Evaluation of biological processing of manure

by

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Daniel S. Andersen, Major Professor
D. Raj Raman
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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

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ABSTRACT

Growth in large-scale animal production systems has resulted in the proportionate increase of animal manure production per unit land area, which is a challenge to manage using conventional methods. Manure in the United States is typically land applied onto adjacent croplands, but new technologies must be employed to overcome cost constraints on hauling large amounts of manure onto land relatively far away from animal farms. While there are numerous manure management strategies, this thesis evaluates and builds on existing research of solid manure composting and liquid manure anaerobic digestion. Composting has historically been proven to be a simple and effective method of waste treatment. A techno-economic analysis of solid manure composting was conducted to identify cost constraints and get an idea on what it takes to make composting feasible. We found a relatively large farm (>6000 beef and dairy cows) is required to make composting economically feasible with the mass loss percentage of compost pile being the most critical factor in successful deployment of composting technologies. Anaerobic digestion has gained tremendous interest in recent years due to heighten government incentives. Many manure anaerobic digestion research and experiments have been conducted on a lab-scale with many promising results mainly attributed to increased methane yield by introducing treatments on substrate or manipulating process parameters. However, success in lab results do not directly translate into successful and increased deployment of digesters on a farm scale. A sub-pilot scale plug-flow anaerobic digesters was designed, built, tested and validated to overcome this knowledge gap in hope to support future research on manure anaerobic co-digestion with different substrates concentrations, hydraulic retention times, and biochar addition.

CHAPTER 1. GENERAL INTRODUCTION

The demand for animal protein has markedly increase over the years. Farmers, especially from the Midwest United States, have responded to the global animal protein demands by incorporating animal production systems onto farmland which includes animal feeding operation (AFO) and concentrated animal feeding operation (CAFO) with the United States alone housing 450,000 AFOs and 10,000 CAFOs (United States Department of Agriculture, 2020). A CAFO is defined as a facility with more than 1,000 animal units (AU) for at least 45 days a year kept on areas without permanent vegetation (Federal Register, 2003).

These concentrated animal feeding operations do help meet the global meat demand, but it also inevitably increased animal waste production per unit land area. According to the United States Department of Agriculture (USDA), 335 million tons of manure are produced on a dry-basis and almost two billion tons of manure is produced per year if liquid portion of manure is included (Main, 2015). Animal agriculture should be viewed as a chain of cyclic nutrient transfers from the soil to the crops, then to humans or animals and from humans' and animals' waste to the soil again (Schroder, 2005). Manure is typically collected on-site and spread onto adjacent croplands to complete the nutrient cycle. It is increasingly viewed as a valuable resource to soil as a replacement to synthetic fertilizers due to its many benefits on soil health as it contains high macro- and micronutrients content, improves soil structure, increases water holding capacity, improves water drainage, and promotes growth of beneficial microorganisms (Sefeedpari, et al., 2019). While manure is an important resource for crop nutrient and soil health, manure stored or produced by CAFOs might have adverse effects on the environment if not management properly (Chadwick, et al., 2011). Concerns generally revolve around its potential of nitrogen (N), phosphorus (P), and carbon (C) losses, which have detrimental consequences such as greenhouse gasses (GHG) emissions, eutrophication, acidification of environmental waters, and offensive odors when storing and land applying (Vries, Groenestein, & De Boer, 2012). However, numerous improvement and strategies have been employed to mitigate these environmental risks on manure land application like advances in manure application equipment and manure application timing. Improvements in best manure management practices has showed positive environmental impacts, but as farms increase in size and become more concentrated, non-conventional manure treatment strategies must be employed to overcome cost constraints on hauling large amounts of manure onto land relatively far away from animal farms.

Manure treatment strategies can be defined as a single or a series of unit operations designed to fulfill constraints of local fertilization of field crops using manure (Flotats, Bonmati, Palatsi, & Foged, 2013). These treatment strategies have the common goal of either to reduce volume or mass of manure to be managed or change its physical-chemical properties and nutrient content while also possibly recovering some energy from these animal by-products (Flotats, Bonmati, Palatsi, & Foged, 2013). Manure treatment strategies are divided into six main categories which include separations techniques, additives and pretreatments of manure, treatment of solid fraction of manure, treatment of liquid fraction of manure, anaerobic treatment, and air cleaning (Foged, et al., 2011). This dissertation fundamentally dives into two methods of manure processing to encourage greater implementation and optimization of best manure management practices, namely manure composting which is part of the solid fraction treatment and anaerobic digestion.

Composting

Composting is an aerobic process involving the mineralization and partial humification of high solid organic wastes, leading to a stable product by microorganisms (Bernal, et al, 2009).

Composting occurs naturally in our surroundings, but efficient composting requires the control of multiple parameters to obtain optimal mass reduction and nutrient retention. This technique is ideally used on solid manure, such as bedded-pack manure and poultry litter. While the benefits of composting have been widely described in literature, it is still not widely practiced due to economic constraints and investment needed to ensure efficient composting. However, emergence of CAFOs might give light to the feasibility of this technology because of the high cost associated with transporting manure from large farms to surrounding croplands.

Anaerobic Digestion

Anaerobic digestion (AD) is a process involving bacteria breaking down organic matter into a stable product in the absence of oxygen (Mata-Alvarex, et al., 2014). AD has a long history of being used in wastewater treatment plants for its distinctive advantage of allowing for low sludge yield, low nutrients requirement, low energy demand, high organic loading rates, and biogas production (Maleki, et al, 2018). The Low Carbon Fuel Standard (LCFS) and Renewable Fuel Standards (RFS) have recently incentivized Renewable Natural Gas (RNG) production from dairy and swine manure anaerobic digestion, which drives more animal producers to capitalize on these incentives (California Air Resources Board, 2019). While literature has conventionally shown numerous benefits of manure AD, high capital cost and technicality in maintaining the delicate balance of the system outweigh the benefits AD brings to farmers (Mathias, 2014). Hence, more cost effective and simple methods should be employed to not only optimize biogas yield, but also focusing on effluent quality for ease of management.

Research Objectives

The objectives of this dissertation are to 1) investigate the feasibility of solid manure composting and 2) evaluate methods and treatments for efficient manure anaerobic digestion.

These studies will provide recommendations for sustainable and economically feasible methods of manure treatment for farmers to optimize the utilization of manure.

Thesis Organization

Chapter 2 is a literature review on types of composting and Chapter 3 is a literature review that summarizes research on optimization strategies of manure anaerobic digestion. Chapter 4 and 5 address the research objective outlined above. Chapter 4 is titled “Techno-economic analysis of solid manure composting”, which is a modified from a paper preparing to be published on The Transactions of the ASABE. Chapter 5 is titled “Design and construction of mesophilic plug flow anaerobic digesters”. Chapter 6 gives conclusions that were gained from the previous five chapters. Throughout the thesis, references are included at the end of each chapter.

References

Bernal, M., Alburquerque, J., & Moral, R. (2009). Composting of animal manures and chemical criteria for compost maturity assessment. A review. *Bioresource Technology, 100,* 5444-5453.

California Air Resources Board. (2019). Determining Carbon Intensity of Dairy and Swine Manure. *Low farbon Fuel Standard (LCFS) guidance 19-06.*

Chadwick, D., Sommer, S., Thorman, R., Fangueiro, D., Cardenas, L., Amon, B., & Misselbrook, T. (2011). Manure manaegement: Implication for greenhouse gas emissions. *Animal Feed Science and Technology, 167,* 514 - 531.

Flotats, X., Bonmati, A., Palatsi, J., & Foged, H. (2013). Trends of manure processing in Europe. *WASTES: Solutions, Treatments and Opportunities.* Braga, Portugal.

Foged, Kyngso, H., Flotats, X., Blasi, A., palatsi, J., Magri, A., & Schelde, K. (2011). *Inventory of manure processing activities in Europe. Technical Report No. 1 concerning "Manure Processing Activities in Europe" to the European Commission.* Directorate-General Environment.

Main, D. (2015, 12 8). *Two Numbers: Animal Manure a Growing Headache in America*. Retrieved from Newsweek.

