, polysaccharides, and phospholipids (Shuler & Kargi, 1992). This process is called hydrolysis and produces soluble organic compounds (Khanal, 2009; Rittmann & McCarty, 2001). Once the compounds are broken down into simpler forms, the fermentative bacteria use energy obtained from these soluble compounds to produce a mixture of organic acids, hydrogen, and carbon dioxide in a process known as fermentation (Khanal, 2009).

Next, a different group of fermentative bacteria partially oxidizes the organic acids produced during fermentation (Rittmann & McCarty, 2001) into volatile fatty acids (with less than two carbons) in a process called acidogenesis (Khanal, 2009; Shuler & Kargi, 1992). The volatile fatty acids of significance formed in this step are: propionic acid, n-butyric acid, and isobutyric acid (Rittmann & McCarty, 2001). Alcohol formation also takes place during this step (Shuler & Kargi, 1992).

Hydrogen- producing acetogenic bacteria convert the volatile fatty acids and ethanol produced in acidogenesis into acetic acid, hydrogen, and carbon dioxide in a

process called acetogenesis (Khanal, 2009). Acetogenesis and methanogenesis are syntrophic processes (Madigan & Martinko, 2006; Rittmann & McCarty, 2001). In order for acetogenesis to be a thermodynamically favorable process and for the reaction to proceed in a forward direction, the partial pressure of hydrogen in the system must be less than 10^{-3} atm (Khanal, 2009). Hydrogen is scavenged by methanogenic archaea which, in turn, results in a low partial pressure of hydrogen and maintains a thermodynamically favorable acetogenesis process (Madigan & Martinko, 2006).

Methane can be generated via two different pathways during methanogenesis. One pathway takes the substrates hydrogen and carbon dioxide and forms methane through hydrogenetrophic methanogenesis. Some of the hydrogen and carbon dioxide is converted into acetate through homoacetogenesis. The remaining pathway converts acetate into methane and carbon dioxide in a process called acetotrophic methanogenesis (Khanal, 2009).

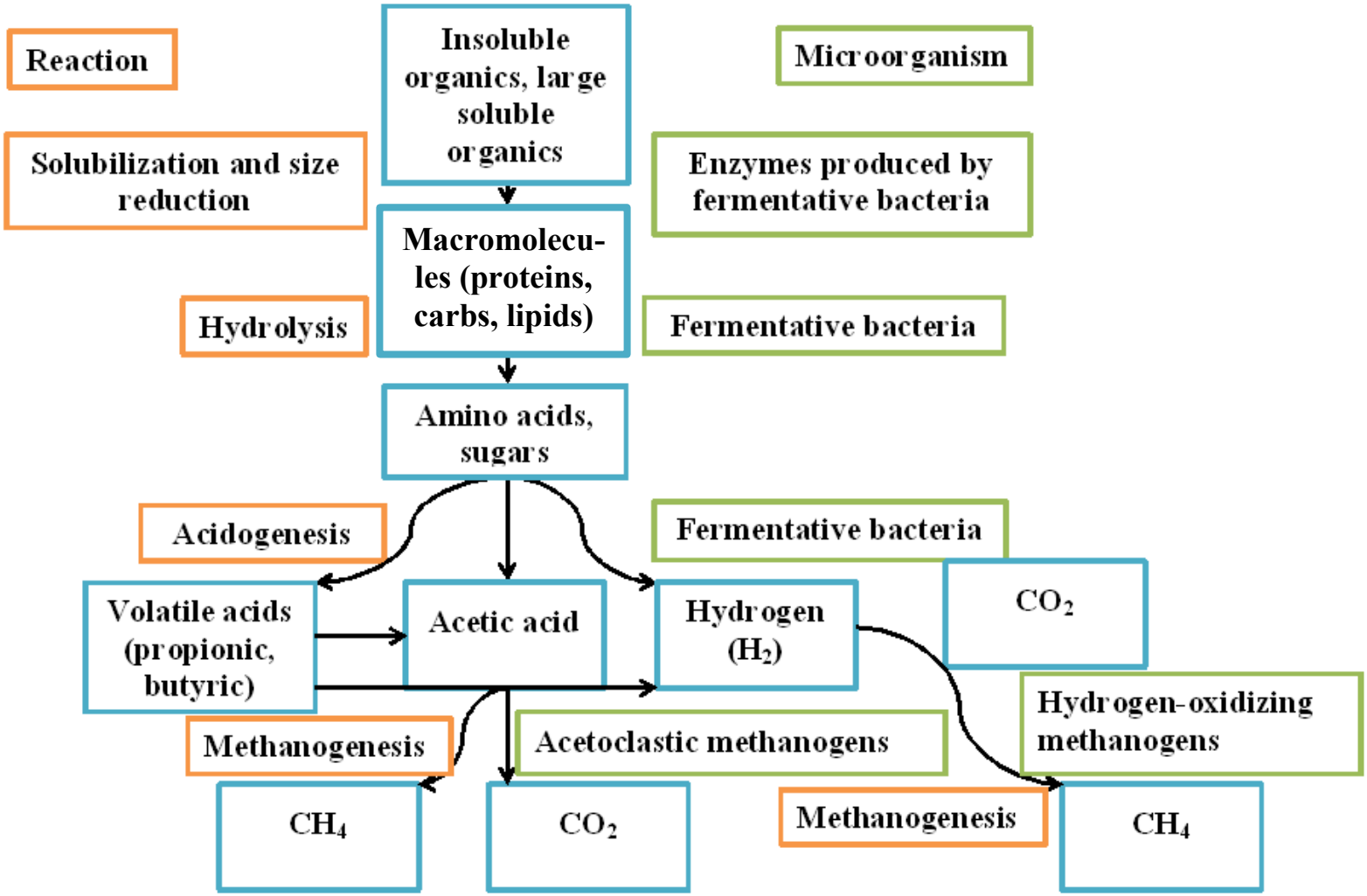


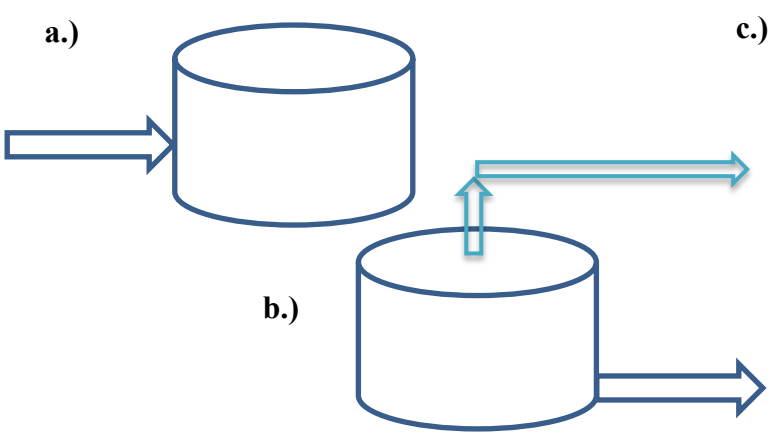
Figure 2.1: Anaerobic Digestion Process Diagram. (Grady et al., 2009)

2.2 Simple Reactor Technologies

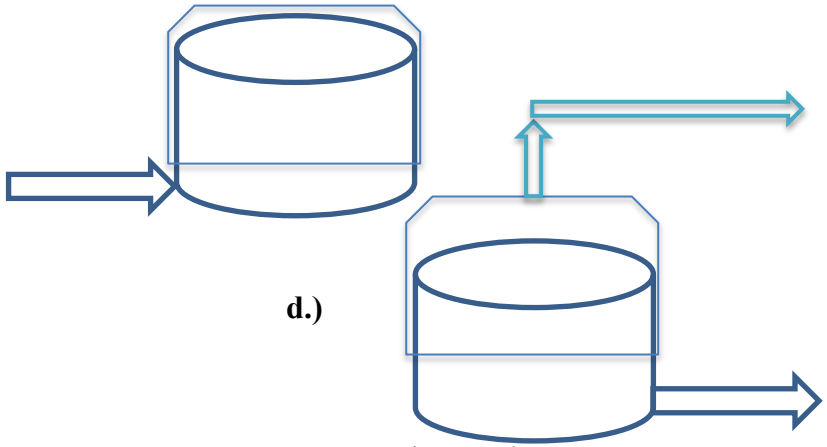
In wastewater treatment, reactors are designed to use microorganisms for removal of organic matter, oxygen demand, and nutrient content from the influent waste streams. Reactor designs facilitate mass and energy transfer from the bulk solution to the microorganism. Suspended growth reactors do this with suspended microbial flocs. In biofilm or attached growth reactors, the microorganisms are attached to a surface. Less loss of biomass in the effluent stream occurs in attached growth reactors. (Rittmann & McCarty, 2001).

Two basic suspended growth reactor types that are applicable to rural areas of the developing countries include: semi – batch reactors (which are discussed in Section 2.3.6) and plug flow reactors (PFRs). Semi – batch reactors can be designed to operate as constant – volume or constant – pressure reactors. Figure 2.2 shows diagrams of these simple reactor designs (Rittmann & McCarty, 2001).

Attached growth reactors are not usually used for treatment of waste streams containing high solids concentrations. Because of the high solids concentrations in the influent waste streams, attached growth reactors are not ideal choices without additional treatment prior to anaerobic digestion.

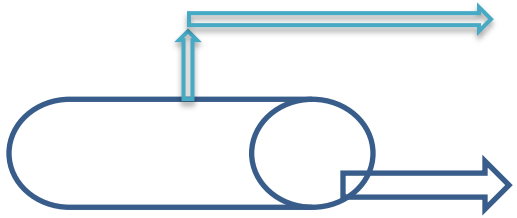


Constant Volume Semi – Batch Reactor
Reactor Design in use in Developing Countries:
Fixed – Dome Anaerobic Digester
a.) Manure and water mixture fed into digester
b.) Biogas exits from the top of digester, liquid slurry exits from the bottom of digester



Constant Pressure Semi – Batch Reactor
Reactor Design in use in Developing Countries:
Floating – Drum Anaerobic Digester
c.) Manure and water mixture fed into digester
d.) Biogas exits through the top of the floating drum, liquid slurry exits from bottom of digester

Plug Flow Reactor, Semi – Batch Operation
Reactor Design in use in Developing Countries:
Polyethylene Tubular Anaerobic Digester
e.) Manure and water fed into digester



f.) Biogas exits through the top of the PFR, liquid slurry exits from the bottom of the digester

Figure 2.2 Simple Reactor Designs for Rural Developing Country Applications

2.2.1 Batch Reactor

Batch reactors are operated by filling the reactor with slurry, letting the reactions that take place in the reactor proceed to completion, and then removing some or all of the contents of the reactor. This procedure is then repeated. Stirring may or may not be part of the operation of a batch reactor. Advantages of a batch reactor include: ease of operation, absence of mechanical mixing, and high removal efficiency of an individual contaminant. Kinetics in a batch reactor are similar to the kinetics in an ideal plug flow reactor (Rittmann & McCarty, 2001). Biosolids from one batch of operation may be used to seed the subsequent batch reaction with microbes.

In what is known as standard-rate digestion, anaerobic digestion, sludge thickening, and the formation of a supernatant take place in the same batch reactor space simultaneously. No mixing occurs, except that which takes place from entering and exiting flows and gas bubbles forming at the bottom of the reactor and rising to the top. As shown in Figure 2.3, at the bottom of a standard-rate digester, a layer of digested sludge, also known as biosolids, forms. Next, a layer of actively digesting sludge forms above the digested sludge layer. A layer of supernatant liquid stratifies above the layer of actively digesting sludge. A scum layer forms above the supernatant liquid layer. Finally, gas storage space constitutes the top space in the digester. Slurry enters the digester in the actively digesting sludge layer. Liquid effluent exits the digester at the level of the supernatant liquid layer. Biosolids exit the digester from the bottom layer of digested sludge (Tchobanoglous et al., 2003). Reactions taking place in the actively digesting sludge layer form gas, which then rises to the top of the reactor. The rising gas lifts particles, and grease, oil, and fat molecules, which eventually form the scum layer above

the supernatant liquid layer. Because of the lack of mixing, not more than fifty percent of the total digester volume is used (Tchobanoglous et al., 2003). This is important to consider in sizing a standard-rate digester.

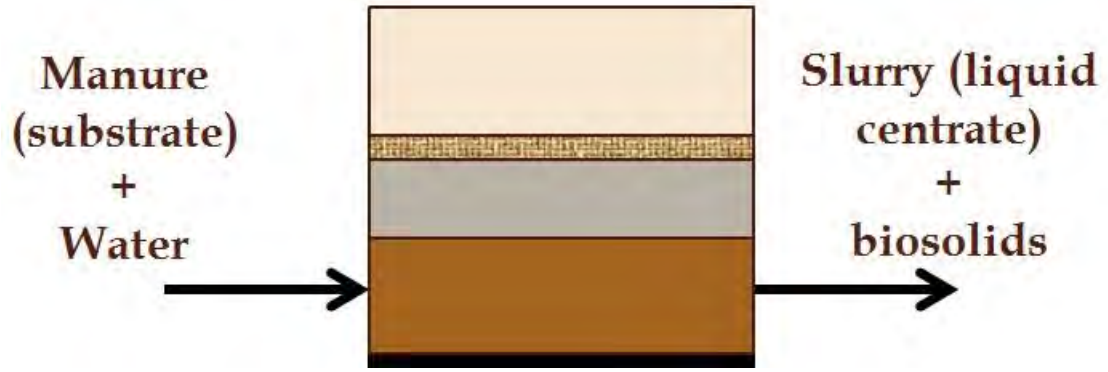


Figure 2.3: Stratification in a Standard – Rate Anaerobic Digester

2.2.2 Continuous Stirred Tank Reactor (CSTR)

Operation of CSTRs, also known as completely mixed reactors, includes continuous introduction of slurry into the reactor and continuous removal of the liquid contents from the reactor. In a CSTR, microorganisms in the reactor continuously grow, replacing microorganisms that are removed with the effluent. In an ideally-mixed CSTR, the concentrations of the substrate and microorganisms are uniform throughout the reactor. Therefore, the concentrations of substrate and microorganisms in the effluent stream are the same as those respective concentrations within the reactor (Rittmann & McCarty, 2001).

2.2.3 Plug Flow Reactor (PFR)

A PFR is a tubular reactor with an influent slurry entering continuously at one end and an effluent slurry exiting continuously at the opposite end of the reactor. In an ideal PFR, the flow moves through the reactor as a "plug," in which no mixing occurs with earlier or later entering flows or "plugs." Because no mixing occurs in an ideal PFR, the concentrations of substrate and microorganisms change through the length of the reactor. However, mixing will occur in a PFR in the direction of flow due to friction on the walls of the reactor. One advantage of a PFR is that very efficient removal of individual contaminants, such as ammonium and trace organics, is possible. A possible disadvantage of PFRs is that concentrations of substrate are highest where the influent enters the reactor. Because the concentrations of substrates are high at the entrance, the rates of reaction are high. In anaerobic PFRs, this high reaction rate may result in the production of additional organic acid, which, in turn, results in pH problems (Rittmann & McCarty, 2001).