Maleki, E., Bokhary, A., & Liao, B. (2018). A review of anaerobic digestion bio-kinetics. *REviews in Environmental Science and Bio/Technology, 17*, 691-705.

Mata-Alvarex, J., Dosta, J., Romero-Guiza, M., Fonoll, X., Peces, M., & Astals, S. (2014). A critical review on anaerobic co-digestion achievements between 2010 and 2013. *Renewable and Sustainable aEnergy Reviews, 36*, 412-427.

Mathias, J. (2014). Manure as a resource: livestock waste management from anaerobic digestion, opportunities and challenges for Brazil. *International Food and Agribusiness Management Review, 17*(4).

National Pollutant Discharge Elimination System Permit Regulation and Effluent Limitation Guidelines and Standards for Concentrated Animal Feeding Operations (CAFO's). (2004). *Federal Register, 68*(29).

Schroder, J. (2005). Revisiting the agronomic benefits of manure: a correct assessment and exploitation of its fertilizer value spares the environment. *Bioresource Technology, 96*(2), 253-261.

Sefeedpari, P., Vellinga, T., Rafiee, S., Sharifi, M., Shine, P., Hassan, S., & Komleh, P. (2019). Technical, environmental and cost-benefit assessment of manure management chain: A case study of large scale dairy farming. *Journal of Cleaner Production, 233*, 857-868.

United States Department of Agriculture. (2020). Retrieved from Natural Resources Conservation Service: https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/plantsanimals/livestock/afo/

Vries, J., Groenestein, C., & De Boer, I. (2012). Environmental consequences of processing manure to produce mineral fertilizer and bio-energy. *Journal of Environmental Management, 102*, 173-183.

CHAPTER 2. LITERATURE REVIEW OF COMPOSTING

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Modified from a manuscript to be submitted to *Transactions of the ASABE*

Introduction

Composting has long been a method of solid waste disposal throughout the world with the goal of improving soil structure and quality by recycling organic matter (Bertoldi, Vallini, & Pera, 1983). This method has evolved over the years as an environmentally sound waste treatment technology that utilizes readily available microbes to destroy pathogens, stabilize nitrogen (N) content, reduce volume, and improve the quality of the waste (Imbeah, 1998). Wastes that are being composted are municipal solid waste, yard and garden waste, food waste, animal manure and mortalities, and almost any organic matter with moisture content between 50% to 70% wet basis (Richard, Hamelers, Veeken, & Silva, 2002). With such a wide application of composting, literature has conventionally segregated the composting process based on the waste being composted and independently investigate the process parameters for each type of waste. However, the objective of this literature review will be to explore broadly the mechanism of the composting process and types of composting methods or technologies available regardless of the waste being composted.

Composting Process

The composting process is a controlled aerobic decomposition of organic matter by microorganisms to produce a humus-like final product that offers many benefits to soil and crop health. However, for compost to be truly beneficial, it is ideal for it to reach stability and maturity before being applied onto soils. Compost stability is associated with microbial activity and its resistance to further decomposition, while compost maturity is associated with its quality of not having an adverse effect on soil and crop health when applied (Wichuk & McCartney, 2010). The input of the composting process includes carbon (C) and nitrogen (N) sources from organic matter, microorganisms, oxygen, and moisture. As shown in Figure 1, a mature compost is not only the final product of this process but also water vapor, heat, SO_4^{2-}, NH_3 and greenhouse gases, which are all a result of organic carbon mineralization from the microorganisms' metabolism (Assandri, Pampuro, Zara, Cavallo, & Budroni, 2021)

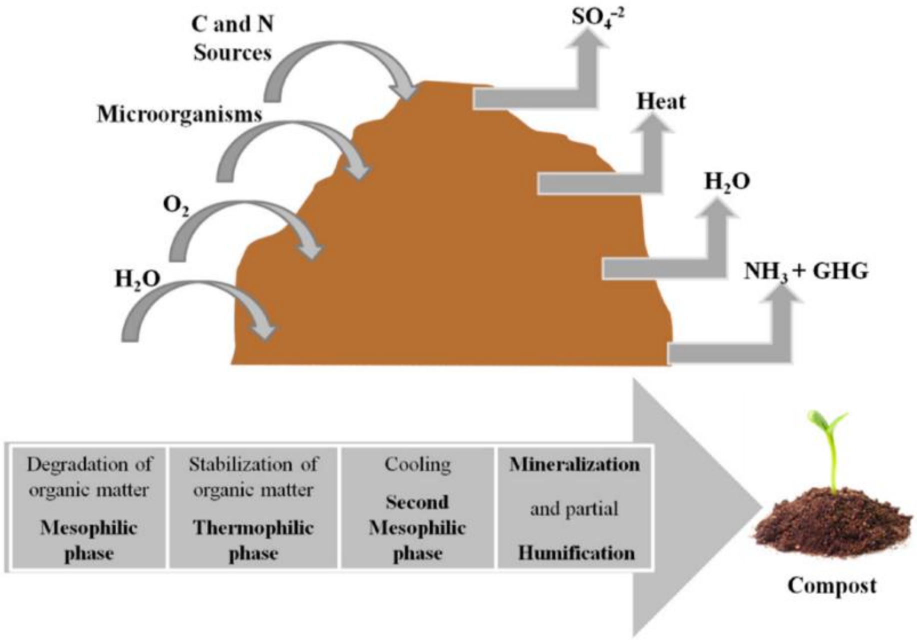

Figure 1. Schematic of the composting process (Assandri, Pampuro, Zara, Cavallo, & Budroni, 2021)

Factors Affecting the Composting Process

Composting occurs spontaneously and naturally, but with the goal to yield high-quality compost efficiently, controlled composting is required. Composting process parameters are divided into two categories. The first category is factors affecting the composting mix, including nutrient balance, pH, particle size, porosity, and moisture, while the second category is factors involving process management, including oxygen content, temperature, and water content (Bernal, Alburquerque, & Moral, 2009).

Nutritional balance within a composting mix is commonly expressed as a C/N ratio. Carbon is used as an energy, while nitrogen is consumed for maintaining metabolic activity and development. The optimal C/N ratio is anywhere between 25 to 35 (Bernal, Alburquerque, & Moral, 2009). A high C/N ratio results in a slow composting process, with excess degradable C being present for microbes, while a low C/N ratio will increase risk or N lost through ammonia volatilization or leaching.

The optimum pH for composting is around 7 to 8 (Nakasaki, Yaguchi, Sasaki, & Kubota, 1993). pH is not of major concern for composting since compost materials typically fall within the pH range, so Bernal et al. (2009) recommends a pH range of 5.5 to 8.0. However, pH plays a major role in controlling ammonia volatilization when pH goes above 7.5. Porosity plays an important factor in ensuring an adequate amount of air penetrates the compost pile. Too high of a porosity will prevent compost pile temperature from increasing, but when porosity goes below 50%, composting will start turning anaerobic and odor concerns will start to surface (Bernal, Alburquerque, & Moral, 2009). While aeration is crucial in ensuring efficient composting, turning, and tumbling of compost pile may facilitate N losses through volatilization. A delicate balance should be established so the desired nutrient retention and mass reduction are optimized based on the desired outcome of compost. Moisture content of feedstock should be around 70%, but high moisture content (> 65%) will reduce oxygen accessibility of microbes (Kim, Lee, Won, & Ahn, 2016).

Optimal temperature of compost varies depending on which stage the composting process is at and the microbial community most active at specific stages. Composting first starts at a mesophilic phase where fungi, bacteria, and actinomycetes break down readily degradable compounds like glucose and proteins to facilitate the next phase. Once temperatures go beyond 40 °C, thermophilic microbial communities take over. Temperatures as high as 70 °C are not unusual in this composting phase which are the result of healthy and active microbial communities (Bertoldi, Vallini, & Pera, 1983). This hike in temperature is essential for killing pathogenic microorganisms, fungi, and weed seeds that may be present in compost. After the consumption of substrate, the second mesophilic phase or cooling phase commence, which involves degradation of starch and cellulose (Bernal, Alburquerque, & Moral, 2009). It is during this phase that humification of lignocellulose compounds begin which is the key indicator of compost quality and maturity (Assandri, Pampuro, Zara, Cavallo, & Budroni, 2021).