2.3 Operational Configurations of Reactors

Reactors may be combined and operated in different fashions in order to achieve more desirable treatment.

2.3.1 Recycle

Operating reactors with recycle is one example of a way to achieve more efficient treatment in certain reactor types. In PFRs and batch reactors, where the concentrations of substrate and microorganisms in the effluent are not the same as those respective

concentrations in PFRs and batch reactors, recycle is advantageous. Recycle flows return the effluent in some form to the entrance of the reactor. Recycle may consist of recycle of the effluent stream, recycle of settled cells after gravity settling, or recycle of the supernatant effluent after gravity settling. Returning the effluent through the methods mentioned returns microorganisms to the reactor, results in PFRs and batch reactors of reduced size, and maintains reactor efficiency (Rittmann & McCarty, 2001).

2.3.2 Reactors in Series

Operating reactors in series is a method used when some combination of aerobic, anoxic, and anaerobic treatment are required. Reactors of the same type (such as two CSTRs or two PFRs) or of different types can be connected in series, allowing the engineer to achieve higher treatment efficiencies with various reactor combinations (Rittmann & McCarty, 2001). A single-stage anaerobic digester is one reactor. Multi-staged digestion consists of multiple digesters connected in series.

2.3.3 Two-Stage Anaerobic Digestion

Two-stage anaerobic digestion consists of one CSTR that is operated as an acidogenic (hydrogen-producing: see Section 2.1) reactor followed by a second CSTR that is operated as a methanogenic reactor. Sludge is recycled from the second CSTR into the influent of the first CSTR. Gas is collected in two separate streams from the two reactors (DiStefano & Palomar, 2010).

2.3.4 Phased Anaerobic Digestion

Phased anaerobic digestion also consists of reactors operated in series. Two-phase anaerobic digestion consists of one CSTR operated as an acidogenic reactor followed by a second CSTR operated as a methanogenic reactor. There is no recycle stream. Again, gas is collected in two separate streams from the two reactors (DiStefano & Palomar, 2010). Advantages of two-phase anaerobic digestion are that the process is more stable than a single stage anaerobic digester and that there is consistently higher production of methane in phased anaerobic digestion. There is a 9% theoretical specific energy increase for the two-phased anaerobic digestion system than that of the single stage anaerobic digester. However, the capital investment necessary is often not justifiable with that margin of energy increase (DiStefano & Palomar, 2010). Additionally, pathogens are more readily destroyed in two-phase anaerobic digestion.

2.3.5 Reactors in Parallel

Operating reactors in parallel is a method used commonly in large scale wastewater treatment facilities. If wastewater flow rate exceeds the capacity of the largest reactor unit available, operating multiple reactors in parallel is a solution. When maintenance is required on a reactor, the remaining reactor(s) can continue to operate while one reactor is taken offline for maintenance (Rittmann & McCarty, 2001). Operating reactors in parallel is not usually practical for the small scale anaerobic digesters discussed in this work. One disadvantage is additional capital costs, meaning that reactors in parallel may not be a viable option for rural developing applications.

2.3.6 Semi – Batch

Operating a reactor in semi-batch operation is common for small scale anaerobic digesters in developing countries. Semi-batch operation consists of adding a substrate over a short period of time during the day, which results in slurry exiting the digester over the same short time period. Over the period of time during which substrate is added, the reactor has continuous flow in and continuous flow out, as depicted by Figure 2.4, letter a.). The remainder of the day, the reactor operates as a batch reactor, with no flows in or out of the reactor, depicted by Figure 2.4, letter b.). The reaction does not go to completion before additional substrate is added the following day, which is how semi-batch operation differs from batch operation, where the reaction is allowed to go to completion before the reactor is emptied. See Figure 2.4 for batch and continuous flow reactors.

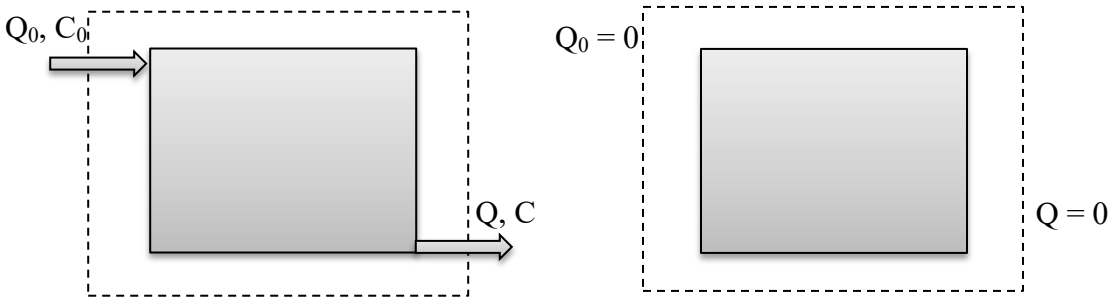


Figure 2.4: Semi-Batch Operation of a Reactor is a Combination Between Continuous Flow Operation and Batch Operation.

2.4 Reactor Designs Currently in Use for Small Scale Anaerobic Digestion in Developing Countries

Small scale anaerobic digesters are usually operated as semi-batch processes. A fixed amount of manure is mixed with a fixed amount of water and fed into the digester once a day. Biogas is utilized at meal times throughout the day. There is a volume of headspace in the digester and usually additional gas storage space in constant – volume systems. A mass of liquid slurry is displaced out the exit pipe from the digester into a slurry storage tank. The slurry is next emptied and often applied directly to fields. However, pathogen concentrations have not been extensively studied under standard – rate anaerobic digestion conditions. See Sections 2.8 and 4.5 for further information.

Currently, three types of small scale anaerobic digesters are most often used in the developing world, including fixed-dome digesters, floating-drum digesters, and polyethylene tubular digesters. Fixed-dome and floating-drum digesters are operated in a semi-batch fashion with no mixing (other than that which occurs when the slurry enters and the effluent exits the digester). One major difference between fixed-dome and floating-drum digesters is that additional gas storage volume is present in the floating-drum digester, whereas in the fixed-dome digester, gas pressure increases inside the fixed-dome digester as biogas is generated. Polyethylene tubular digesters are also operated in semi-batch fashion and are modeled as plug flow reactors.

Local availability of digester parts is very important for an engineer to consider when choosing and/or modifying an existing design. Parts availability is often limited in rural areas, especially rural communities with no road access. When parts break and maintenance is required, community members should be able to access the necessary

parts to continue to operate the anaerobic digester. Availability of parts, and therefore, digester design, will vary from country to country.

Another important design consideration is the local climate throughout the year. Mesophilic anaerobic digestion is optimal at 30-38ºC (Tchobanoglous et al., 2003). If ambient temperatures are not consistently warm, the digester should be insulated or heated. Insulation may include a greenhouse or a shed roof built over a polyethylene tubular digester. Heating can be done using gas produced in the digester. Heating will not be discussed in this work.

Ease of operation of the anaerobic digester is an important consideration in the choice of a particular digester design. For the reason of ease of operation (as well as project sustainability and operating costs), none of the designs reviewed in this work use mechanical pumping or mechanical or gas mixing, all of which would require a power source.

Another important design consideration is the amount of waste available and the amount of water available to input into an anaerobic digester on a daily basis. If a sufficient quantity of animal and/or human waste is not available from one family on a daily basis, a design based on two or more household's animal and/or human waste should be considered. If water scarcity is a problem for the community, anaerobic digestion is not an appropriate engineering solution until water scarcity is addressed.

Finally, skilled labor is required for the construction of an anaerobic digester. All seals must be completely gas-tight in order to keep oxygen from entering the digester. Fixed dome anaerobic digesters require complicated brick or stone work, which must also remain gas-tight when finished.

2.4.1 Fixed-Dome Anaerobic Digester

Fixed-dome digesters are operated by feeding manure mixed with water as a slurry into an entrance pipe. Refer to Figure 2.5. This slurry flows by gravity into the bottom of the digester. The lower part of the digester contains a layer of biosolids and a layer of liquid above the biosolids. As the anaerobic microbial processes take place, volatile solids are consumed and methane and carbon dioxide are produced. Biogas is stored within the digester, creating a gradual pressure buildup. As the pressure increases beyond the equilibrium point[4], the gas pressure will push digested slurry from the bottom of the digester up the second pipe into the collection tank. The slurry mass will accumulate, although the mass is reduced from that of the slurry fed into the digester. The collection tank must be emptied when it becomes full (Ocwieja, 2010).

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

Advantages of fixed-dome digesters are that the digesters have no moving parts, the costs are relatively low, and the design lifespan is 20 years (GTZ / GIZ, 1999). Disadvantages of fixed-dome digesters are that special sealants are required, high technical skills are required for construction, and gas pressures fluctuate, which causes complication of gas use (GTZ / GIZ, 1999). Additionally, operation is not easily

[4] The equilibrium point is the point at which the pressure in the headspace of the tank equals density*gravity constant*height of water column. When the pressure in the headspace of the tank is greater than density*gravity constant*height of water column, then slurry is displaced.

understood by the household, since the amount of gas present in the digester cannot be seen (Ocwieja, 2010).

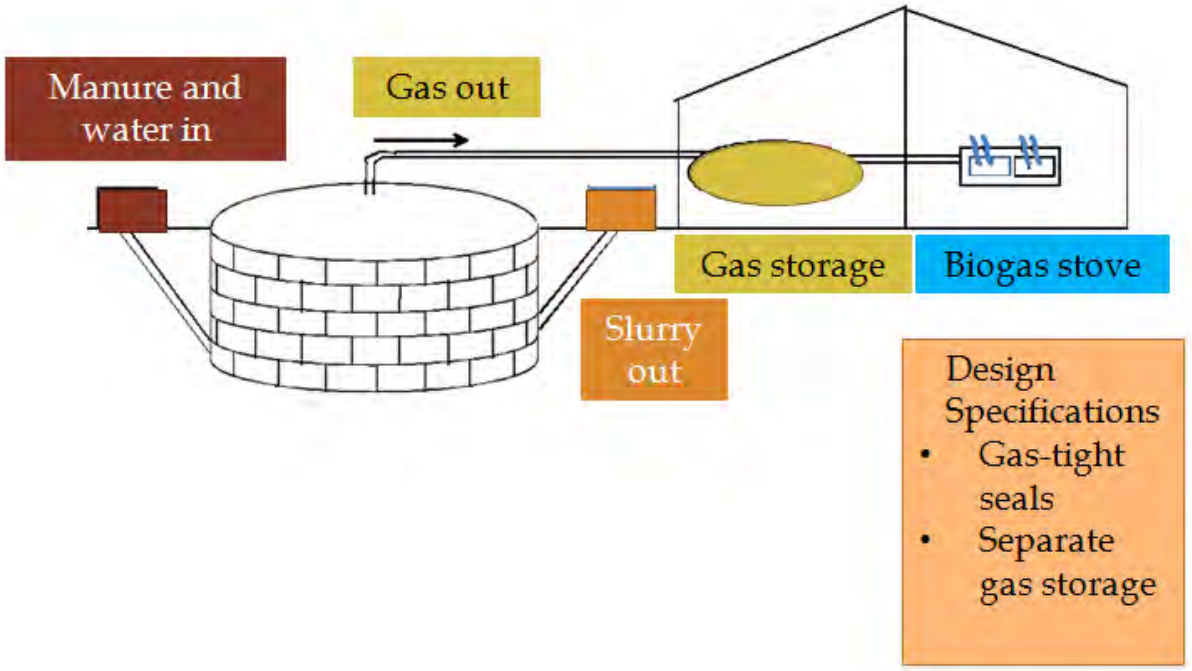


Figure 2.5: Fixed Dome Anaerobic Digester

2.4.2 Floating-Drum Anaerobic Digester

Floating drum digesters are operated by feeding manure mixed with water into a digester inlet pipe. Refer to Figure 2.6. Similar to the fixed-dome digester, the slurry flows down the inlet pipe and enters the bottom of the digester. There is a layer of biosolids on the bottom and a layer of liquid effluent above that. The floating-drum design includes a drum made of steel on a guide frame. The drum floats either in a water jacket surrounding the digester or directly in the digesting slurry (GTZ / GIZ, 1999).

The drum is mounted on a movable guide frame (which can float in the slurry, as shown in Figure 2.6, or in a water jacket located outside the digester), and as the pressure of biogas increases in the drum, the drum rises accordingly (GTZ / GIZ, 1999). Advantages of the floating-drum digester are that the operator can visually see and better understand how the digester works because the dome rises and falls with higher and lower gas pressure, respectively (Ocwieja, 2010). Floating-drum digesters are easy to operate (GTZ / GIZ, 1999). Gas tightness is easier to maintain in the floating- drum design by removing rust and re-painting regularly (GTZ / GIZ, 1999).

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

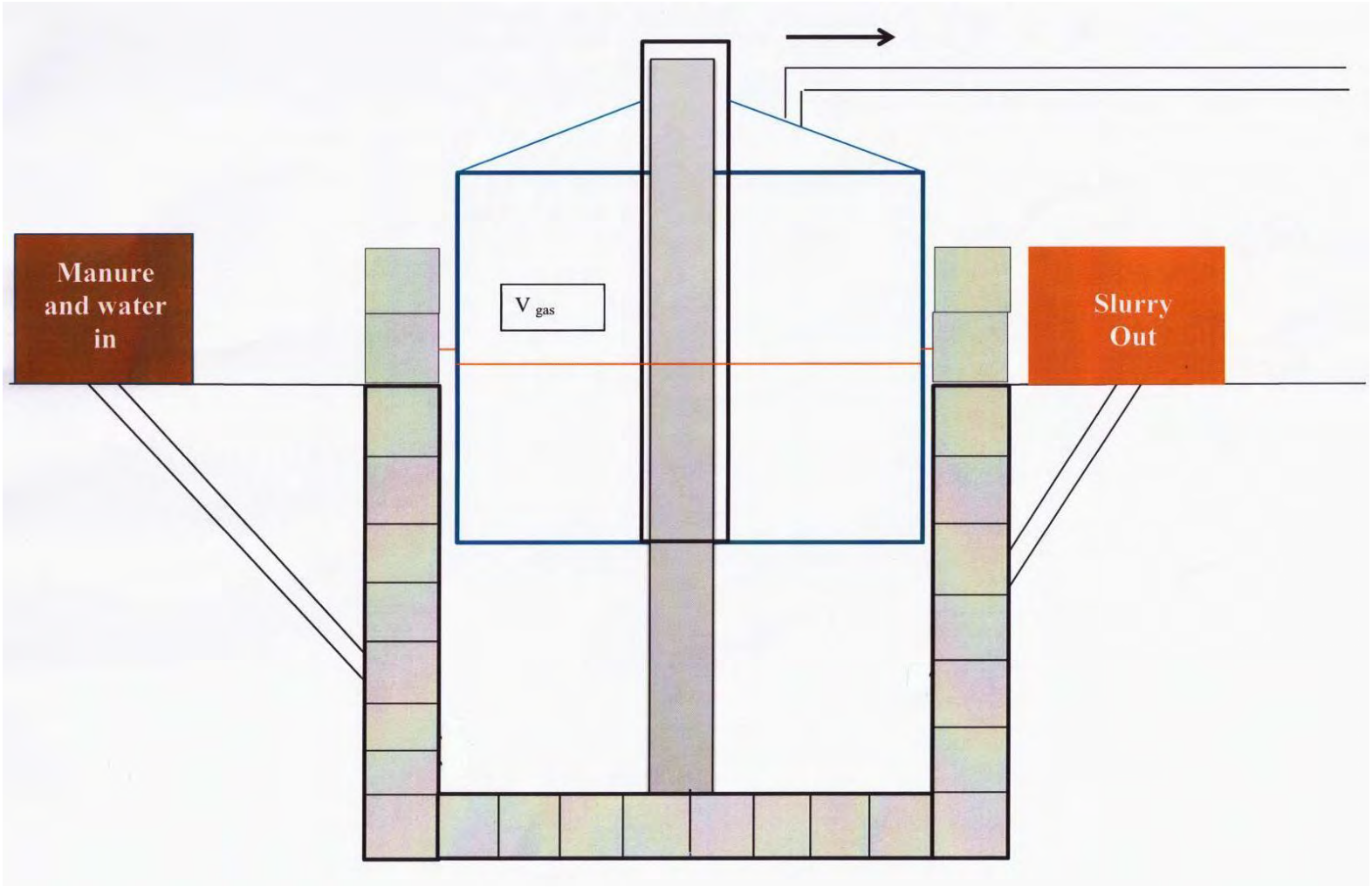


Figure 2.6: Floating Drum Anaerobic Digester

2.4.3 Polyethylene Tubular Anaerobic Digester

Polyethylene tubular digesters are operated as PFRs with semi-batch flow. Refer to Figure 2.7. The tubular digester is the least expensive and easiest to construct; however, the lifetime is only 2-10 years (GTZ/EnDev, 2010). Polyethylene tubular digesters are constructed of two layers of polyethylene plastic in a tubular form. A tubular digester is placed into a trench with a slope of 2-5% to facilitate gravity flow. A slurry is fed into the digester through the inlet pipe. When the digester is in equilibrium, an equal mass of liquid centrate exits the digester through the exit pipe. According to GTZ/EnDev (2010), an equal mass of liquid effluent exits the digester as manure and water are fed into the digester. However, this does not follow because biosolids accumulate in the digester and must be emptied periodically (GTZ/EnDev, 2010). Gas is stored above the digesting sludge and there is additional external gas storage (GTZ/EnDev, 2010).

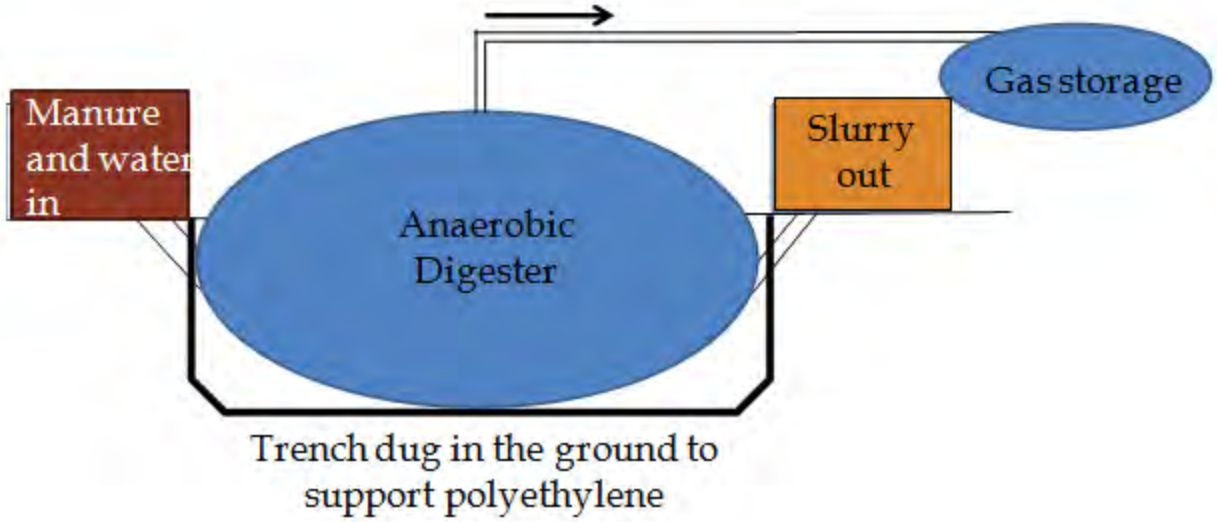


Figure 2.7: Polyethylene Tubular Anaerobic Digester

2.5 Organic Substrates

A substrate is the carbon source electron donor in the biochemical reactions that take place in anaerobic digestion. When there is not sufficient substrate for microbial growth and maintenance, the reactor is considered substrate- limited, and process performance will become impaired. Characteristics of six agricultural manure substrates encountered in rural developing countries are documented in Table 2.1. These substrates are: **1.)** cattle (beef), **2.)** cattle (dairy- lactating cow), **3.)** poultry (layer- eggs), **4.)** poultry (broiler- meat), **5.)** swine (gestating sow), and **6.)** swine (boar). Values are reported on a per-animal, per-day basis.

Pour-flush latrines may be connected to small scale anaerobic digesters when treating human waste is also an objective. Small scale anaerobic digesters as a human waste treatment option are most often implemented treating human waste from community health centers, hospitals, schools, boarding schools, or prisons (Ocwieja, 2010). Latrines connected to anaerobic digesters must be pour-flush latrines in order to carry the waste into the digester in the absence of oxygen. The biogas produced can be shared and used by the community as a whole.

An individual family may connect a pour flush latrine to its family-sized anaerobic digester. The human waste would be a substrate in addition to agricultural substrates and would increase the amount of biogas produced per day. However, it would not be worth the investment in materials to implement an anaerobic digester to treat human waste from an individual family without additional agricultural wastes because a

family of five people[5] does not generate sufficient quantities of waste to produce a sufficient quantity of biogas per day to do the family cooking.

The author was not able to find all the necessary characteristics of human feces to calculate the $C_nH_aO_bN_c$ formula for human feces. Therefore, it is recommended in Chapter 5, Section 5.2: Future Work that measurements be collected for human feces in order to characterize human feces and add human waste as an input substrate for the model presented in the current work.

Additionally, guinea pigs are commonly raised for food in the mountainous regions of Peru (Garfi et al., 2011). Guinea pig manure can be a substrate for anaerobic digestion, as can manure from other agricultural animals not discussed in the current work. The author was not able to find information on the characteristics of guinea pig manure, so it is recommended in Chapter 5, Section 5.2: Future Work that measurements from guinea pig manure be collected and the subsequent information incorporated into the model presented in the current work.

Food waste is often fed to livestock as food in rural areas of developing countries. For that reason, food waste was not included in the current work. According to Lansing et al. (2010), adding small amounts of cooking grease resulted in a 124% increase in methane production in unheated plug flow reactors.

[5] Average family size in rural Dominican Republic (Peace Corps Dominican Republic, 2010)

Table 2.1: Characteristics of Agricultural Substrates Used to Calculate $C_nH_aO_bN_c$ Formulas. (McCarty, 1976)

Animal	Total Solids (kg/(d*a))	Volatile Solids (kg/(d*a))	COD (kg/(d*a))	Nitrogen (kg/(d*a))	Total Manure (kg/(d*a))=(L/(d*a))	Moisture
Cattle- Beef-finishing cattle[1]	2.353	1.895	1.961	0.163	29.412	92
Cattle- Dairy-lactating cow[1]	8.900	7.500	8.100	0.450	68.000	87
Poultry- layer[1]	0.022	0.016	0.018	0.002	0.088	75
Poultry- broiler[1]	0.027	0.020	0.022	0.001	0.102	74
Swine- gestating sow[1]	1.200	1.000	1.100	0.085	12.000	90
Swine- boar[1]	0.380	0.340	0.270	0.028	3.800	90
Human feces[2]	*	*	*	0.077	0.26	*
Guinea Pig	*	*	*	*	*	*

* Could not find values in literature.

[1] ASAE (2005)

[2] Schouw et al. (2002)

2.6 Factors Affecting Performance

A number of factors are important in the operation of an anaerobic digester, including: hydraulic retention time, solids retention time (also known as mean cell residence time), organic loading rate, mixing, pH, alkalinity, temperature, pH, and reactor configuration (discussed in Section 2.3). Recommended parameters are listed in Table 2.2.

Table 2.2: Suggested Operation Parameters for Rural Developing World Applications

Operation Parameters		Source(s)
SRT^{min}_{lim} (d)	4	(Tchobanoglous et al., 2003)
Safety Factor (SF)	10 – 30	(Rittmann & McCarty, 2001)
SRT (d)	20 – 70	(Garfi et al., 2011)
pH	6.6 - 7.6	(Tchobanoglous et al., 2003)
OLR (kg VS/(d*m^3))	1.0 - 3.5	(Sharma & Pellizzi, 1991)

2.6.1 Hydraulic Retention Time (HRT)

Hydraulic retention time, θ (days), is defined as the average amount of time one reactor volume of actively digesting sludge stays within the reactor. The numeric definition is

$$\theta = \frac{V}{Q} \qquad \textbf{(2.6.1)}$$

where: θ = hydraulic retention time (d)

V = volume of reactor (m^3)

Q = influent flow rate (Rittmann & McCarty, 2001).

Hydraulic retention time is important to reactor operation and design because it defines the length of time the substrate and particular constituents targeted for removal will be in contact with the biomass within the reactor. Reaction kinetics of methanogenesis and fermentation are the rate-limiting kinetics in anaerobic digestion (Khanal, 2009). Most often, methanogenesis is the rate-limiting step. Garfi et al. (2011) studied psychrophilic anaerobic digestion at temperatures as low as 10°C, and recommend an SRT of 70 days for a polyethylene tubular anaerobic digester with no mixing. At temperatures close to 30°C, SRT*'s* 20 to 30 days are recommended (Garfi et al., 2011). It is important to design reactors for sufficient retention times so that volatile solids destruction can take place (Vesilind, 1998).

2.6.2 Solids Retention Time (SRT)

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

$$\theta_c = \frac{\text{active biomass in system}}{\text{production rate of active biomass}} = \frac{V*X}{Q_w* X_w} \qquad \textbf{(2.6.2)}$$

where θ_c = Solids retention time (d)

V = reactor volume (m^3)

X = cell concentration in reactor

Q_w = flow rate out of reactor

X_w = cell concentration in the flow out of the reactor

Solids retention time (SRT) is important because if SRT is too low, there will be organism washout. If SRT is too long, then the system becomes nutrient-limited. SRT impacts which organisms have optimal growth conditions within the reactor, and changes the microbial ecology of the system (see Section 2.1). SRT is equal to HRT when there is no solids recycle (Vesilind, 1998). Increasing SRT increases the extent the reactions involved in anaerobic digestion go to completion (Vesilind, 1998). A longer SRT stabilizes the process, lowers the amount of sludge produced, and increases biogas production (Rittmann & McCarty, 2001). According to Rittmann & McCarty (2001), the minimum SRT for an anaerobic CSTR at 35ºC is 10 days.

2.6.3 Organic Loading Rate

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

$$\text{OLR} = \frac{(Q)(C_{VS})}{V_{reactor}} = \frac{C_{VS}}{HRT} \qquad \textbf{(2.6.3)}$$

where OLR = Organic loading rate

Q = volumetric flow rate (m^3/d)

C_{VS} = concentration volatile solids (kg VS/m^3)

$V_{reactor}$ = reactor volume (m^3)

HRT = hydraulic retention time.

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

$$\text{OLR} = \frac{C_{VS}}{SRT} \quad \textbf{(2.6.4)}$$

Volatile solids (VS) are made up of the active biomass concentration X, cell debris following decay, and non-biodegradable VS (Tchobanoglous et al., 2003). According to Rittmann & McCarty (2001), the recommended organic loading rate for high-rate anaerobic digestion is 1.6- 4.8 kg VSS/(m^3*d), and the recommended organic loading rate for low-rate anaerobic digestion (digestion with no heat and no mixing) is 0.5- 1.6 kg VSS/(m^3*d). Speece (1996) recommended organic loading rates of 5-10 kg VSS/(m^3*d). Vesilind (1998) recommended that the peak organic loading rate for high-rate anaerobic digestion should be 1.9- 2.5 kg VS/(m^3*d). Sharma & Pellizzi (1991) recommended that the organic loading rate for standard – rate anaerobic digesters discussed in this work should be 1.0 – 3.5 kg VS/(m^3*d).

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

2.6.4 Safety Factor

In biological wastewater treatment, large scale reactors are designed with safety factors for various reasons, including: the lack of operator oversight, variability of waste water stream, and fluctuations in operating conditions. Safety factors in biological treatment systems are different from safety factors used in structures. The minimum SRT,

or the SRT at which washout[6] occurs is multiplied by a safety factor. Because the minimum SRT is the borderline of system failure, it is important to have a large safety factor. Specifically, in rural areas of developing countries, there will be fluctuations in ambient temperature, fluctuations in the substrate manure feed over time, limited operator oversight, and no process control. Lastly, if the anaerobic digester fails, it will likely result in failure of the anaerobic digestion development project, and the community will lose faith in the technology. Loss of faith in a technology can be significant, and can impede other anaerobic digestion projects for the future. A Safety Factor of 10 (Rittmann & McCarty, 2001; Speece, 1996) was used in the semi-empirical kinetic model piece of the Excel spreadsheet (Subsection 3.2.6).

2.6.5 Mixing

Mixing is another important parameter to consider in the design of an anaerobic digester. Mixing increases the rate kinetics of anaerobic digestion, accelerating the biological conversion process. Additionally, mixing allows uniform heating of the reactor (Tchobanoglous et al., 2003). Mixing can be done mechanically through motorized impellers or turbines within the reactor or pneumatically by injecting gas (in anaerobic digestion, methane and carbon dioxide gas) via spargers at the bottom of the reactor (Tchobanoglous et al., 2003).