Composting Process Kinetics and Modeling

Two prominent models used for the degradation rate of composting process are the first-order hydrolysis expressions and the Monod-type equations (Walling, Tremier, & Vaneeckhaute, 2020). Even though composting is rarely expressed hydrolysis as its sole degradation process, the rate-limiting step has been expressed as follows:

$$R_{degradation\ ,\ first\ order} = -\frac{d[S_i]}{dt} = k_i * [S_i] \qquad (1)$$

where k_i is the rate constant (s^{-1}) and $[S_i]$ is the concentration of substrate (Kg m^{-3}).

The Monod equation is expressed as follows:

$$R_{degradation\ ,\ Monod} = -\frac{d[S_i]}{dt} = \frac{\mu_i X_i}{Y_{S_i}} = \frac{\mu_{max,i}[S_i]}{K_{S_i}+[S_i]}\ \frac{X_i}{Y_{S_i}} \qquad (2)$$

where μ_i and $\mu_{max,i}$ are the specific and maximum growth rate of microorganisms (s^{-1}), respectively, K_{S_i} is the half-velocity constant (Kg m^{-3}) and Y_{S_i} is the coefficient (Kg Kg^{-1}).

Types of Composting

Composting is a proven environmentally friendly means of waste treatment with numerous benefits compared to landfilling (Bertoldi, Vallini, & Pera, 1983). The types of composting method are largely based on the amount and end goal of composting, which may vary greatly depending on its social, economic, and environmental impact. There are multiple styles of composting which include but are not limited to: onsite composting, aerated static pile, aerated windrow composting, in-vessel composting, vermicomposting, and black soldier larvae fly composting (United States Environmental Protection Agency, n.d.).

Open Pile Composting

Entities or organizations that plan to compost small amounts of waste, typically food and yard waste, utilize onsite composting methods to reduce the amount of waste generated by municipalities. Wastes, which can be categorized as green matter (food scraps which contain higher proportions of N) and brown matter (yard trimmings contains higher proportions of C), are piled in backyards or bins to produce compost which has multiple benefits for plant health (Direct Compost Solutions, 2018). Small piles take advantage of natural air movement, as shown in Figure 2. This style of composting requires the least amount of management and effort and yields environmental benefits from home waste reduction. However, the temperature within the small compost pile does not reach high temperatures and can be easily affected by climate and season changes (United States Environmental Protection Agency, n.d.).

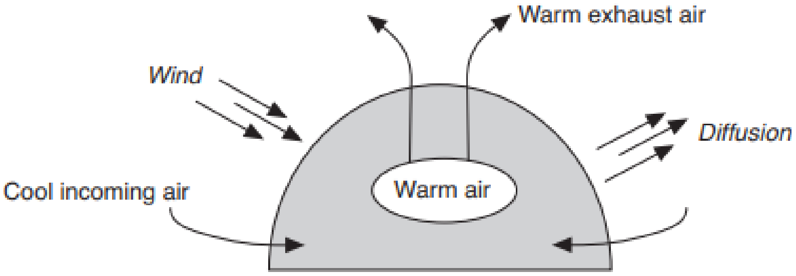

Figure 2. Natural air movement in a composting pile (NRAES, 1992)

Windrow Composting

Turned windrows and piles are the most common form of on-farm composting method, as it can accommodate a larger compost pile. Windrows can range from 2 to 6 m in width at the base and 1 to 3 m in height, of any length. Smaller to mid-sized windrows are turned using a pull behind turner along with a tractor while large windrows are turned using self-propelled turners which can process up to 4000 tons per hour (NRAES, 1992). Tiquia, et al. (2002) showed that windrow turning has a significant impact of increasing the composting rate with temperatures dropping out of the thermophilic range within 21 days compared to unturned windrows, which the thermophilic phase lasted for 42 days. They also discovered a significantly higher mass and C loss for turned piles and showed that no significant N losses occurred despite the concerns of excessive N volatilization from turning. In addition to allowing better air exchange between organic matter, turned windrows also allow for the exchange of materials between the surface and the interior, which promotes a more uniform composting process.

Aerated Static Pile

Aerated static pile (ASP) is means of composting by forcing air through the compost pile either by pulling (negative pressure) or forcing (positive pressure) air through the compost pile, as shown in Figure 3. Bulking agents, like woodchips, are usually added to enhancing airflow while also adding porosity to the pile (Lim, et al., 2017). ASP is claimed to enhance the composting process compared to windrow turning by reducing the time required for compost to reach maturity by 50% (Leton & Stentiford, 1990). Aeration rates are conceived as a means of meeting the oxygen demand required by aerobic microorganisms to thrive. The higher the rate of aeration, the higher the oxygen content and vice versa. Problems with odor and inefficient composting will arise when oxygen levels fall below 5%, while levels above 15% are an indication of high airflow rates, which might cool the pile (Leton & Stentiford, 1990). Aeration rates recommended for agricultural wastes fall within 0.5 – 0.9 L min^{-1} $\text{Kg}_{\text{om}}^{-1}$ while municipal solid wastes fall within 0.4 – 0.5 L min^{-1} $\text{Kg}_{\text{om}}^{-1}$ (Rasapoor, Nasrabadi, Kamali, & Hoveidi, 2009). To prevent heat losses, a layer of finished compost bulking agent, or a top covering, can be added over the pile not only to maintain temperature, but also reduce odor and N volatilization.

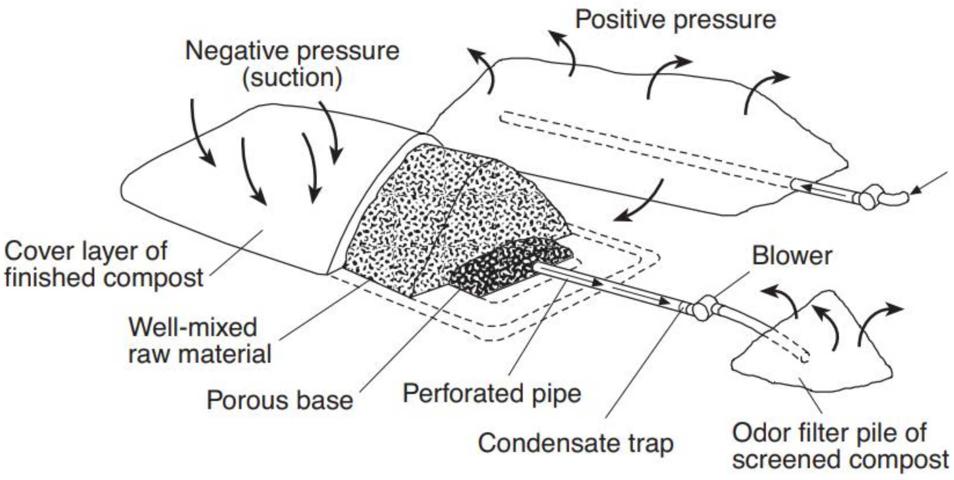

Figure 3. Aerated static pile layout (NRAES, 1992)

In-Vessel Composting

In-vessel composting is a highly versatile system in a building, container, vessel, or any confined space, can accelerate the composting process while greatly reducing the composting time required (Pandey, et al., 2016). This system can typically handle less organic matter than windrows and ASP and requires a much higher capital cost and power consumption. However, the short composting period, low land usage requirement, production of high-quality compost, and versatility of process control indicates that in-vessel composting is more viable in highly populated municipalities (Lim, et al., 2017). A more advanced composting system in Korea, as shown in Figure 4, almost ensures an efficient composting process that produces high-quality compost which meets all operational indices (Kim, Park, In, Kim, & Namkoong, 2008).