In the fixed dome and floating drum anaerobic digester designs, no mixing takes place, other than the mixing that occurs as a result of gas formation in the digesting sludge layer, which then rises to the top of the digester (Tchobanoglous et al., 2003). In

[6] Washout is the point at which the growth of the microorganisms contained in the reactor is less than the loss of cells in the reactor effluent. There is a net loss of cells in the system.

the tubular PFR, as with PFRs in general, “plugs” within the digester have uniform concentrations of substrate and microorganisms, and in the ideal case, no mixing occurs in a forward direction.

2.6.6 pH

The pH of the digester is yet another important parameter in anaerobic digestion. The pH should be maintained between 6.6 and 7.6 (Rittmann & McCarty, 2001). One difficulty is maintaining pH above 6.6. During digester start-up, overloading, or instability, organic acids are intermediate products produced by the microorganisms. The presence of too high a concentration of organic acids decreases the pH, decreases methane production, and can cause reactor souring or reactor failure (Rittmann & McCarty, 2001).

The carbonic acid system dominates pH control most of the time in anaerobic digestion. Furthermore, carbon dioxide equilibrium is approached in anaerobic digestion. From calculating the dependence of pH on bicarbonate alkalinity (discussed in Sub-section 2.6.7), it can be deduced that pH in the anaerobic digester depends on bicarbonate alkalinity concentrations in the liquid phase and carbon dioxide in the gas phase (Rittmann & McCarty, 2001).

2.6.7 Alkalinity

Alkalinity is defined as the capacity of water to neutralize acid (Rittmann & McCarty, 2001). In anaerobic digestion, the normal percentage of carbon dioxide in the gas phase is 25 – 45 %. For anaerobic digestion where the carbonate system dominates, the following proton condition applies:

$$[H^+] + [\text{Alkalinity}] = [HCO_3^-] + 2\,[CO_3^{2-}] + [OH^-] \quad \textbf{(2.6.5)}$$

In comparison with the remaining species, carbonate, hydroxide, and hydrogen are present in negligible concentrations. Finally, taking the logarithm of both sides of the reduced equation, the following equation relating pH, bicarbonate alkalinity, and % carbon dioxide is derived:

$$pH = pK_{a_1} + \log\left(\frac{\frac{Alk.(bicarb.)}{50000}}{\frac{[CO2(g)]}{KH}}\right) \quad \textbf{(2.6.6)}$$

Bicarbonate alkalinity of at least 500 – 900 mg/L $CaCO_3$ is required for a pH greater than 6.5. The addition of alkaline materials when proper carbonate buffering is not present in the wastewater helps to maintain the pH in the recommended range for anaerobic digestion. Lime, sodium hydroxide, and ammonia are three of the least expensive chemicals available for the addition of alkalinity. Finally, from the equation for pH above, if pH and bicarbonate alkalinity are known for the anaerobic system, the partial pressure of carbon dioxide may be calculated, which is important for monitoring the digestion process (Rittmann & McCarty, 2001).

2.6.8 Temperature

Because bacterial growth is mediated by a complex set of enzymatic chemical reactions and the reaction rate of all chemical reactions depends on temperature, bacterial growth rate depends on temperature. As a general rule, bacterial growth rates double for each 10°C rise in temperature over a temperature range, which varies by bacterial species. Above normal temperatures for the particular bacterial species, essential enzymes may denature, or permanently lose their structure and function, killing the microorganism (Rittmann & McCarty, 2001).

For mesophilic anaerobic digestion, the operational temperature range is 10 to 30°C. Above 40°C, enzyme denaturation is a concern. The operational temperature range for thermophilic anaerobic digestion is 55 to 65°C. Specific methane production rates are 50 to 100 percent higher for thermophilic anaerobic digestion than for mesophilic anaerobic digestion (Rittmann & McCarty, 2001).

2.6.9 Volatile Solids Reduction

In order to measure VFA concentration and carbonate alkalinity, Lahav & Morgan (2004) reviewed different published titration methods. They concluded that computerized and programmable titration equipment was sufficiently accurate for monitoring of anaerobic digesters in developing countries (Lahav & Morgan, 2004).

2.6.10 Gas Production

Aklaku et al. (2006) used a Hermann Sewerin GmbH SR2-DO portable gas analyzer to analyze the gas composition of the anaerobic digester. After an initial analysis, it was determined that ammonia was absent and that the composition of hydrogen sulfide gas was 0.002 %wt. basis. Therefore, in the interest of time, Aklaku et al. (2006) measured the %wt. carbon dioxide in the gas mixture and used the following formula to determine the %wt. methane in the mixture (since there was a negligible amount of hydrogen sulfide gas): $CH_4 = 100 - CO_2$.

2.7 Monitoring Parameters

Many anaerobic digesters operating in the field are operated with no monitoring. However, if a study is conducted in the field, parameters commonly monitored include: total solids, volatile solids, organic loading rate, conductivity, pH, alkalinity, temperature, ammonia, total nitrogen, total phosphorus, COD, BOD, TOC, HRT, SRT, gas production, and gas composition (Aklaku et al., 2006; Lang & Smith, 2008). Additionally, if a community digester is having difficulty with operation, monitoring may be an option to improve operation. Monitoring methods and sample preservation techniques are detailed in Table 2.3. Sample preservation is important because transporting samples from a rural village to a partner laboratory for analysis may take a significant amount of time. The author recommends a cooler of ice as an alternate method of refrigerating samples.

Table 2.3 Monitoring Tests for Anaerobic Digestion Field Studies. (Eaton et al., 2005 and Hach, 2011)

Parameter to Monitor	Method	Field Application	Sample Preservation and Time Length	Instrument(s) Required
Manure loading rate	Volume, Mass	Bucket of known volume	N/A	Scale for mass measurement
Water loading rate	Volume	Bucket of known volume	N/A	None
Gas Production	Gas Analyzer	Gas Analyzer	-	Hermann Sewerin GmbH SR2-DO portable gas analyzer
Gas Composition	Standard Method 2720 B	Partner lab	Connect one end of sample collector to gas, vent other stopcock to atmosphere, open gas stopcock, pass 10-15 volumes of air through sample collector, close both stopcocks.	Orsat-type gas-analysis apparatus, gas sampling bulb with TFE stopcocks on each end
	Standard Method 2720 C	Partner lab	Connect one end of sample collector to gas, vent other stopcock to atmosphere, open gas stopcock, pass 10-15 volumes of air through sample collector, close both stopcocks.	Gas chromatograph, sample introduction apparatus, chromatographic column, integrator/recorder

Table 2.3, Continued

Total Solids, Volatile Solids	Standard Method 2540 B, Standard Method 2540 E	Partner lab	Refrigerate sample at 4°C. Prefer analysis within 24h. Do not store samples more than 7d.	Muffle furnace, steam bath, desiccator, drying oven, analytical balance (0.1 mg accuracy), stir plate
Organic loading rate (OLR)	Calculate volatile solids/day	-	-	-
Conductivity	Standard Method 2510 B	Partner lab	N/A	Conductivity instrument, temperature, conductivity cell
pH	Standard Method 4500-H^+	Partner lab	N/A	pH meter
	Test strips	pH strips- EMD Chemicals USA #9578 (2.0-9.0)	N/A	None
Alkalinity	Standard Method 2320 B	Partner lab	Polyethylene or borosilicate glass bottle, store at low temperature for 1d	pH meter, magnetic stirrer
Temperature	Thermometer	Thermometer	N/A	Thermometer
Ammonia (NH_3)	Standard Method 4500-NH_3.F	Partner lab	24h: refrigerate unacidified 4°C. 28d: acidify to pH<2, store 4°C	Distillation apparatus, pH meter, spectrophotometer

Table 2.3, Continued

Ammonia (NH3)	Hach Method 10205	Possible in the field	24h: refrigerate unacidified 4°C. 28d: acidify to pH<2, store 4°C	Colorimeter
Total Nitrogen	Standard Method 4500-P J.	Partner lab	Acidify with H_2SO_4 to 1.5 ≤ pH ≥ 2, store at 4°C	Autoclave, automated analytical equipment: flow-through colorimeter
	Hach Method 10071	Possible in the field	Acidify with H_2SO_4 to 1.5 ≤ pH ≤ 2, store at 4°C	Digital reactor block
Total Phosphorus	Standard Method 4500-P J.	Partner lab	Acidify with H_2SO_4 to 1.5 ≤ pH ≤ 2, store at 4°C	Autoclave, automated analytical equipment: flow-through colorimeter
	Hach Method 8190	Possible in the field	Acidify with H_2SO_4 or HCl to pH < 2, store at 4°C up to 28d.	Digital reactor block
Chemical Oxygen Demand (COD)	Standard Method 5220 D	Partner lab	Use glass bottles, acidify in H_2SO_4 to pH ≤ 2. Blend before analysis.	Borosilicate culture tubes with TFE-lined screw caps, block heater, mechanical ampule sealer
	Hach Method 8000	Possible in the field	Use glass bottles, acidify in H_2SO_4 to pH ≤ 2. Blend before analysis.	Digital reactor block

Table 2.3, Continued

Biological Oxygen Demand (BOD)	Standard Method 5210 B, Standard Method 4500-O G	Partner lab	Store samples at 4°C, prefer analysis before 6h. If time > 6h, report length and storage temp. with results. Do not start analysis longer than 24h after sampling.	pH meter, incubation bottles, air incubator or water bath, oxygen-sensitive membrane electrode and meter, polyethylene or fluorocarbon membrane, stir plate, thermometer
	Dissolved oxygen probe and meter	Partner lab	Store samples at 4°C, prefer analysis before 6h. If time > 6h, report length and storage temp. with results. Do not start analysis longer than 24h after sampling.	Dissolved oxygen probe and meter, incubator
Total Organic Carbon (TOC)	SM 5310 B	Partner lab	Collect in glass bottle, seal with TFE-backed septum. Acidify with H_2SO_4 or H_3PO_4 to pH ≤ 2, store at 4°C.	Glass bottles, septa, injection syringe, total organic carbon analyzer, sample blender, stir plate, filtering apparatus
Hydraulic Retention Time (HRT)	Calculate Volume/Flowrate	Bucket of known volume	N/A	None
Solids Retention Time (SRT)	Measure Flowrate of slurry out, Standard Method 2540 B (TS)	Bucket of known volume, TS=Partner lab	Refrigerate sample at 4°C. Prefer analysis within 24h. Do not store samples more than 7d.	Muffle furnace, steam bath, desiccator, drying oven, analytical balance (0.1 mg accuracy), stir plate

2.8 Pathogen Reduction

Pathogen reduction is an important end goal of anaerobic digestion. Cote et al. (2006) studied the reduction in swine manure of coliforms, *E. coli, Salmonella, Y. enterocolitica, Cryptosporidium,* and *Giardia* in non-mixed, sequencing batch reactors at 20ºC. The reactor volumes were 40 L, and the SRT was 20 days. Total coliforms were reduced by 97.94-100%, *E. coli* populations were reduced by 99.67-100%, and *Salmonella, Cryptosporidium,* and *Giardia* were reduced to undetectable levels (Cote et al., 2006).

Mara & Cairncross (1989) have public health recommendations in place for the use of reclaimed water for irrigation of crops. Crops which may be eaten raw, sports fields, and public parks should have a microbial quality of less than or equal to 1 intestinal nematode/L. The level of fecal coliforms should be less than or equal to 1000/100 mL (Mara & Cairncross, 1989). These recommendations are less stringent than reclaimed water regulations and guidelines in the United States (Tchobanoglous et al., 2003).

The author found very little literature regarding pathogen reduction of standard rate (low temperature) anaerobic digesters with no mixing. Pathogen reduction is largely a function of the environmental conditions present in the reactor, such as temperature and retention time. Therefore, more research is needed on pathogen reduction of small scale standard rate anaerobic digesters, particularly with pathogens of interest in developing countries. It is recommended that a set of guidelines for application or disposal of residuals be developed and taught as part of any anaerobic digester implementation project.

2.9 Social Components of Development Projects

Development projects comprise a four-stage project cycle, beginning with project initiation, continuing to planning, implementation, and conclusion (Mihelcic et al., 2009). Project initiation includes site selection, determining community resources, and conducting a needs assessment. Planning includes feasibility studies and preliminary design. Implementation includes construction design documents, contractor selection, and construction. The conclusion stage includes turn-over, follow-through, and maintenance (Mihelcic et al., 2009).

Development workers must be knowledgeable in conducting a needs assessment, a topic discussed in-depth in the fields of anthropology and public health. Needs assessments are vital to project success and emphasize community stakeholders' participation. Development workers often have a specified engineering solution in mind, but, for the project to be successfully implemented, community members must be the most important informants in the process.

The information in this Section, 2.9, stems directly from the author's personal experiences, unless otherwise cited. The author was placed in rural Dominican Republic as a Water and Sanitation Peace Corps Volunteer. The author worked on gravity-fed drinking water supply systems, but many of the author's experiences with community needs assessments for drinking water supply can be applied to needs assessments for anaerobic digester design and implementation.

Often in development work, an engineer will be challenged with teaching community members with minimal education about potential engineering solutions. Another challenge may be that community members are slow to do something differently

than it has been done for as long as they have been alive. Although it will not eliminate the challenges of working in development, a needs assessment conducted in a participatory manner should help immensely in addressing these challenges.

A needs assessment should be conducted by a team of people with differing backgrounds (Mihelcic et al., 2009). A project, in community development, includes the social environment in which the physical structure is located, and the community of people who will need to operate, manage, and benefit from the project after it has been built (Mihelcic et al., 2009). A needs assessment as applied to development work should:

- Investigate the importance the members of a community attribute to different problems in their community,
- Discuss different potential solutions to solve the problem agreed upon by the community,
- Illuminate the barriers to implementing a(n engineered) solution to a problem or problems,
- Collectively plan ways in which to address each barrier to implementing the chosen solution.

Needs assessments are simple to learn how to do, and can be carried out by engineers or others with experience outside the fields of anthropology and public health. Many methods or tools are available in the completion of a needs assessment, including the collection of qualitative or quantitative data. The use of many methods and both qualitative and quantitative data in a needs assessment is known as a mixed methods approach. A mixed methods approach allows for triangulation[7] of the data collected and increases the likelihood that the project will be successful.

[7] Triangulation is the appearance of the same data from more than one method.

Methods that may be used in a needs assessment include: community mapping, house-to-house surveys, focus groups, key stakeholder interviews, observations (either participatory or non-participatory), and conducting a literature review of the topic[8].

Community mapping can be done in different ways, and it is best to create multiple maps of the community to identify all community resources. One method of community mapping is through walking all of the paths or roadways within the community with multiple members of the community. Community members are most familiar with their own community, and can point out important details that may not be obvious at first to an outsider. Community maps will often focus on the type of problem that the community is interested in addressing with the help of the engineer. House locations, school locations, water resources, wastewater disposal areas, household organic waste disposal areas, household non-compostable waste disposal areas, livestock locations, agricultural land use, roadways, and land formations are all important features that may be mapped on a community map.

Another method of community mapping includes breaking community members into smaller groups (5 – 9 people) based on gender, age, or location within the community. The development worker asks community members to draw maps of their community and to include some or all of the important features mentioned above. At the end of a time limit, community members are asked to present their map to the larger group. Finally, the development worker can ask questions of community members and discuss similarities and differences among the different group maps. For example,

[8] Literature review is not discussed further in this work.

women may emphasize different resources in the community than men. Children may bring to light resources in the community that adults may not have considered.

House-to-house surveys are another method available in conducting a needs assessment. Development workers create a survey to gather quantitative data about the community and can include questions to investigate the population, health, water use, sanitation, hygiene, solid waste, nutrition, youth activities, educational background, and other important information. Development workers may conduct surveys orally or in written form. This choice will depend on the local community. Depending on the size of the community and the size of the project, all households or a sampling of households may be surveyed. Suggested questions specific to a needs assessment for an anaerobic digester project are available in Ocwieja (2010).

Focus groups are a method of obtaining qualitative data. Different groups within the community, such as leaders, women, men, children, people of different socioeconomic statuses, single women, and older people are invited to participate in a discussion of community needs with the development worker at different times. Focus groups can bring forth perspectives within subgroups of the community that may not be expressed in a meeting with the larger community. Focus groups may allow people with less power to voice differing perspectives.

Key stakeholder interviews may be conducted informally or formally. The identification of key stakeholders within a community may not be initially apparent, but with some time, will become more obvious to an outsider. Key stakeholders are often leaders in a community, and are also people willing to take a chance on a new engineering solution. Development workers may identify a few key stakeholders and ask

more in-depth questions than those asked in the house-to-house surveys. Development workers can gain qualitative information about the community through interviewing key stakeholders.

Observations noted by the development worker are an important method in community development. There are two types of observations: participatory and non-participatory. Participatory observations, or observations made by the development worker while actively participating in meetings, events, interviews, or focus groups, may be noted immediately after the respective event. Non-participatory observations, or observations about the community noted while separately observing events or conditions (such as those of latrines, for example), may be noted as they are observed or immediately after they are observed.

In addition to conducting a needs assessment in the community, community members and development workers must work together to establish a management framework in which to manage and operate the project once it is completed. The earlier the management framework is created during the project cycle, the greater the likelihood of project success (Mihelcic et al., 2009). A set of statutes is created by the community which provide guidance for the operation and maintenance of communal infrastructure (Mihelcic et al., 2009).

Management frameworks must be appropriate for the type of infrastructure and must be appropriate to the community. Community water supply projects will often be managed and operated by a communal water committee. Sanitation projects may be managed by a sanitation committee, but the household sanitation infrastructure will probably be operated by each household or small group of households.

The inclusion of women, traditionally the cooks, water carriers, and managers of the household, in management boards or committees is important because women bring differing perspectives to the table than men. Cultural issues must also be considered when electing a committee (Mihelcic et al., 2009). For example, women may place importance on alternatives to cooking on a traditional three-stone fire, which creates many respiratory health problems, while men, who do not traditionally spend a lot of time in the kitchen, may not place such importance on alternatives to the three-stone fire.

Hygiene of persons operating the anaerobic digester is extremely important. Development workers must work to educate the community about sanitation. Often, fecal-oral disease transmission is a new concept for uneducated people, and hands-on activities, skits, games, and coloring pictures can help illustrate the importance of hand-washing with soap, when it is important to wash one's hands (after handling feces, before cooking, before eating, after using the bathroom, and after handling animals), routes of disease transmission, and how to treat mild symptoms of diarrhea (using rehydration salts and eating foods like rice). In addition to hygiene of digester operators, care must be taken in residuals disposal to prevent pathogenic contamination of waterways and food crops and potential disease transmission.

2.10 Operation of an Anaerobic Digester Project

Operator knowledge of the anaerobic digestion process is one potential barrier to smooth operation of an anaerobic digester. Anaerobic digestion is a relatively complicated biological process, and as conditions in the reactor change over time, an operator may run into difficulties. Two important things that may be done to help overcome this potential barrier are training of the local operator (probably the farmer of that household) in basic daily operating techniques and creating a system that includes a more skilled technician who could fix more complicated problems. It is important that the technician be a person who lives in the area of the community, and who could be contacted when the operator encounters a problem with the anaerobic digester.

Seeding the digester speeds up the time required for digester start-up by inputting a population of anaerobic bacteria and archaea. Seeding the digester may be done in a few different ways. The most preferable method of seeding the digester is to obtain biosolids from a nearby operating digester. There may not be any digesters nearby, so this may not be possible. Another method of seeding the digester is to obtain microorganisms from the stomachs of cattle. Finally, if no existing anaerobic processes may be accessed, a large quantity of animal or human waste may be collected and the digester filled. The microorganisms will take longer to proliferate and the digester will take longer to reach a stable operating condition if this method is followed.

Chapter 3: Design Tool Development for Sizing the Bioreactor and Gas Storage Unit

3.1 Model Inputs

A Microsoft Excel spreadsheet was developed to be used as a design tool for computer-literate individuals with little engineering knowledge to size anaerobic digesters in rural developing countries. The person implementing an anaerobic digester is referred to the cited construction manuals for specific materials lists and instructions. The target audience is development workers.

Figure 3.1 is a flowchart of user inputs, internal model calculations, and model outputs. User inputs include the combination of different types of manure to be fed into the digester, the number of animals of each type, the mean annual ambient temperature in which the digester will be built, and the type of digester design. The manure type options are: swine – gestating sow, swine - boar, poultry, cattle – beef, and cattle – dairy. Human feces were excluded because a literature search did not yield results of all required parameters for calculation of CHON formula of the waste. Additionally, guinea pigs are common in Peru and their waste may also be used for anaerobic digestion. Guinea pig waste was excluded for the same reason as human waste was excluded. If human feces were to be used, the waste could be introduced into the digester through the means of a pour-flush latrine. The digester design types are: floating drum digester, fixed dome digester, and polyethylene tubular digester. Table 3.1 shows the user inputs in the model.

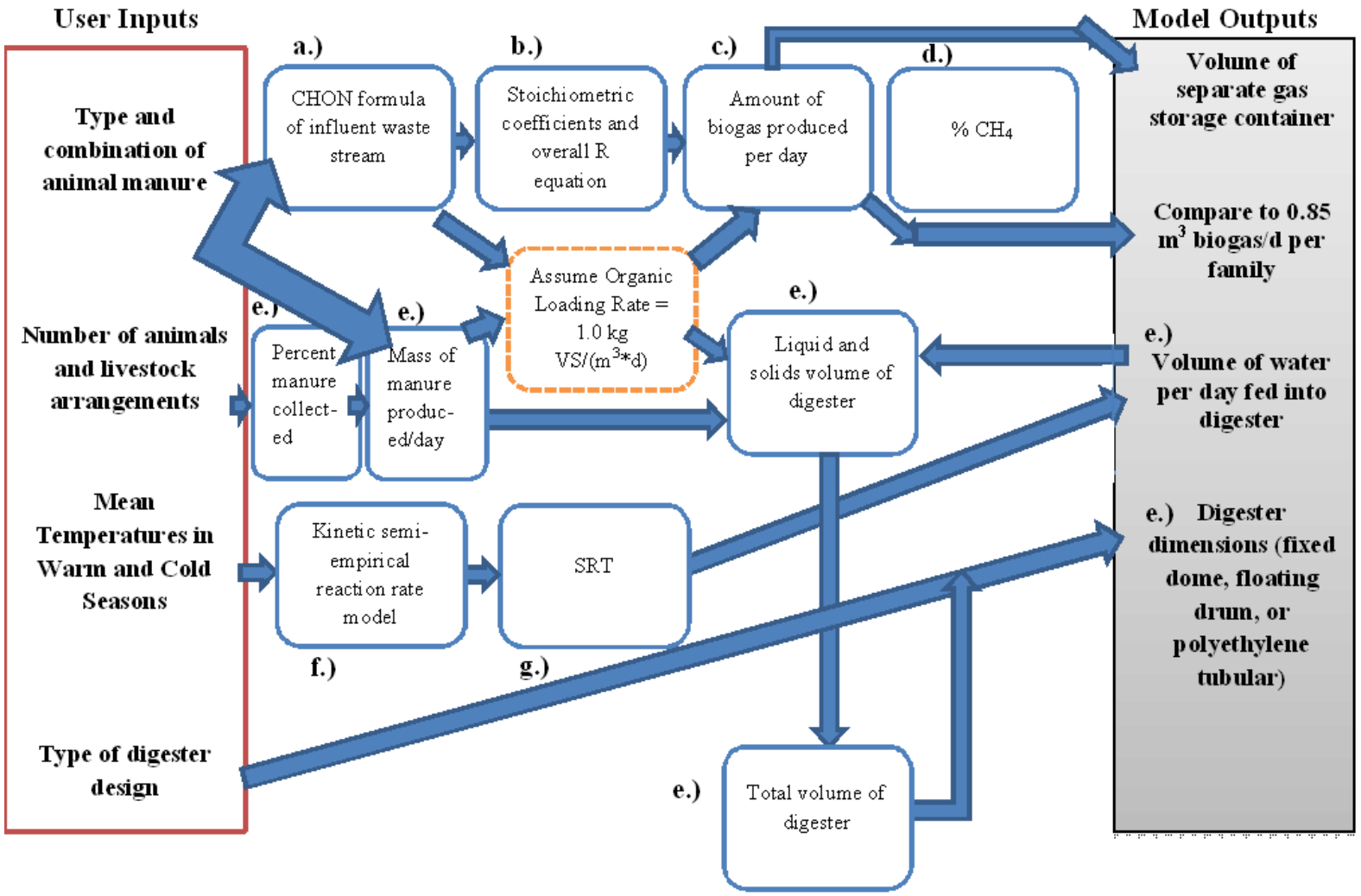


Figure 3.1 Anaerobic Digester Design Tool Flowchart.
Model calculations a.) through g.) are explained in Section 3.2. Multiple boxes are involved in calculation e.).

Table 3.1: User Inputs into the Model

Mean warm season temperature (°C)	
Mean cold season temperature (°C)	
Type of animals	Cattle- beef
	Cattle- lactating dairy cow
	Poultry
	Swine- gestating sow
	Swine- boar
Number of each type of animal	
Reactor design type	Fixed dome
	Floating drum
	Polyethylene tubular
Arrangements of the livestock	Livestock are free ranging during the day, penned at night.
	Livestock are free ranging during half the year, penned half the year.
	Livestock are penned all the time.

There are a number of assumptions that are made in the design spreadsheet tool. These are detailed in Table 3.2 and will be discussed in Section 3.2.

3.2 Model Calculations

Based on the six basic user inputs, type and combination of animal manures, number of animals, mean warm season temperature, mean cold season temperature, type of digester design, and livestock arrangement, the model uses the concepts of mass balance and reaction rate kinetics to calculate volume and dimensions of the reactor vessel, volume and dimensions of the separate gas storage container, volume of water per day fed into the digester, and compares the volume of biogas produced to an estimated volume of biogas needed per family per day.

Each step, a.) through g.), in Figure 3.1 is calculated by an equation or set of equations. Additionally, the values of steps a.) through g.) must be adjusted to account for different combinations of animals, as well as their respective numbers. These adjustments to the original values may be averages, weighted averages, or concentration calculations. In Sections 3.2.1-3.2.6, the basic equations or sets of equations for each step are discussed.

3.2.1 CHON Formula of Influent Waste Stream

The CHON molecular formula of the influent stream, letter a.) in Figure 3.1, was calculated using the method cited by (McCarty, 1976). The values for COD (g) and organic nitrogen content were taken from (American Society of Agricultural Engineers, 2005). American Society of Agricultural Engineers (2005) reported COD in units of kg/(d*animal). Assuming a basis of 1 day, the COD value was converted into grams and multiplied by the number of animals inputted by the user. Because Total Kiehldahl Nitrogen (TKN) content was not reported, total nitrogen was assumed to be equal to the organic nitrogen content.

The generalized oxidation half reaction for an organic molecule is:

$$C_aH_bO_cN_d + (2a - c)H_2O =$$

$$aCO_2 + dNH_4^+ + (4a + b - 2c - 4d)H^+ + (4a + b - 2c - 3d)e^- \qquad \textbf{(3.2.1)}$$

where $a = \frac{TOC}{12}$

$$b = \frac{1}{9}\left(Weight + COD - \frac{11}{3}TOC - \frac{19}{7}TKN\right)$$

$$c = \frac{1}{18}(Weight) + \frac{COD}{8} - \frac{2}{3}TOC - \frac{17}{14}TKN$$

$$d = \frac{TKN}{14}.$$

Case III from McCarty (1976) was used, where the COD (g) and the organic nitrogen content (g) of the organic waste stream are known, and the weight of the organic molecule and the organic carbon content (g) of the waste stream are unknown. Per Case III (McCarty, 1976), the organic content of the waste stream was calculated as:

$$TOC\ (g) = \frac{COD\ (g)}{4} \quad \textbf{(3.2.2)}$$

The weight of the organic molecule (g) was calculated as:

$$Weight, organic\ molecule = \frac{COD\ (g)}{2} \quad \textbf{(3.2.3)}$$

The CHON formula is normalized by dividing the number of each type of molecule (n, a, b, and c in the formula $C_nH_aO_bN_c$) by c, the number of molecules of N. Therefore, five molecular formulas for the five different types of manure were calculated. The final molecular formula of the influent waste stream was obtained by averaging n, a, b, and c for each animal type inputted by the user.

Degradability of the waste stream as degradable COD was estimated as 65.6% of the COD (Lee et al., 2008). COD values were multiplied by 0.656 before calculating the CHON formula of the waste stream.

3.2.2 Stoichiometric Coefficients and Overall R Equation

Stoichiometry is a very important aspect in the design of anaerobic digesters. Mass is always conserved, and charge is always conserved. Conservation of mass is illustrated through mass balances, which can be written for elements in every intermediate step before final methane formation on the major elements carbon, nitrogen, hydrogen, and oxygen, as well as other elements (Rittmann & McCarty, 2001).

Conservation of charge is illustrated through balancing electron equivalents in the oxidation-reduction reaction pairs. For example, most electron equivalents entering the reactor as BOD_L are conserved through the reduction of carbon to its lowest oxidation state, -4, in methane (CH_4). In this manner, BOD_L is removed from the liquid phase by transferring electron equivalents to methane in the gas phase. Further, the removal of BOD_L and, subsequently, waste stabilization depends entirely on methane formation (Rittmann & McCarty, 2001).

End products of methanogenesis are carbon dioxide, methane, water, and biomass (typically represented as $C_5H_7O_2N$). One percentage of electron equivalents, f_s, is synthesized into biomass, and the other percentage of electron equivalents, f_e, is transformed into energy (Rittmann & McCarty, 2001).