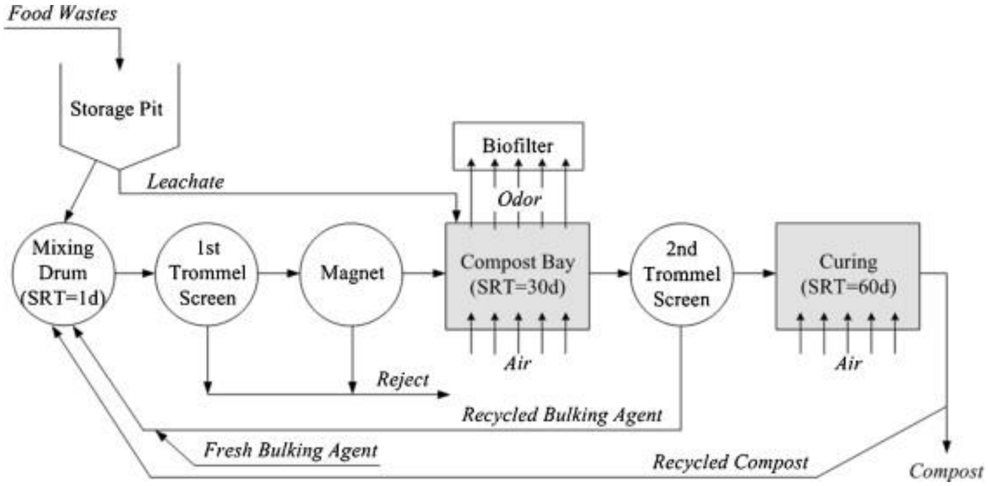

Figure 4. Schematic of a pilot-scale in-vessel composting plant (Kim, Park, In, Kim, & Namkoong, 2008)

Other Composting Methods

Vermicomposting is a simple technology utilizing a certain earthworm species to enhance the waste conversion process and produce a better product. It differs in composting in several ways as it takes place within the mesophilic range, which is optimal for earthworms (Adhikary, 2012). Although the mechanism behind this process is not fully understood, vermicomposting is faster than composting, as materials pass through the earthworms’ guts, producing castings (earthworm manure), which are rich in microbial activity fortified with pest repellence attributes. The nitrogen, phosphorus, and potassium in vermicompost treatments were higher than its control, while increases in pH and decline in total organic carbon content are observed as a function of the composting period (Garg, Gupta, & Satya, 2006). Not all organic matter can be processed by earthworms; higher precautions must be taken for kitchen waste as only plant-based materials are suitable for vermicomposting (Adhikary, 2012).

Black soldier fly (*Hermetia illucens*) composting is like vermicomposting; it utilizes the larvae's high metabolism to breakdown organic matter in the mesophilic temperature range. This method is utilized not primarily to produce quality compost; rather, it is used to produce high-quality alternative pig and fish feed which contains around 40% protein and 30% fat (Lalander, Fidjeland, Diener, Eriksson, & Vinneras, 2015). This has the potential to play a key component in closing the nutrient cycle while also achieving comparable mass reduction to other composting methods.

References

Adhikary, S. (2012). Vermicompost, the story of organic gold: A review. *Agricultural Sciences, 3*(7), 905-917.

Assandri, D., Pampuro, N., Zara, G., Cavallo, E., & Budroni, M. (2021). Suitability of Composting Process for the Disposal and Valorization of Brewer's Spent Grain. *Agriculture, 11*(1), 2.

Bernal, M., Alburquerque, J., & Moral, R. (2009). Composting of animal manures and chemical criteria for compost maturity assessment. A review. *Bioresource Technology, 100*(22), 5444-5453.

Bertoldi, M., Vallini, G., & Pera, A. (1983). The biology of composting: A review. *Waste Management & Research, 1*, 157-176.

Direct Compost Solutions. (2018, May). *8 Methods of Composting*. Retrieved September 14, 2021, from Direct Compost Solutions: https://directcompostsolutions.com/8-methods-composting/

Garg, P., Gupta, A., & Satya, S. (20006). Vermicomposting of different types of waste using Eisenia foetida: A comparative study. *Bioresource Technology, 97*(3), 391-395.

Imbeah, M. (1998). Composting piggery waste: A review. *Bioresource Technology, 63*, 197-203.

Kim, E., Lee, D.-H., Won, S., & Ahn, H. (2016). Evaluation of Optimum Moisture Content for Composting of Beef Manure and Bedding Material Mixtures Using Oxygen Uptake Measurement. *Asian-Australasion Journal of Animal Sciences, 29*(5), 753-758.

Kim, J., Park, J., In, B., Kim, D., & Namkoong, W. (2008). Evaluation of pilot-scale in-vessel composting for food waste treatment. *Journal of Hazardous Materials*, *154*(1-3), 272-277.

Leton, T., & Stentiford, E. (1990). Control of aeration in static pile composting. *Waste Management & Research, 8*, 199-306.

Lim, L., Cong, C., Lee, C., Klemes, J., Sarmidi, M., & Lim, J. (2017). Review on the Current Composting Practices and the potential of improvement using two-stage composting. *Chemical Engineering Transactions, 61*, 1051-1056.

Nakasaki, K., Yaguchi, H., Sasaki, Y., & Kubota, H. (1993). Effects of pH control on composting of garbage. *Waste Management & Research, 11*, 117-125.

NRAES. (1992). *On-farm composting.* Natural Resource, Agriculture, and Engineering Service (NRAES).

Pandey, P., Vaddella, V., Cao, W., Biswas, S., Chiu, C., & Hunter, S. (2016). In-vessel composting system for converting food and green wastes into pathogen free soil amendment for sustainable agriculture. *Journal of Cleaner Production*, *139*, 407-415.

Rasapoor, M., Nasrabadi, T., Kamali, M., & Hoveidi, H. (2009). The effects of aeration rate on generated compost quality, using aerated static pile method. *Waste Management, 29*(2), 570-573.

Richard, T., Hamelers, B., Veeken, A., & Silva, T. (2002). Moisture relationships in composting process. *Compost Science & Utilization*, *10*(4), 286-302.

Tiquia, S., Richard, T., & Honeyman, M. (2002). Carbon, nutrient, and mass loss during composting. *Nutrient Cycling in Agroecosystems, 62*, 15-24.

United States Environmental Protection Agency. (n.d.). *Types of composting and inderstanding the process*. Retrieved September 13, 2021, from Sustainable management of food: https://www.epa.gov/sustainable-management-food/types-composting-and-understanding-process

Walling, E., Tremier, A., & Vaneeckhaute, C. (2020). A review of mathematical models for composting. *Waste Management, 113*, 379-394.

Wichuk, K., & McCartney, D. (2010). Compost stability and maturity evaluation — a literature review. *Canadian Journal of Civil Engineering, 37*(11), 1505-1523.

CHAPTER 3. OPTIMIZATION STRATEGIES OF MANURE ANAEROBIC DIGESTION

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Introduction

Centralized livestock farms have multiple advantages in productivity and quality control; however, it results in large amounts of manure being constantly produced, which may pose a potential hazard to the environment (Li, et al., 2021). Alternative technologies like biodigesters, which produce methane, and quality fertilizers are adequate forms of animal waste treatment (Mathias, 2014). Many other countries, such as China, India, and Germany, demonstrate successes in using anaerobic digestion (AD) as a means to avoid negative environmental consequences such as greenhouse and toxic gas emissions from manure. AD has recently gained more attention in the United States due to the government incentives and programs for the production of renewable natural gas (RNG) from such systems. Research on manure AD has been done since the 1980s, with much of the work focused on optimizing biogas production with relatively less emphasis on effluent quality until recent years. A wide array of manure AD technologies has been proposed over the years, which contributed to a substantial pool of data on multiple treatments on manure AD. This review aims to consolidate current research related to optimizing anaerobic digestion while recommending future work needed to fill current knowledge gaps on this topic.

Fundamentals of Anaerobic Digestion

AD is a stepwise sequence of processes by mutually dependent groups of bacteria and archaea to break down organic matter in an anoxic environment. A stable and efficient process can be achieved if correct conditions and system balance are met. Organic feedstocks like manure, food waste, and municipal wastewater are converted into biogas for energy production and digestate for crop nutrients (Bhatt & Tao, 2020). There are several steps that take place in the degradation of organic matter into methane, namely: hydrolysis, acidogenesis, acetogenesis, and methanogenesis, as shown in Figure 1.

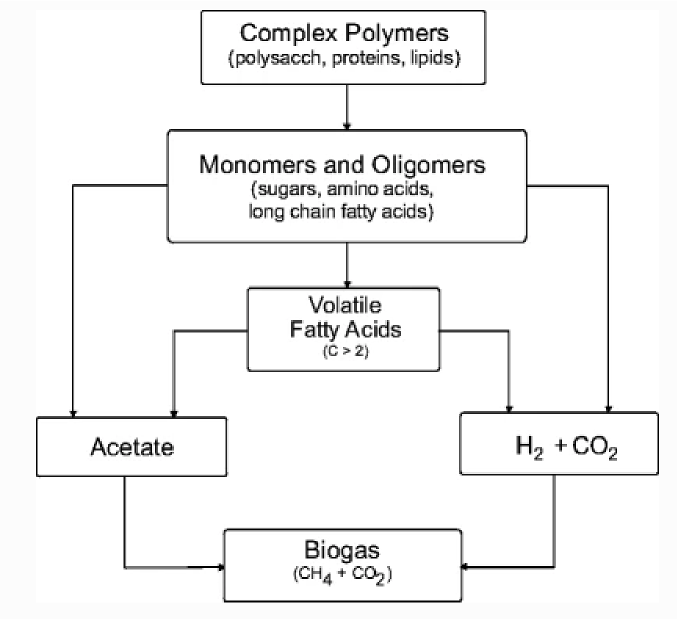

Figure 1: Stages of methane production from anaerobic digestion (Weiland, 2009)

Hydrolysis. Microorganisms need accessible nutrients for metabolism. Hydrolysis aims to break down large insoluble organic matter such as lipids, polysaccharides, proteins, fats, and nucleic acids, etc., into soluble organic compounds or monomers which are more accessible for use as energy and cell growth. Enzymes are secreted by microorganisms for this breaking down process. Microorganisms involved in this process are anaerobes such as Bacteroides, clostridia, and facultative bacteria such as streptococci (Adekunle, 2015). This step is crucial because nutrients such as nitrogen, carbon, and sulfur locked in large organic molecules are inaccessible to the microbes involved in AD.

Acidogenesis. Once large organic matters are broken down by hydrolysis, this process further breaks down the remaining components into various smaller compounds such as volatile fatty acids (VFA), alcohols, carbon dioxide, and hydrogen sulfide, etc.

Acetogenesis. In this step, products that are not converted into methane by methanogenic bacteria like VFAs and alcohols are converted into acetate, carbon dioxide and hydrogen. It is a process in which carbon dioxide or organic acids are being reduced to form acetate.

Methanogenesis. This step dictates the main production phase of carbon dioxide and methane from products formed in the previous steps. The production of biogas is typically composed of about 60% methane and 40% carbon dioxide. This step is the rate-limiting step of the whole AD process as it has the slowest biochemical reaction among all the phases (Adekunle, 2015).

The AD process can generally be modeled using the Gompertz equation:

$$P = P \cdot \exp\left\{ -\exp\left[\frac{\mathrm{Rm}}{P_0}(\lambda - t)e + 1\right]\right\}$$

where P is the cumulative methane production (mL/g VS) at time t (d), P_0 is the methane yield potential (the maximum methane yield; mL/g VS), Rm is the maximum methane production rate (mL/g (VS·d)), λ is the lag time (d), and e is a mathematical constant (Euler’s number) that represents the base of the natural logarithm (Meng, et al, 2020).

Anaerobic Digestion in the Midwest

Farm digesters gained interest in the 1980s with respect to its potential to mitigate climate change increase air and water quality while increasing land use efficiency. Low relative United States average energy prices do not justify the high capital cost for farm digesters (Lazarus, 2008). The fact that animal production facilities are spread out compared to European counterparts means more resources are needed to haul AD feedstocks, manure, in this case, to the digesters. Being in the mid-upper northern hemisphere means temperature swings pose more risks to digester operations and affect profitability from biogas production without any heating system in place (Ulenhuth, 2020). With all these challenges, more effort and financial incentives are required to make farm-scale digesters more profitable.

An AD economic model by Faulhaber (2012) indicated a carbon credit price of \$20 Mg^{-1}, more than a 1000 head of dairy cows are required for a farm-scale plug-flow digester to break even. However, due to the recent enactment of the California Low Carbon Fuel Standard (LCFS), the carbon credit price increased ten times more than when the study was conducted to a high of around \$200 Mg^{-1}. Combined heat and power (CHP) systems pose positive economic incentives when integrated with farm digesters, with the payback period being 3.4 years (Akbukut, 2012) and a general internal rate of return of 3.51% to 5.57% (Aui, Li, & Wright, 2019). These research and government incentives have incentivized farmers to employ this technology and capitalize both on carbon credit markets and energy savings. However, technical challenges of AD associated with local climate, manure feedstock availability and quality also dictate the employment feasibility and efficiency of anaerobic digesters (Aui, Li, & Wright, 2019). Optimization strategies for anaerobic digestion are critical in ensuring efficient methane production and the production of quality digestate.

Pretreatment of Manure

Pretreatment of manure is based on the principle of increasing its rate of hydrolysis in the anaerobic digestion process to enhance the breakdown of lignocellulosic materials present within manure. Pretreatment methods must meet the criteria of decrease in substrate particle size, increasing its degradability and solubility, elimination of inhibitory compounds, and lowering the energy input for cost efficiency (Atelge, et al., 2020). Manure is typically composed of 20% of cellulose, 220% hemicellulose, and 7% lignin depending on types of animals and feed composition fed to animals (Orlando & Borja, 2020). There are various pretreatment methods of anaerobic digestion substrate presented in literature, namely physical treatments, chemical treatments, biological treatments, and a combination of either treatment, as shown in Figure 2 (Atelge, et al., 2020).

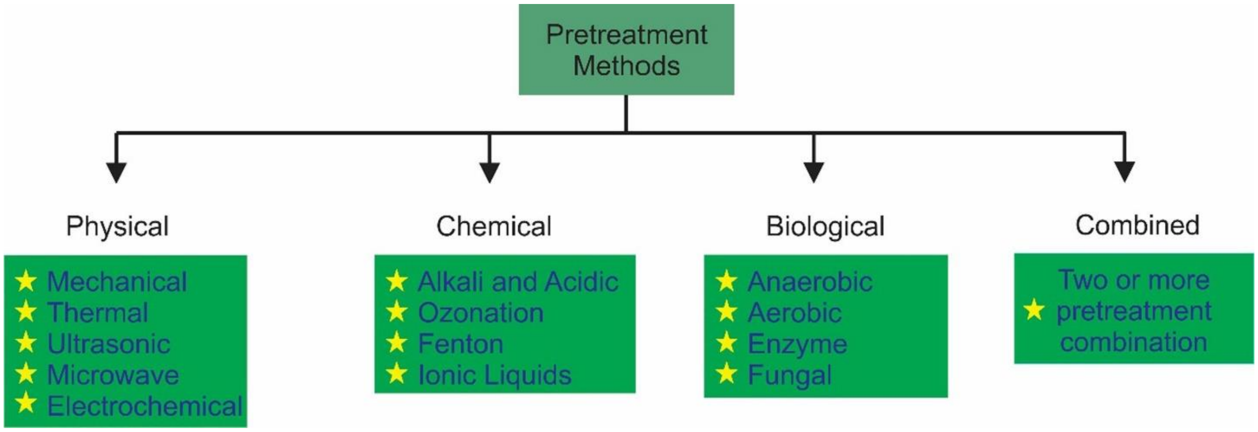

Figure 2: Overview of pretreatment methods of anaerobic digestion (Atelge, et al., 2020)

Steam explosion is one of the means of physio-chemical pretreatment of manure for anaerobic digestion presented in literature. This technology relies on pressurized and depressurized steam presented in a reactor to break intermolecular bonds within biomass (Orlando & Borja, 2020). A study conducted by Ferreira, et al. (2014) showed steam explosion conducted at 170 °C for 30 minutes doubled methane yield from 150 to 329 mL CH4/g-VS on pig manure. Plasma-assisted pretreatment also presents opportunities in improving anaerobic digestion based on similar principles of breaking intermolecular bonds of lignocellulosic biomass (Heiske, Schultz, Leipold, & Ejbye, 2013). In terms of chemical pretreatment methods, alkaline pretreatment of manure is the most prominent method presented in literature for improving anaerobic digestion. Khan and Ahring (2021) have shown that alkali pretreatment methods have improved manure fibers degradation by 43.6% with 3% w/w NaOH addition while improving methane yield by 180% compared to its control.