In anaerobic digestion, methane is formed through two pathways: the oxidation of hydrogen and the cleavage of acetic acid. Carbon dioxide is the electron acceptor in the oxidation of hydrogen to form methane. In the cleavage of acetic acid, for the purposes of writing stoichiometric reactions, it can be assumed that carbon dioxide is the electron acceptor because the overall reaction is the important reaction in writing stoichiometric reactions, not the specific reaction pathway (Rittmann & McCarty, 2001).

R equations (represented as letter b.) in Figure 3.1) for the electron acceptor (CO_2), the electron donor (the organic waste molecule), and cell synthesis were calculated based upon the CHON molecular formula as follows.

The custom organic half reaction (Rittmann & McCarty, 2001) for the organic molecule $C_nH_aO_bN_c$ is defined as:

$$R_d = \frac{c}{d} NH_4^+ + \frac{c}{d} HCO_3^- + \frac{(n-c)}{d} CO_2 + H^+ + e^- = \frac{1}{d} C_nH_aO_bN_c + \frac{(2n-b+c)}{d} H_2O \qquad \textbf{(3.2.4)}$$

where R_d = electron donor half reaction

d = (4n + a – 2b – 3c).

The electron acceptor in anaerobic digestion is carbon dioxide. The electron acceptor half reaction (Rittmann & McCarty, 2001) is defined as:

$$R_a = \frac{1}{8} CO_2 + H^+ + e^- = \frac{1}{8} CH_4 + \frac{1}{4} H_2O \qquad \textbf{(3.2.5)}$$

where R_a = electron acceptor half reaction.

The cell synthesis half reaction with ammonium as the nitrogen source (Rittmann & McCarty, 2001) is defined as:

$$R_c = \frac{1}{5} CO_2 + \frac{1}{20} HCO_3^- + \frac{1}{20} NH_4^+ + H^+ + e^- = \frac{1}{20} C_5H_7O_2N + \frac{9}{20} H_2O \qquad \textbf{(3.2.6)}$$

where R_c = cell synthesis half reaction.

The overall R equation (Rittmann & McCarty, 2001) is defined as:

$$R = f_e Ra + f_s R_c - R_d \quad \textbf{(3.2.7)}$$

where R = overall R equation

f_e = fraction of energy conserved through waste stabilization.

f_s = fraction of energy that goes toward cell synthesis.

It was assumed that $f_e = 0.92$.

According to Lee et al. (2008), swine manure waste is 65.6 % degradable. This value depends on temperature and SRT, as well as the type of manure. For the purposes of this work, it was assumed that all livestock wastes are 65.6% degradable. It is recommended that different percentages for each animal type be incorporated into the Excel spreadsheet model in future work. The COD for each animal waste was multiplied by 0.656, and the subsequent degradable fraction of the waste stream was used instead of the COD in calculating the CHON formula for the waste stream. Calculating the CHON formula was described in Subsection 3.2.1.

3.2.3 Amount of Biogas Produced per Day

Amount of livestock manure collected (based on the total amount of manure produced per day) was determined through three user output options. Livestock arrangements are important in the collection of manure. If livestock were free-ranging during the day and penned at night, 50% of the manure was assumed to accumulate in the penned area. Manure collection in a penned area is feasible, whereas manure collection from free-ranging livestock is not feasible. If livestock were free-ranging during half of

the year and penned during half of the year, manure collection was assumed to be 50%. If livestock were penned or tied up all the time, manure collection was assumed to be 100%. For the following calculations, percent manure collection was multiplied by the mass VS in the manure type.

The amount of biogas produced per day, letter c.) in Figure 3.2, was calculated by first finding the mass of volatile solids (VS) loaded into the reactor on a daily basis. Equation 3.2.8 shows this calculation.

$$\text{mass VS} = (\text{mass VS})_{\text{swine boar}}*(\text{no. animal})_{\text{swine boar}} + (\text{mass VS})_{\text{swine sow}}*(\text{no. animal})_{\text{swine sow}} + (\text{mass VS})_{\text{poultry}}*(\text{no. animal})_{\text{poultry}} + (\text{mass VS})_{\text{beef cattle}}*(\text{no. animal})_{\text{beef cattle}} + (\text{mass VS})_{\text{dairy cattle}}*(\text{no. animal})_{\text{dairy cattle}} \quad \textbf{(3.2.8)}$$

where mass VS = total mass VS loaded per day (kg VS/(m^3*d))

no. animal = number of animals

The number of moles of the organic molecule, $C_nH_aO_bN_c$, added to the reactor per day (mol $C_nH_aO_bN_c$/d) was calculated as:

$$\frac{mass\ \text{VS}\left(\frac{kgVS}{d}\right)*1000}{MW} = \text{mol } C_nH_aO_bN_c/\text{d} \quad \textbf{(3.2.9)}$$

where MW = molecular weight of $C_nH_aO_bN_c$ (g)

mass VS = mass VS added per day (kg VS/d).

Next, the number of moles of methane produced per day was calculated as:

$$r\ (\text{mol } CH_4/d) = x\ (\text{mol } C_nH_aO_bN_c/d) * \frac{M}{C} \quad \textbf{(3.2.10)}$$

where r = number of moles of methane per day, (mol CH_4/d)

x = number of moles of $C_nH_aO_bN_c$ per day, (mol $C_nH_aO_bN_c$ /d)

M = coefficient of methane in the overall R equation

C = coefficient of $C_nH_aO_bN_c$ in the overall R equation.

Number of moles of carbon dioxide produced per day was calculated as:

$$m\ (\text{mol } CO_2/d) = x\ (\text{mol } C_nH_aO_bN_c/d) * \frac{B}{C} \quad \textbf{(3.2.11)}$$

where m = number of moles of carbon dioxide per day, (mol CO_2/d)

x = number of moles of $C_nH_aO_bN_c$ per day, (mol $C_nH_aO_bN_c$ /d)

B = coefficient of carbon dioxide in the overall R equation

C = coefficient of $C_nH_aO_bN_c$ in the overall R equation.

Volume of biogas produced per day, letter c.) in Figure 3.1, was calculated from the Ideal Gas Law.

$$V = (n*R*T)/P \quad \textbf{(3.2.12)}$$

where V = volume of biogas produced per day (m^3 biogas/d)

n = total number of moles of biogas generated per day; n = r + m (number of moles biogas/d)

R = gas constant = 8.3144 J/(mol*K) = (m^3*Pa)/(mol*K)

T = temperature (K)

P = total pressure of system (Pa).

3.2.4 Percent Methane

The percent methane (wt.%) in the biogas, letter d.) in Figure 3.1, was calculated as:

$$\text{methane wt.\%} = \frac{\text{r (mol CH4/d)}}{\text{r}\left(\text{mol}\frac{\text{CH4}}{\text{d}}\right)+\text{m}\left(\text{mol}\frac{\text{CO2}}{\text{d}}\right)} * 100 \qquad \textbf{(3.2.13)}$$

where methane wt.% = percent methane in the biogas

r = number of moles of CH_4 produced per day (mol CH_4/d)

m = number of moles of CO_2 produced per day (mol CO_2/d).

The amount of biogas produced per day was compared to 0.85 m^3 biogas/day, the volume of biogas required to cook for a family of five in India (Nijaguna, 2002). A comparison was made dividing the amount of biogas by the number of households included in the ownership of the digester.

3.2.5 Volume of Water Fed per Day and Total Volume of Digester

Next, the calculations labeled letter e.) in Figure 3.1 are presented. The mass of manure produced per day was calculated as a weighted average of manure mass values cited in American Society of Agricultural Engineers (2005) (see Table 2.1) and the number of each animal inputted by the user. This value was multiplied by the percent manure collected, which was explained in Subsection 3.2.3.

An organic loading rate (OLR) of 1.0 kg VS/(m^3*d) was assumed for all cases in the model. Tchobanoglous et al. (2003) recommended organic loading rates for standard

rate anaerobic digestion (no mixing, mesophilic) in the range of 0.5 – 1.6 kgVS/(m^3*d), and Sharma & Pellizzi (1991) recommended OLR*'s* in the range of 1.0 – 3.5 kgVS/(m^3*d). Ferrer et al. (2009) recommended 1.0 kgVS/(m^3*d) or higher; 1.0 kgVS/(m^3*d) was superior to 0.5 kgVS/(m^3*d) because both digesters tested had very similar specific biogas production rates, meaning that gas production did not significantly decrease from the increase in OLR from 0.5 to 1.0 kgVS/(m^3*d) (Ferrer et al., 2009). An OLR of 1.0 kgVS/(m^3*d) was chosen to be within a conservative end of the range of OLR*'s* recommended.

Next, the total mass of water in the manure of each species was calculated as follows:

$$total\ mass_{water} = \frac{moisture * no.animals * TS}{1 - moisture} \quad \textbf{(3.2.14)}$$

where total $mass_{water}$ = total mass of water in the total manure of one species (kg H_2O/d)

moisture = mass fraction of water in the manure

TS = mass of total solids in manure generated per animal per day (kg TS/(animal*d)

no. animals = number of animals.

Again, the TS generated per animal per day were multiplied by the percent of manure collected. The volume occupied by the liquid fraction of the manure added to the reactor per day was calculated as follows. It was assumed that the volume that the solid fraction of the manure was a negligible volume in this calculation. See Figure 3.2 for a visual representation.

$$V_{1,l} = \frac{\sum total\ mass_{water_i}}{\rho_{water}} \quad \textbf{(3.2.15)}$$

where $V_{1,l}$ = volume of liquid fraction of manure added per day (m^3)

total $mass_{water\ i}$ = total mass of water in manure for species *i* per day (kg water/d)

i = animal species

ρ_{water} = density of water (kg/m^3). Assumed to be 1000 kg/m^3 in the model, regardless of temperature.

Next, the initial concentration of volatile solids in the manure added to the reactor per day was calculated as follows:

$$C_1 = \frac{\sum C_i * V_{manure_i} * no.animals}{V_{1,l}} \quad \textbf{(3.2.16)}$$

where C_1 = initial concentration of volatile solids in the total manure volume (kg VS/m^3)

C_i = concentration of VS in manure of species *i* (kg VS/(m^3*d*animal))

no. animals = number of animals

$V_{1,l}$ = volume of liquid fraction of manure added per day (m^3).

The liquid and solids volume of the reactor (reactor volume not including the headspace) was calculated as follows:

$$V_R = \frac{C1 * V1,l}{OLR} \quad \textbf{(3.2.17)}$$

where V_R = liquid and solids volume of the reactor (m^3)

C_1 = initial concentration of volatile solids in the total manure volume (kg VS/m^3)

$V_{1,l}$ = volume of liquid fraction of manure added per day (m^3)

OLR = organic loading rate (kgVS/(m^3*d). Assumed to be 1.0 kgVS/(m^3*d).

The volume of the reactor vessel, which included the gas headspace volume above the liquid, was calculated by multiplying the liquid and solids volume of the reactor by a ratio of 1.2:

$$V_{vessel} = V_R * (1.2) \quad \textbf{(3.2.18)}$$

where V_{vessel} = volume of reactor vessel, including the headspace (m^3)

V_R = liquids and solids volume of the reactor (m^3)

3.2.6 Digester Dimensions

Based on the user input of the digester design type, equations 3.2.19 through 3.2.21 were utilized to calculate dimensions of the specified digester. For the polyethylene tubular digester, the diameter was fixed at 1.11 meters based on polyethylene tube availability in Bolivia (GTZ/EnDev, 2010). The length of the polyethylene tubular digester was calculated as follows:

$$L_{polyethylene} = \frac{V_{vessel}}{\pi * \left(\left(\frac{D_{polyethylene}}{2}\right)^2\right)} \quad \textbf{(3.2.19)}$$

where $L_{polyethylene}$ = length of polyethylene reactor (m)

V_{vessel} = volume of reactor vessel, including the headspace (m^3)

$D_{polyethylene}$ = diameter of polyethylene tube (m)

The dimensions of the fixed dome digester were calculated as follows. The H/D ratio was defined as 2.0 (Nijaguna, 2002).

$$D_{fixed\ tank} = \frac{V_{vessel}*4}{\left(\pi*\frac{H}{D}\right)^{1/3}} \quad \textbf{(3.2.20)}$$

where $D_{fixed\ tank}$= diameter of fixed dome anaerobic digester (m)

V_{vessel}= volume of reactor vessel, including the headspace (m^3)

H/D = height-to-diameter ratio (2.0 for fixed dome reactor) (dimensionless)

The height of the fixed dome reactor was calculated as follows:

$$H_{fixed\ tank} = (H/D)*D_{fixed\ tank} \quad \textbf{(3.2.21)}$$

where $H_{fixed\ tank}$ = height of the fixed dome digester (m).

The dimensions of the floating drum digester were calculated similarly to equations 3.2.20 and 3.2.21. The H/D ratio was defined as 3.5 (Nijaguna, 2002).

3.2.7 Rate Kinetics and SRT

The kinetic piece of the model used a semi-empirical model to relate SRT to temperature and solubility of the substrate. The input values for this piece of the model are the mean warm season temperature and the mean cold season temperature inputted by the user. The model bases the calculation of the digester volume on the lower temperature. The model outputs a warm season loading rate and a cold season loading rate.