Despite the advancement of pretreatment technologies present for manure anaerobic digestion, every technology presented also adds more costs for the operations of such digesters. Energy efficiency is the essential factor impacting economic feasibility of pretreatment methods (Atelge, et al., 2020). More research on the scale-up of these pretreatment technologies has to be conducted for wider implementation of manure anaerobic digestion as farmers are not equipped with huge capital.

Hydraulic Retention Time

Hydraulic retention time (HRT) is the average amount of time liquid and soluble compounds stay in a reactor or tank. It is calculated using the following equation:

$$HRT = \frac{V}{Q}$$

where V is the volume of the reactor and Q is the influent flow rate. HRT is one of the most important parameters affecting reactor efficiency, which is relatively easy to manipulate (Dareioti & Karnaros, 2014). Short HRT or high organic loading rate is typically desired in digesters to minimize reactor volume to ensure thorough mixing and prevent sedimentation, while long HRT is typically required for anaerobic digestion of lignocellulosic biomass due to its low digestibility and hardy nature of lignin (Shi, et al., 2017). Furthermore, HRT also affects the microbial community within a digester. The delicate balance between fast-growing hydrolytic bacteria and acetogens and the slow-growing methanogens is important to prevent washout of products or methanogens (Bi, et al., 2020).

Farmers typically set their HRT based on the decision whether to maximize specific methane yield, which is methane produced per mass of volatile solids added, by increasing HRT or to maximize methane production, which is methane produced per day, but sacrifice on volatile solids destruction with a short HRT. A dimension of complexity is added to this economic consideration when the capital cost of building an anaerobic digester follows a diseconomy of scale pattern where a larger digester will cost less per unit volume. Although HRT recommendations of manure AD typically fall within the 20 days to 40 days window, HRT still varies greatly depending on the feedstock being co-digested and operating conditions of specific digesters (Nasir, et al, 2012).

Biochar Addition

Biochar is a product of pyrolysis where biomass undergoes controlled burning in an oxygen-limited environment. Biochar is typically made of agricultural and forest residue and has been proven to work well as a soil amendment due to its high cation exchange capacity, large porosity, and surface area (Pan, et al., 2019). It has gained much interest in recent years due to its low-cost production compared to its counterparts, like zeolite and activated carbon.

Based on the characteristics of biochar, it was hypothesized the benefits of biochar observed as a soil amendment can also be utilized in anaerobic digestion to act as an inhibitor adsorbent, increase buffer capacity, and allow cell immobilization while also increasing the quality of digestate (Fagbohungbe, et al., 2016). Ammonia inhibition is one of the major factors of failure of AD systems. Mumme, et al, (2014) demonstrated that with a small-scale 100 mL syringe reactor that 2% biochar can mitigate mild ammonia inhibition at 1500 mg-N Kg^{-1}. This is largely attributed to biochar's high ion exchange capacity, which allows ammonia and ammonium ions to adsorb onto its large surface area. This is especially applicable for manure, where it not only contains a high amount of nitrogen, but also a high amount of heavy metals, which have the potential to inhibit AD. Biochar can also help overcome acid accumulation in AD, which is caused by the overproduction of VFAs while the methanogens could not keep up with converting them into methane. Wang et al (2019) demonstrated that VFA accumulation at the threshold of inhibition is delayed when biochar is added into a high organic loading rate reactor. Cell immobilization is highly favorable for microbial processes because it facilitates interspecies electron transfer, which creates a micro-ecosystem for microbes to work efficiently within a system. While substrate-induced inhibition happens to a certain extent in all anaerobic digestion, the ability of microorganisms to adapt in unfavorable conditions plays a significant role in alleviating the negative effects of inhibition (Fagbohungbe, et al., 2016). The study conducted by Xu, et al (2021) further showed the superiority of biochar at different HRT compared to activated carbon in reducing VFA accumulation, alleviating substrate inhibition, and shortening start-up time in a semi-continuous stirred tank reactor.

Conclusion and Future Recommendation

Pretreatment technologies have shown positive impacts on anaerobic digestion across the literature regardless of which technology is being investigated. Unless larger-scale pilot-testing and more extensive economic analysis are conducted for each treatment method, these technologies will face resistance from farmers or the industry due to the additional cost incurred for employing such technologies.

References

Adekunle, K., & Okolie, J. (2015). A REview of Biochemical Process of Anaerobic Digestion. *Advances in Bioscience and Biotechnology, 6*, 205-212.

Akbukut, A. (2012). Techno-economic analysis of eletricity and heat generation from farm-scale biogas plant: Cicekdagi case study. *Energy, 44*(1), 381-390.

Atelge, M., Atabani, A., Rajesh, J., Krisa, D., Kaya, M., Eskicioglu, C., . . . Duman, F. (2020). A critical review of pretreatment technologies to enhance anaerobic digestion and energy recovery. *Fuel, 270*, 117494.

Aui, A., Li, W., & Wright, M. (2019). Techno-economic and life cycle analysis of a farm-scale anaerobic digestion plant in Iowa. *Waste Management, 89*, 154-164.

Bhatt, A., & Tao, L. (2020). Economic Perspectives of Biogas Production via Anaerobic Digestion. *Bioengineering, 7*, 74.

Bi, S., Hong, X., Yang, H., Yu, X., Fang, S., Bai, Y., . . . Wang , Y. (2020). Effect of hydraulic retention time on anaerobic co-digestion of cattle manure and food waste . *Renewable energy, 150*, 213-220.

Dareioti, M., & Karnaros, M. (2014). Effect of hydraulic retention time (HRT) on the anaerobic co-digestion of agro-industrial wastes in a two-stage CSTR system. *Bioresource Technology, 167*, 407-415.

Fagbohungbe, M., Herbert, B., Hurst, L., Ibeto, C., Li, H., Usmani, S., & Semple, K. (2016). The challenges of anaerobic digestion and the role of biochar in optimizing anaerobic digestion. *Waste Management, 61*, 236-249.

Faulhaber, C., Raman, D., & Burns , R. (2012). An engineering-economic model for analyzing dairy plug-flow anaerobic digesters: cost structures and policy implications. *Transactions of the ASABE, 55*(1), 201-209.

Ferrerira, L., Souza, T., Polanco, F., & Perez, S. (2014). Thermal steam explosion pretreatment to enhance anaerobic biodegradability of the solid fraction of pig manure. *Bioresource Technology, 152*, 393-398.

Heiske, S., Schultz, N., Leipold, F., & Ejbye, J. (2013). Improving anaerobic digestion of wheat straw by plasma-assisted pretreatment. *Journal of Atomic and Molecular Physics*, 791353.

Khan, M., & Ahring, B. (2021). Anaerobic Digestion of Digested Manure Fibers: Influence of Thermal and Alkaline Thermal Pretreatment on the Biogas Yield. *BioEnergy Research, 14*, 891-900.

Lazarus, W. (2008). *Farm-based anaerobic digesters as an energy and odor control technology.* USDA. Agricultural Economic Report.

Li, Y., Zhao, J., Krooneman, J., & Euverink, G. (2021). Strategies to boost anaerobic digestion performance of cow manure: Laboratory achievements and their full-scale application potential. *Science of The Total Environment*, *755*(1), 142940.

Mathias, J. (2014). Manure as a resource: livestock waste management from anaerobic digestion, opportunities and challenges for Brazil. *International Food and Agribusiness Management Review, 17*(4).

Meng, L., Xie, L., Suenaga, T., Riya, S., Terada, A., & Hosomi , M. (2020). Eco-compatible biochar mitigates volatile fatty acids stress in high load thermophilic solid-state anaerobic reactors treating agricultural waste. *Bioresource Technology, 309*, 123366.

Mumme, J., Srocke, F., Heeg, K., & Werner, M. (2014). use of biochars in anaerobic digestion. *Bioresource Technology, 164*, 189-197.

Nasir, I., Chazi, T., & Omar, R. (2012). Anaerobic digestion technology in livestock mnure treatment for biogas production: A review. *Engineering in Life Sciences, 12*(3), 256-269.

Orlando, M.-Q., & Borja, V. (2020). Pretreatment of animal manure biomass tom improve biogass production: A review. *Energies*, *13*(14), 3573.

Pan, J., Ma, J., Zhai, L., Luo, T., Mei, Z., & Liu, H. (2019). Achievements of biochar application for enhanced anaerobic digestion: A review. *Bioresource Technology, 292*, 122058.

Shi, X.-S., Dong, J.-J., Yu, J.-H., Yin, H., Hu, S.-M., Shu-Xia, H., & Yuan, X.-Z. (2017). Effect of hydraulic retention time on anaerobic digestion of wheat straw in the semicontonuous stirred-tank reactors. *BioMed Research International, 2017*, 2457805.

Ulenhuth, K. (2020, August 25). *Iowa researchers see wasted potential in agricultural biofuels*. Retrieved from Energy News Network: https://energynews.us/2020/08/25/iowa-researchers-see-wasted-potential-in-agricultural-biofuels/

Wang, G., Li, Q., Gao, X., & Wang, X. (2019). Sawdust-Derived Biochar Much Mitigates VFAs Accumulation and Improves Microbial Activities To Enhance Methane Production in Thermophilic Anaerobic Digestion. *ACS Sustainable Chem. Eng., 7*(2), 2141-2150.

Weiland , P. (2009). Biogas production: current state and perspectives. *Applied Microbiology and Biotechnology, 85*, 849-860.

Xu, M., Uludag-Demirer, S., Fang, D., Zhou, L., Liu, Y., & Liao, W. (2021). Effects of Pyrogenic Carbonaceous Materials on Anaerobic Digestion of a Nitrogen-Rich Organic Waste - Swine Manure. *Energy & Fuels, 35*, 2282-2292.

CHAPTER 4. TECHNO-ECONOMIC ANALYSIS OF SOLID MANURE COMPOSTING

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Abstract

Manure produced from large, concentrated animal feeding operations is expensive to manage due to the amount of manure produced. While manure composting is a popular method for solid manure management, not many farmers are equipped with the information and tools to evaluate its economic feasibility. The objective of this study was to analyze the economic and process limitations of setting up a compost facility using a simple model, permitting insights into the fundamental constraints of this technology. A model was developed to determine the cost of compost production based on 1000 to 10000 beef and dairy operation sizes. The analysis showed the critical farm size which makes composting economically feasible is at 7300 heads for beef herds and 5250 heads for dairy herds when manure or compost is land applied on an N limiting rate. Sensitivity analysis indicated the biggest factor affecting the critical farm size is mass reduction during the composting process, with the sensitivity coefficient being 0.78. This showed the importance of good composting practices if composting manure might be an option.

Keywords. *Composting, Economics*

Introduction

Livestock production has markedly increased with exponential global population growth and demand for animal proteins from livestock. With this increase in demand for animal proteins, global meat production quadrupled since 1961 (Ritchie & Roser , 2017). In 2017, 52 billion pounds of meat and 48 billion pounds of poultry were produced in the United States alone (North American Meat Institute, 2017). Meat producers have responded to meet global demands with the emergence of concentrated animal feeding operations (CAFO) throughout the Midwest. The increase in CAFOs inevitably increases animal manure production per land area, which can be challenging and costly for farmers to manage. Manure is a valuable resource as it provides nutrients for crop production and improves soil health in many ways. Based on Iowa Farm Bureau, there are about 87,000 farms in Iowa, and most of the farms had conventionally applied animal manure to the fields adjacent to feedlots (Iowa Farm Bureau, 2019). All of these animal farms resulted in the production of more than 50 million tons of manure. If the amount of manure produced is not given the right treatment and management strategies, it can deteriorate the air and water quality in the surrounding areas. When it comes to manure management, farmers either compost solid manure or store and then haul manure for land application onto cropland.

Direct land application of manure onto cropland is the most popular choice of manure management by farmers as it poses several benefits. Even though this has raised some concerns for potential environmental impacts, there are application guidelines and procedures required in Iowa to ensure manure is properly managed. If managed properly, land application of manure increases soil health by increasing organic matter content and forming larger and more stable soil aggregates (Zingore, et al., 2007). In addition, manure application can also reduce erosion and water infiltration rate (Peng, et al., 2016). Compared to commercial fertilizers, animal manure consists of higher content of trace elements, and when applied to the fields, it increases crop yield.

With the great benefits associated with direct land application of manure, there are also multiple incentives for farmers to compost solid manure before land application. Composting is a biological break down of organic matter into mineralized products more common in an aerobic environment (Bernal, Alburquerque, & Moral, 2009). While mass reduction remains the most significant impact and benefit of composting, the stabilized, humus-rich, complex product has proven to improve the physical properties of soil (Larney, Sullivan, Buckley, & Eghball, 2006). With all of these benefits associated with composting, it is still not widely practiced because of the initial cost barrier, variation of compost maturity due to seasonal changes, the requirement for a bulking agent, and a designated area for storage and operation time associated with composting (Viaene, et al., 2016). Composting of animal manure should be seen as a technology that adds value and produces a high-quality product for multiple agricultural uses.

With so much to consider for the use of composting technologies, decision-makers and farmers are not fully equipped with the appropriate decision support tools to analyze the cost and effect of various manure handling methods. This study has three primary objectives: 1) create a robust regional economic framework by comparing composting and storage-hauling of solid manure, 2) justify the herd size of beef cattle and dairy cow which makes composting economically feasible, and 3) evaluate the cost associated with composting manures in the Midwest, United States.

Materials and Methods

This model was implemented in Microsoft Excel, with all computations done using Visual Basic for Applications (VBA) code. The model will compare two scenarios for both bedded-pack solid dairy and beef cattle manure treatment. The first scenario is when manure is stored and then land applied from CAFOs to the fields, and the second scenario is when manure is being windrow composted in a composting facility and then land applied to the fields. Two scenarios will be investigated independently on 1000 to 10000 head barns for both beef and dairy CAFOs. Composting facility costs will only be included in the composting scenario, and the price and calculations of land application costs are assumed to be the same for both cases.

The model will compute the treatment cost of manure for both fresh and compost manure ($ /animal). The critical farm size will be the number of animals a farm needs to make manure composting an economically feasible method of manure treatment. The endpoint of the model is the computation of a dimensionless term called the compost to base ratio (CBR), where the cost per head of compost manure treatment is divided by the cost per head of baseline manure treatment. If the CBR is above 1.0, then composting treatment is cheaper, making long-term composting facilities deployment likely. Conversely, if CBR is below 1.0, then composting treatment is more expensive, making the long-term deployment of a composting facility highly unlikely. Figure 1 summarizes the data flow in this model. The operation size and assumptions for costs associated with setting up and running a composting facility are used to calculate the cost of treatment. This model can further be broken into three sections: manure properties, composting facility, and land application.

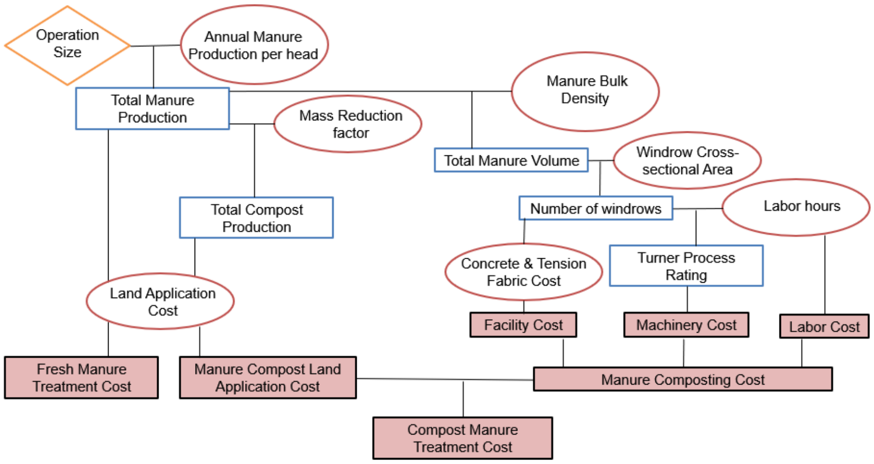

Figure 1 Model flowchart. Diamonds represent input variables, ovals represent assumed values, rectangles represent computed values, and shaded rectangles indicate primary outputs.