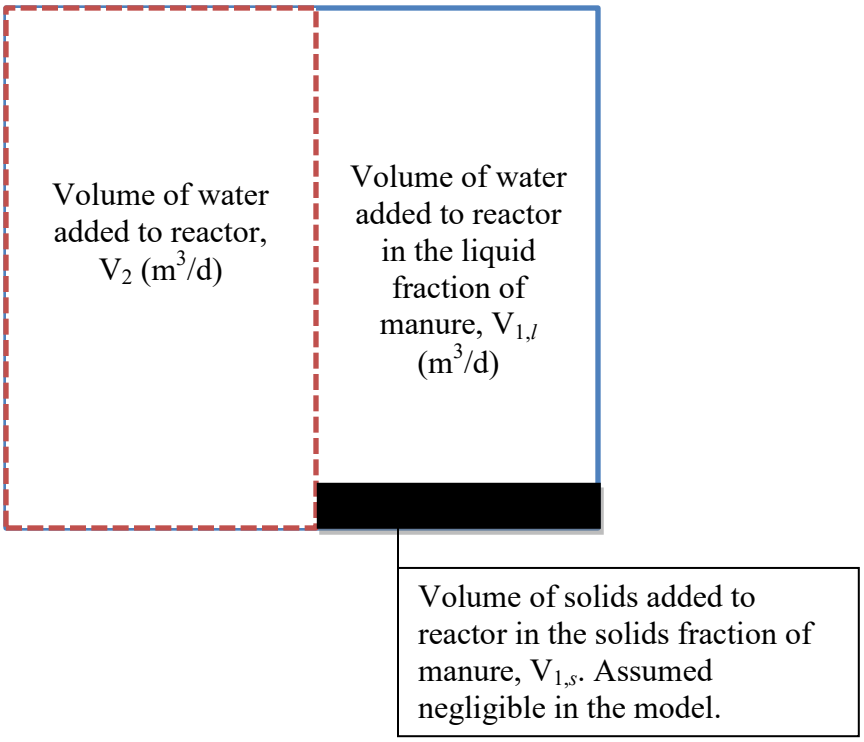


Figure 3.2: Conceptualization of the Volume of Water Added as Water, the Volume of Water Added as Moisture in Manure, and the Volume of Solids Added as Solids in Manure

Table 3.2: Model Assumptions

Assumption	Step of model where assumed	Why assumed	Source (if applicable)
TN = TKN	CHON formula calculation, letter a.) in Figure 3.1	TKN not available	N/A
TOC = COD/4 and formula weight = COD/2	CHON formula calculation, letter a.) in Figure 3.1	TOC, weight not available	(McCarty, 1976)
$f_e = 0.92$	Overall R equation, letter b.) in Figure 3.1	Soluble substrate concentration not available	(Tchobanoglous et al., 2003)
OLR = 1.0 kg VS/(m^3*d)	Volume of reactor vessel, letter f.) in Figure 3.1	Recommended range for standard rate AD	(Garfi et al., 2011)
P_{tot} of biogas in reactor is P= 1 atm = 101.3 kPa	Amount of biogas produced per day, letter c.) in Figure 3.1	low pressure gas systems	N/A
$V_{headspace\ in\ reactor} = V_R/5$	Volume of gas storage container calculation, an output	gas storage space in the reactor is necessary	(Kocak- Enturk, 2007)
$\rho_{water} = 1000\ kg/m^3$	Calculation of liquid and solids volume In the digester, letter f.) in Figure 3.1	Ease of calculations; change in density not significant	N/A

3.3 Model Outputs

Model outputs are summarized in Table 3.3.

Table 3.3: Model Outputs

Biogas production rate per family	0.315	m^3 biogas/d
India 1 family	0.850	m^3 biogas/d
$V_{reactor\ vessel}$ =	0.66	m^3
During the cold season:		
$V_{manure\ added,\ c}$ =	2	L/d = kg/d
$V_{water\ added,\ c}$ =	6	L/d
During the warm season:		
$V_{manure\ added,\ w}$ =	6	L/d = kg/d
$V_{water\ added,\ c}$ =	7	L/d
Floating drum anaerobic digester		
$D_{Digester}$ =	0.62	m
H =	2.18	m
$V_{gas\ storage\ vessel}$ =	No external gas storage required.	m^3
For a polyethylene gas storage vessel:		
$D_{gas\ storage\ vessel}$ =	No external gas storage required.	m
$L_{gas\ storage\ vessel}$ =	No external gas storage required.	m

Chapter 4: Results and Discussion

4.1 Case Study 1: Family-Sized Anaerobic Digester

The values for the following three case studies were taken from data collected by the author while serving in the Peace Corps Dominican Republic. The village is located in the province of Puerto Plata in the Septeptrional Mountains on the northern coast of the Dominican Republic. The village was comprised of 48 households.

In the village where the author lived, the major source of cooking fuel is a solid fuel, wood. Most cooking is done on “fogones”, which are traditional three- stone fires (three cement blocks arranged as the three sides of a rectangle). Wood is fed in from the missing fourth side of the rectangle, and a cooking pot placed above the fire on the cement blocks. There are no chimneys in the community. Most kitchens are located in separate buildings from the rest of the house. The ventilation methods in the kitchens include: one missing wall or part of a wall, open windows, or part of the roof raised up to provide ventilation out the roof. In an oral survey, 42% of households in the village answered that people in the household had a history of suffering from respiratory, lung, cold, or chest illnesses.

Both the clearing of land for agriculture and the collection of firewood have noticeably affected the natural vegetation of the green hills in the area of the village. Although these communities are noticeably more forested than areas where cattle are

raised in large numbers, deforestation is still notable and of major concern for future ecosystem health.

Thirteen families, or 27% of the families in the village, own a small number of pigs. Through conversing with people, the author discovered that it is not cost-effective to sell pigs, due to the recently rising price of pig feed. Therefore, most families that raise pigs butcher them at holiday times to feed their family members. Other families sell the baby pigs at about one month old. Utilizing the pig manure to produce energy and fertilizer for crops would increase the value of owning a pig, and also decrease the environmental impact of runoff of manure into waterways.

Seventy percent of the families in the village own chickens. 63% of the households have unimproved pit latrines. These pit latrines in the village consist of a pit measuring about eight to ten feet deep, four feet wide, and seven feet long. The latrine floors consist of wooden slabs to cover the pit. The seat is usually a wooden box with a seat hole on the top of the box, the walls are wooden, and the roof is zinc sheeting. An improved pit latrine would include mortared bricks or stones lining the upper 1.5 feet of the pit walls for structural support in stable soils, or non-mortared bricks or stones lining the entire pit in unstable soils (Mihelcic et al., 2009). Because a majority of the households in the village have unimproved pit latrines, there is a need for improved sanitation in the community. Improved sanitation could include pour-flush latrines which feed into anaerobic digesters, among other options.

Case Study One was one family-sized digester and included the waste from one pig and six chickens. Inputs and outputs from the model for Case Study 1 are shown in Table 4.1.

Table 4.1: Inputs for Case Study 1: Family-Sized Anaerobic Digester

Animal types: swine - gestating sow, poultry
Numbers of animals: 1 swine - gestating sow, 6 poultry
Warm Season Temperature: 28 °C Cold Season Temperature: 26°C
Digester type: polyethylene tubular
Arrangements of livestock: penned all the time

Table 4.2: Outputs for Case Study 1: Family-Sized Anaerobic Digester

Biogas production for system	0.699	m^3 biogas/d
India 1 family	0.850	m^3 biogas/d
$V_{reactor\ vessel}$ =	0.61	m^3
During the cold season:		
$V_{manure\ added,\ c}$ =	6	L/d = kg/d
$V_{water\ added,\ c}$ =	11	L/d
During the warm season:		
$V_{manure\ added,\ w}$ =	15	L/d = kg/d
$V_{water\ added,\ c}$ =	11	L/d
Polyethylene tubular anaerobic digester		
$D_{Digester}$ =	1.11	m
L =	0.63	m
$V_{gas\ storage\ vessel}$ =	0.60	m^3
For a polyethylene gas storage vessel:		
$D_{gas\ storage\ vessel}$ =	1.11	m
$L_{gas\ storage\ vessel}$ =	0.62	m

According to Nijaguna (2002), one family in India uses 850 L of biogas per day or 0.85 m^3 biogas/d. 0.699 m^3 biogas/d is the calculated biogas production rate. It takes 0.04 m^3 biogas to boil 1 L of water in 10 minutes, and it takes 0.14 m^3 biogas to cook 500 grams of rice for 30 minutes (Nijaguna, 2002). Based on the model calculations, a family would need more manure than 100% of the manure from 1 swine- gestating sow and 6 poultry to meet their daily cooking needs. Connecting a latrine to the digester would be one solution to this problem; however, future work on characterization of human feces is needed before calculations can include this substrate.

4.2 Case Study 2: Anaerobic Digester for Six Households

In order to save on materials and to share in operation and maintenance considerations, it is an option to build a slightly larger anaerobic digester for the animal wastes from six households. Although data was collected on the types of agricultural animals each household owned, the numbers of each animal were not taken into account in the house-to-house needs assessment survey conducted by the author. Because of the lack of data, it was estimated that there was an approximate average of one gestating sow at the households that owned pigs, six chickens at the households that owned chickens, and one beef cattle at the households that owned cattle.

Case Study 2 included the waste from two gestating sows, 25 poultry, and 1 beef cattle. Table 4.2 shows the inputs and outputs of Case Study 2.

Table 4.3: Inputs for Case Study 2: Anaerobic Digester for Six Households

Animal types: swine - gestating sow, poultry, beef cattle
Numbers of animals: 2 swine - gestating sow, 25 poultry, 1 cattle - beef
Warm Season Temperature: 28 ℃
Cold Season Temperature: 26℃
Digester type: polyethylene tubular, floating drum
Arrangements of livestock: penned all the time

Table 4.4: Outputs for Case Study 2: Anaerobic Digester for Six Households

Biogas production for system	2.673	m^3 biogas/d
India 1 family	0.850	m^3 biogas/d
$V_{reactor\ vessel}$ =	2.95	m^3
During the cold season:		
$V_{manure\ added,\ c}$ =	32	L/d = kg/d
$V_{water\ added,\ c}$ =	50	L/d
During the warm season:		
$V_{manure\ added,\ w}$ =	67	L/d = kg/d
$V_{water\ added,\ c}$ =	50	L/d
Floating drum anaerobic digester		
$D_{Digester}$ =	1.02	m
H =	3.58	m
$V_{gas\ storage\ vessel}$ =	No external gas storage required.	m^3
For a polyethylene gas storage vessel:		
$D_{gas\ storage\ vessel}$ =	No external gas storage required.	m
$L_{gas\ storage\ vessel}$ =	No external gas storage required.	m

The calculated flow rate of biogas produced was approximately 2.7 m^3 biogas/d. If one family uses 0.85 m^3 biogas/d (Nijaguna, 2002), that would be an equivalent flow rate of 0.445 m^3/(d*family). This flow rate would be enough biogas for three households, not six. The households would have to supplement their biogas fuel with human waste through pour-flush latrines connected to the digester, additional livestock waste, or continue using some solid fuel along with biogas.

Biogas could be shared by sharing a common kitchen range among households in a small cluster of houses. Additionally, biogas could be transported from the gas storage vessel to individual gas stoves by filling truck tire inner tubes or other small plastic reservoirs with gas.

4.3 Case Study 3: Village-Sized Anaerobic Digester

Centralizing anaerobic digestion of animal wastes to one digester has the advantages of shared costs among shareholders. The village in which the author lived consists of 48 households. From the recorded numbers of households that own at least one of each type of animal, the average number of that animal per household with that animal was estimated. The numbers of animals used in Case Study 3 were: 12 swine – gestating sows, 6 swine – boars, 170 poultry, 20 cattle – beef, and 2 cattle – dairy. Table 4.3 shows the inputs and outputs for Case Study 3.

Table 4.5: Inputs for Case Study 3: Village – Sized Anaerobic Digester

Animal types: swine - gestating sow, swine - boar, poultry, cattle - beef, cattle - dairy
Numbers of animals: 12 swine - gestating sows, 6 swine - boars, 170 poultry, 20 cattle - beef, 2 cattle - dairy
Warm Season Temperature: 28 °C
Cold Season Temperature: 26°C
Digester type: fixed dome
Arrangements of livestock: penned all the time

Table 4.6: Outputs for Case Study 3: Village- Sized Anaerobic Digester

Biogas production for system	43.507	m^3 biogas/d
India 1 family	0.850	m^3 biogas/d
$V_{reactor\ vessel}$ =	48.40	m^3
During the cold season:		
$V_{manure\ added,\ c}$ =	523	L/d = kg/d
$V_{water\ added,\ c}$ =	822	L/d
During the warm season:		
$V_{manure\ added,\ w}$ =	1089	L/d = kg/d
$V_{water\ added,\ c}$ =	822	L/d
Fixed dome anaerobic digester		
$D_{Digester}$ =	3.14	m
H =	6.27	m
$V_{gas\ storage\ vessel}$ =	35.44	m^3

The calculated flow rate of biogas produced was approximately 44 m^3 biogas/d. If 0.85 m^3 biogas/d are needed for one household's cooking each day, there would be enough biogas in the community to supply 51 households with biogas; therefore, the gas

production rate is sufficient to supply all 48 households with sufficient gas for daily cooking. One assumption that is made here; however, is that the community captures 100% of the animal waste. Animals often roam, so it would be more realistic to choose a different livestock arrangement input.

4.4 Discussion

The biogas production values can be converted into specific biogas production rates by dividing them by the volatile solids reduction. It was assumed that 65.6% of the COD is degradable. We can also assume that 65.6% of the volatile solids will be reduced. Therefore, for Case Studies 1, 2, and 3, the specific biogas production rates were 0.0076, 0.0069, 0.102, m^3 biogas/kg VS reduced, respectively.

Ferrer et al. (2011) reported specific biogas production of 0.35 m^3/kg VS reduced in a polyethylene tubular reactor in the Andes of Peru. The values calculated in the model are 1/3 to 1/2 the specific biogas production rate reported by Ferrer et al. (2011). Tchobanoglous et al. (2003) states that specific biogas production rates are in the range of 0.75 – 1.12 m^3 biogas/kg VS destroyed. Chae et al. (2008) conducted a bench-scale study of anaerobic digestion, and reported values which can be converted into the same units used here for comparison. Values reported by Chae et al. (2008) were 0.327, 0.389, and 0.403 m^3 biogas/kg VS destroyed for three different reactors.

4.5 Recommendation for Guidelines for Residuals Disposal

Pathogens pose a public health risk. Diarrheal diseases are prevalent in the developing world due to poor sanitation, poor hygiene, lack of improved water sources, and various other factors. The "F-Diagram," which describes fecal-oral pathogen transmission pathways from feces to the mouth shows that pathogens are easily transmitted if various measures are not taken to ensure the protection of public health (Mihelcic et al., 2009).

Restricting or making recommendations on the use and disposal of pathogen-containing residuals is important and constitutes breaking the line of pathogen transmission from agricultural fields to the human mouth. There is not much literature yet published about the pathogen contents of residuals from low temperature, no mixing small scale anaerobic digesters.

Chapter 5: Conclusions and Recommendations

5.1 Conclusions

Literature reviewed revealed there are gaps in the literature regarding very limited data on small scale anaerobic digester operation studies in the field, lack of digester sizing design equations, and lack of studies on pathogen reduction in slurry effluent and biosolids from standard rate anaerobic digesters in the field in developing countries. The author addressed the second gap in the literature, lack of digester sizing design equations.

Typical parameters monitored in anaerobic digestion studies were identified and individual methods for those parameters selected using Standard Methods (Eaton et al., 2005). The author determined based on equipment required for each sample test whether the test could be done in the field. Sample preservation methods were documented, along with time lag allowed before analysis in a lab.

The Excel spreadsheet design tool developed in this work was evaluated using three case studies in a rural village in the Dominican Republic. In Case Study 1, the household-sized anaerobic digester with one gestating sow – swine and 6 poultry did not supply sufficient biogas per day for that household's cooking needs. In Case Study 2, the anaerobic digester for 6 families with 2 gestating sow- swine, 25 poultry, and one beef cattle did not supply sufficient biogas per day for those 6 households; the digester supplied sufficient biogas for 3 households. In Case Study 3, the village-sized anaerobic digester with 12 gestating sow-swine, 6 boar- swine, 170 poultry, 20 beef cattle, and 2

dairy cattle supplied sufficient biogas for the cooking needs of the 48 households in the community. All of the case studies assumed that livestock were penned all of the time.

Biogas cooking needs were met with the village-sized digester, but not with the household-sized or 6-family-sized anaerobic digesters. It can be concluded that village-sized anaerobic digesters may be more efficient or that the village in the case studies had sufficient animal waste to cook for all the people, but that livestock ownership was skewed due to poverty.

Specific biogas production rates were low compared to those reported in the literature, especially of Ferrer et al. (2011) in similar digester conditions. The assumptions made in the model, such as 65.6% of the volatile solid reduction may be higher.

The values for reactor vessel size presented in the case studies are reasonable. Future work includes validating the spreadsheet design tool in both the lab and in the field.

5.2 Future Work

The Excel spreadsheet model could be improved in a few ways. First, the order of the substrate inputs could be programmed so that the user does not have to input animals and numbers of animals in a certain order. The percent degradability of the volatile solids was assumed for all substrates to be 65.6%. This number should be different for different types of manure. In the future, percent degradability for additional types of manure should be analyzed. There are three user inputs for livestock arrangements during the year, which is a limited number of options. These inputs could be expanded in the future. Human and guinea pig feces could be characterized for COD, TS, VS, TKN, TOC, and total manure volume per day. Floating drum diameters could be set in the model based on size availability of floating drums in developing countries. Xw, or the concentration of cells in the waste stream was not accounted for in the model; therefore, future research could include calculation or measurement in the field of Xw and take into account separate SRT and HRT values.

One gap in the literature includes the re-purposing of storage vessels. Plastic fifty-five gallon drums are often available in developing countries. If metal drums are to be used, they must be sealed with a polymer to protect the metal from corrosion. In the village in which the author lived in the Dominican Republic, multiple families in the community had fifty-five gallon drums used for water storage. These drums are appropriate for use as anaerobic digesters. Future work could include designing parameters for the use of fifty-five gallon drums as anaerobic digesters.

The use of antibiotics in agriculture is widespread in the United States. Future work in the design of anaerobic digesters in developing countries should include

investigating the use of antibiotics in developing countries and whether the use of antibiotics negatively impacts the biogas yield of anaerobic digestion.

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Appendices

Appendix A: Calculation of Organic Loading Rates

The organic loading rate can be calculated from the mass of manure and the volume of water recommended for loading the PFR tubular digester (for developing world applications from GTZ, 2001 in the following manner:

$$Organic\ Loading\ Rate = \frac{mass\ VSS\ added\ each\ day}{working\ digester\ volume}$$

$$\left(mass\ manure\ (kg)\right) * (\%\ solids\ content) = mass\ Total\ Solids\ (kg)$$

Manure moisture content was reported by Fukumoto et al. (2003) to be 68%.

$$mass\ TS = \ (20\ kg\ manure)(1 - 0.68) = 6.4\ kg\ TS$$

Assume VS to TS ratio is 90%.

$$\frac{VS}{TS} = 90\%$$

$$mass\ VS\ (kg) = \ \frac{0.90}{mass\ TS\ (kg)}$$

$$mass\ VS\ (kg) = \ \frac{0.90}{6.4\ kg\ TS} = 0.14\ kg\ VS$$

$$Organic\ Loading\ Rate = \frac{mass\ VS\ (kg) * \frac{1}{d}}{reactor\ volume\ (m^3)}$$

$$Organic\ Loading\ Rate = \ \frac{0.14\ kg\ VS}{5.84\ m^3 * d} = 0.024\ \frac{kg\ VS}{m^3 * d}$$

In GTZ / GIZ (1999), the suggested organic loading rate given is below the recommended organic loading rate for low-rate anaerobic digestion. The spreadsheet model in Chapter 3 addresses the problem of reactor design and process operation in a way that is valuable and easy-to-use.

Appendix B: Design Tool Excel Spreadsheet
Table B.1: User Input Interface for the Excel Spreadsheet Design Tool

1.	What type or types of animals will you collect manure from?				
	1 = swine - gestating sow				
	2= swine - boar				
	3= poultry				
	4= cattle - beef				
	5= cattle - dairy cow				
	Answer 1=	**1**	swine - gestating sow		
	Answer 2=	**0**	FALSE		
	Answer 3=	**3**	poultry		
	Answer 4=	**0**	FALSE		
	Answer 5=	**0**	FALSE		
2.	How many animals of each answer type are there?				
	Answer 1=	**1**	swine - gestating sow		
	Answer 2=	**0**	FALSE		
	Answer 3=	**6**	poultry		
	Answer 4=	**0**	FALSE		
	Answer 5=	**0**	FALSE		
3.	a. What is the approximate mean temperature during the warmest 6 months of the year where the digester will be built? b. What is the mean temperature during the coldest six months of the year where the digester will be built?				
	Answer a: Temperature =	**28**	°C		
	Answer b: Temperature =	**26**	°C		
4.	What type of digester are you building?				
	1 = Polyethylene tubular anaerobic digester				
	2 = Fixed dome anaerobic digester				
	3 = Floating drum anaerobic digester				
	Answer =	**1**	Polyethylene tubular anaerobic diges		
5.	What are the arrangements of the livestock?				
	1 = Livestock are free ranging during the day, penned at night.				
	2 = Livestock are free ranging during half the year, penned half the year.				
	3 = Livestock are penned all the time.				
	Answer =	**3**	100% manure capture expected.		

Appendix B, Continued
Table B.2: Mass Balance Piece of the Model

	swine - gestating sow	swine - boar	poultry	cattle - beef	cattle - dairy cow
Mass loading (kg VS/(d*animal))	1.000	0.340	0.018	1.895	7.500
C (kg VS/(m^3*d*animal))	83.333	89.474	188.295	64.444	110.294
V_{manure} (m^3/(d*animal))	0.012	0.004	0.00010	0.029	0.068
moisture (mass fraction basis)	0.900	0.900	0.750	0.740	0.920
kg TS/(d*animal)	1.200	0.380	0.025	2.353	8.900
total mass of water in manure for species(kg water/d)	10.800	3.420	0.074	6.697	102.350
COD- mass basis (kg)	1.100	0.270	0.020	1.961	8.100
COD, $_{\text{influent waste stream}}$ (g)	1100.000	270.000	19.938	1960.784	8100.000
TOTN, mass basis (kg)	0.085	0.028	0.001	0.163	0.450
TOTN, $_{\text{influent waste stream}}$ (g)	85.000	28.000	1.352	163.399	450.000
TOC (g) = COD/4	275.000	67.500	4.984	490.196	2025.000
Weight of organic (g) = COD/2	550.000	135.000	9.969	980.392	4050.000

Appendix B, Continued
B.1: Code from Volume Calculations in the Model

Cool temperature of the digester :		
T =	=IF('User Inputs'!H5<'User Inputs'!H4,'U	°C
SRT =	=VLOOKUP(C38,A8:J33,5,FALSE)	d
OLR actual	=(N50*'User Inputs'!C18+O50*'User In	kg VS/(m^3*d)
Assume Organic Loading Rate (OLR) =	1	kg VS/(m^3*d)
Factor: OLR/OLR actual	=C41/C40	
C_1 =	=('User Inputs'!C18*N51*N52+'User In	kg VS/m^3
$V_{water\ added}$ =	=SUM(N55,O55,P55,Q55,R55)/1000	m^3
$V_{Reactor}$ =	=C39*(C44+C47)	m^3
$V_{total\ added}$ =	=C44+C47	m^3
$V_{manure\ added}$ =	=IF(C42<1,IF(C41<=C40,C51,C50),C5	m^3
$V_{gas\ storage\ in\ reactor\ vessel}$ =	=C45/5	m^3
V_{vessel} =	=C45*(1.2)	m^3
V manure, have	=SUM(N52*'User Inputs'!C18+O52*'Us	m^3
V manure, gives OLR	=SUM(C42*N52*'User Inputs'!C18+C4	m^3
Polyethylene Tubular Reactor		
$D_{polyethylene\ tube}$ =	1.11	m
$L_{reactor}$ =	=C49/(PI()*(C53/2)^2)	m
Fixed Dome Reactor		
D_{tank} =	=((C49*4)/(PI()*C59))^(1/3)	m
H_{tank} =	=C59*C57	m
H:D ratio	2	
Floating Drum Reactor		
D_{tank} =	=((C49*4)/(PI()*C64))^(1/3)	m
H_{tank} =	=C64*C62	m
H:D ratio	3.5	

Appendix B, Continued
Table B.3: Semi-Empirical Kinetic Model Piece of the Model

Safety Factor =	10
θ at 20-30 °C	1.04
θ at 10-20°C	1.12

$SRT = SF/\mu_{max}$

$\mu_{max} = SF/SRT$

Temperature (°C)	θ (activity coefficient)	μ_{20} (1/d)	μ_{max} based on SRT (1/d)	SRT (d)
10	1.12	0.444	0.143	70
11	1.12	0.396	0.143	70
12	1.12	0.354	0.143	70
13	1.12	0.316	0.143	70
14	1.12	0.282	0.143	70
15	1.12	0.252	0.143	70
16	1.12	0.225	0.143	70
17	1.12	0.201	0.143	70
18	1.12	0.179	0.143	70
19	1.12	0.160	0.143	70
20	1.04	0.250	0.250	40
21	1.04	0.240	0.250	40
22	1.04	0.231	0.250	40
23	1.04	0.222	0.250	40
24	1.04	0.285	0.333	30
25	1.04	0.274	0.333	30
26	1.04	0.263	0.333	30
27	1.04	0.253	0.333	30
28	1.04	0.292	0.400	25
29	1.04	0.281	0.400	25
30	1.04	0.270	0.400	25
31	1.04	0.260	0.400	25
32	1.04	0.312	0.500	20
33	1.04	0.300	0.500	20
34	1.04	0.289	0.500	20
35	1.04	0.278	0.500	20

Appendix B, Continued
B.2: Calculation of Overall CHON Formula and Overall R Equation

swine - gestating sow

$C_nH_aO_bN_c$		Normalized
n =	91.7	15.1
a =	45.7	7.5
b =	12.7	2.1
c =	6.1	1.0

swine - boar

$C_nH_aO_bN_c$		Normalized
n =	5.6	2.8
a =	17.5	8.7
b =	1.2	0.6
c =	2.0	1.0

poultry

$C_nH_aO_bN_c$		Normalized
n =	0.4	4.3
a =	1.3	13.4
b =	0.1	1.4
c =	0.1	1.0

cattle - beef

$C_nH_aO_bN_c$		Normalized
n =	40.8	3.5
a =	127.0	10.9
b =	11.7	1.0
c =	11.7	1.0

cattle - dairy cow

$C_nH_aO_bN_c$		Normalized
n =	168.8	5.3
a =	524.9	16.3
b =	63.4	2.0
c =	32.1	1.0

	n	a	b	c
s-gc	15.1	7.5	2.1	1.0
s-b	2.8	8.7	0.6	1.0
p	4.3	13.4	1.4	1.0
c-b	3.5	10.9	1.0	1.0
c-dc	5.3	16.3	2.0	1.0

Appendix B, Continued

Average $C_nH_aO_bN_c$

n =	=AVERAGEIF(N76:N80,">0")
a =	=AVERAGEIF(O76:O80,">0")
b =	=AVERAGEIF(P76:P80,">0")
c =	=AVERAGEIF(Q76:Q80,">0")

Formula: $C_{6.2}H_{11.4}O_{1.4}N_{1.0}$

$d = 4n + a - 2b - 3c$

d = 30.288

Custom Organic Half Reaction:

$R_d = c/d\ NH_4^+ + c/d\ HCO_3^- + ((n-c))/d\ CO_2 + H^+ + e^- = 1/d\ C_nH_aO_bN_c + ((2n-b+c))/d\ H_2O$

c/d =	0.033
(n-c)/d =	0.171
(2n-b+c)/d =	0.395
1/d =	0.033

Half Reaction of CO_2 to CH_4 as electron acceptor:

$R_a = \frac{1}{8} CO_2 + H^+ + e^- = \frac{1}{8} CH_4 + \frac{1}{4} H_2O$

Half Reaction with Ammonium as the Nitrogen Source:

$R_c = \frac{1}{5} CO_2 + \frac{1}{20} HCO_3^- + \frac{1}{20} NH_4^+ + H^+ + e^- = \frac{1}{20} C_5H_7O_2N + \frac{9}{20} H_2O$

f_e =	0.92
f_s =	0.08

Appendix B, Continued

R_d: $0.033\ NH_4^+ + 0.033\ HCO_3^- + 0.171\ CO_2 + H^+ + e^- = 0.033\ C_{6.2}H_{11.4}O_{1.4}N + 0.395\ H_2O$

$f_e R_a$: $0.115\ CO_2 + 0.920\ H^+ + 0.920\ e^- = 0.115\ CH_4 + 0.230\ H_2O$

$f_s R_c$: $0.016\ CO_2 + 0.004\ HCO_3^- + 0.004\ NH_4^+ + 0.080\ H^+ + 0.080\ e^- = 0.004\ C_5H_7O_2N + 0.036\ H_2O$

$-R_d$: $0.033\ C_{6.2}H_{11.4}O_{1.4}N + 0.395\ H_2O = 0.171\ CO_2 + 0.033\ NH_4^+ + 0.033\ HCO_3^- + H^+ + e^-$

R: $0.033\ C_{6.2}H_{11.4}O_{1.4}N + 0.129\ H_2O = 0.004\ C_5H_7O_2N + 0.115\ CH_4 + 0.040\ CO_2 + 0.029\ NH_4^+ + 0.033\ HCO_3^- + H^+ + e^-$

Appendix B, Continued

B.3: Code for Calculation of Biogas Production Rate and Volume of Storage Container

molecular weight of organic waste molecule:

=(F113*12.01+H113*1.01+J113*16+L113*14.01)

Total VS mass loading in influent waste stream (total kg VS/d):

=N50*'User Inputs'!C9+O50*'User Inputs'!C10+P50*'User Inputs'!C11+Q50*'User Inputs'!C12+R50*'User Inputs'!C13

number of moles of organic waste molecule in influent:

=(B119*1000)/B116

number of moles of methane produced per day:

=B121*R113/D113

number of moles of carbon dioxide produced per day:

=B121*T113/D113

volume of biogas produced per day:

PV = nRT

V = nRT/P

=(B123+B125)*N127*(C37+273)/(101.325*1000)

percent methane:

=B123/(SUM(B123,B125))*100

volume of methane produced per day:

=(B123)*N127*(C37+273)/(101.325*1000)

gas storage unit

=B129-M134

About the Author

Laurel Rowse received her Bachelor of Science in Chemical Engineering from Northeastern University in May 2008. She studied abroad in Bilbao, Spain, volunteered in rural Honduras, did research through the NSF IRES program in Delft, Holland, and served in the Peace Corps in the Dominican Republic.