Manure Properties

Fresh manure properties and production is shown in Table 2, and these will be the parameters used for modelling. Mass reduction remains one of the most prominent benefits of manure composting. While the optimum C:N ratio required for composting is 30:1, there are wide ranges of parameters being manipulated in literature for composting manure, resulting in a large mass and nutrient loss distribution (Bernal, Alburquerque, & Moral, 2009). With reference to Table 1, the mass or carbon reduction from composting will be assumed to be 50%, while nitrogen and phosphorus losses will be assumed to be 50% and 30%, respectively.

Table 1. Composting mass reduction from literature

	Initial C:N ratio	Mass reduction	N reduction	P reduction
Swine manure composting with windrow turning (Tiquia, Richard, & Honeyman, 2000)	11:1	52%	50%	32%
Dairy Manure composting with sawdust and straw (Pecchia, Michel, Rigot, & Keener, 2004)	40:1	63%	24%	17%
Beef cattle feedlot manure composting (Larney, Buckley, Hao, & MaCaughey, 2006)	16:1	66%	46%	18%
Beef cattle feedlot manure composting (Eghball, Power, Gilley, & Doran, 1997)	13:1	50%	40%	7%
Beef cattle manure composting in the UK (Parkinson, Gibbs, Burchett, & Misselbrook, 2004)	25:1	-	37%	28%
Meta-analysis of C and N losses of pig manure composting (Zhang, et al., 2021)	-	49%	28%	-

Table 2. Iowa manure and nutrient production assumptions for modelling (Manure Management Plan Form Appendix A, 2021)

Animal Type	Fresh Solid Manure Production (tons per year per head)	N produced per head (lb)	P produced per head (lb)
Beef	11	132	66
Dairy	20	180	80

Composting Facility

The facility cost is estimated based on variable farm scales starting from 1000 heads to 10,000 heads of bedded pack beef and dairy production. Based on the total manure produced per year by each individual farm scale, as shown in Table 1, the cost of a hoop barn was estimated based on the capacity required to manage a three-month composting cycle. A hoop barn is a structure that mainly consists of hemispherical tension fabric over the top and cement on the ground for simplicity. Hence, the cost of setting up a hoop barn includes the cost of concrete as the base and tension fabric over the top, which is $1.50 per sqft and $6.50 per sqft, respectively. With the bulk density of bedded pack manure being 55.3 lb per cu-ft, the total volume of manure the hoop barn needs to handle can be calculated in cubic feet (Russelle, Blanchet, Randall, & Everett, 2009). The composting windrows’ cross-sectional area is assumed to range from 45 sqft to 208 sqft based on windrow turner specifications. With a hoop barn length of 120 ft and an effective windrow length of 110 ft, the number of windrows needed to cover a 3-month composting cycle is calculated for each of those farm scales. The hoop barn size is then calculated based on the land area required by both the windrows and floor space required between windrows, with the floor space requirement being 75 inches between rows for facilities.

Price and processing rate data of both pull-behind and self-propelled windrow turners were collected from various industrial windrow turner manufacturers. The cost of a new tractor based on the pull-behind windrow turner horsepower requirement was also included in the total price of a pull-behind turner. A linear regression of the price of turners and its processing rate (yd^3/hour) was computed to estimate capital equipment investment for a windrow turner, as shown in Figure 2. The price of composting equipment will be the following regression equation:

$$P = 75.664X + 61302 \qquad (1)$$

where X is the processing rate of a windrow turner (yd^3/hour).

The machine cost is annualized based on a 15% interest rate over a 10-year period, while composting facility cost is annualized on a 15% interest rate over a 25-year period. The labor cost is assumed to be $50 per hour, which will be calculated assuming that the windrows be turned once a week at 8 hours each time throughout the process.

Figure 2. Linear regression of windrow turner price as a function of volumetric processing rate.

Manure Land Application Cost

Manure application cost is calculated based on what is typically being charged for solid manure application in Iowa, which is at six dollars per ton-mile of manure with an increment of two dollars per ton for an additional mile radius spread. Assuming 60% of the land around the animal production facility is utilized for crop production, and approximately 50% of the land was to be planted with corn and the remaining 50% with soybean, based on a corn and soybean rotation, with manure application only occurring to the corn phase of the rotation. The manure application rate will be either 150 lb-N/acre for N limiting application or 60 lb-P/acre for P limiting application. We will also assume a 50% nutrient availability factor for N and 90% for P for solid beef and dairy manure for this analysis (Sawyer & Mallarino, 2016). Manure nutrients value, both composted and fresh manure, will be calculated to offset land application cost. Nitrogen within compost or manure will be valued at $0.29 per lb-N and phosphorus value will be $1.10 per lb-P (USDA, 2014).

Sensitivity Analysis

To understand how assumed values impacted the calculated CBR, a sensitivity analysis was completed on the breakeven farm size. Sensitivity coefficients are calculated based on the percent changes in output per percent change in inputs at the critical farm size (Hamby, 1994).

Results and Discussion

The results indicated the cost of compost-haul treatment method will be lower than the baseline storage-haul method when beef herd size is greater than 7300 heads when manure or compost is applied at an N-limited rate and 6350 heads when applied at a P-limited rate, as shown in Figure 3. The herd size requirement for dairy herds is significantly smaller than beef herds, with the cost of composting being lower at 5250 heads herd size when manure is applied at an N-limited rate and 4650 heads herd size when manure is applied a P-limited rate, as shown in Figure 4. These breakeven numbers are attributed to a CBR value of 1.0, as shown in Figure 5. The general trend showed the per head cost of the storage-haul treatment method increases, and the per head cost of the compost-haul treatment method decreases as the number of animals increases. The temporal upward trend observed at 5000 heads animal is due to the increase in windrow width from 10 ft to 16 ft as larger barns greater than 5000 heads produce much more manure to accommodate for a 10 ft windrow width due to windrow turner equipment height constraint.

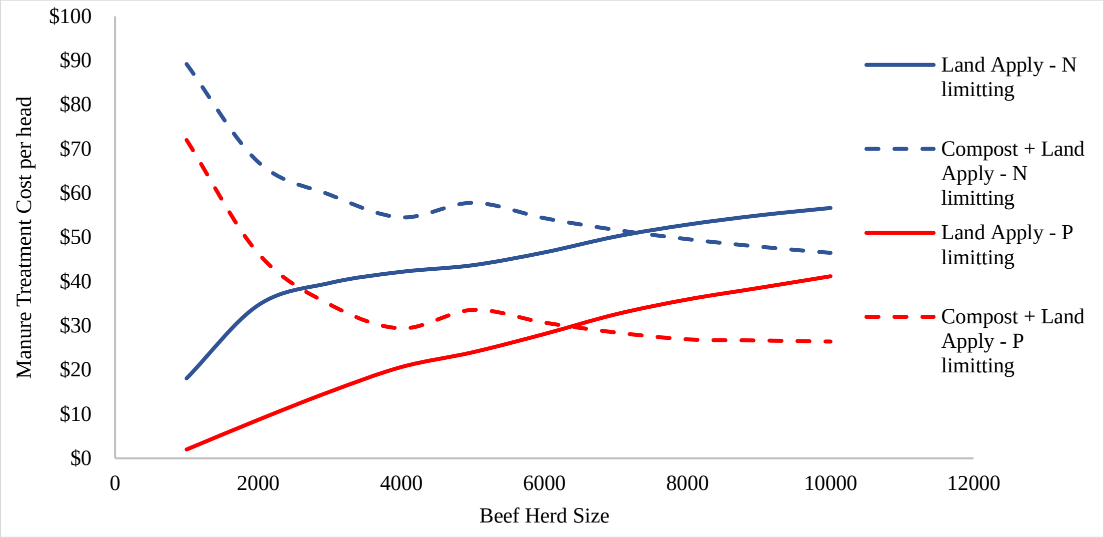

Figure 3. Beef herds economic comparison between base case land application only scenario and compost + land application scenario at two land application rates.

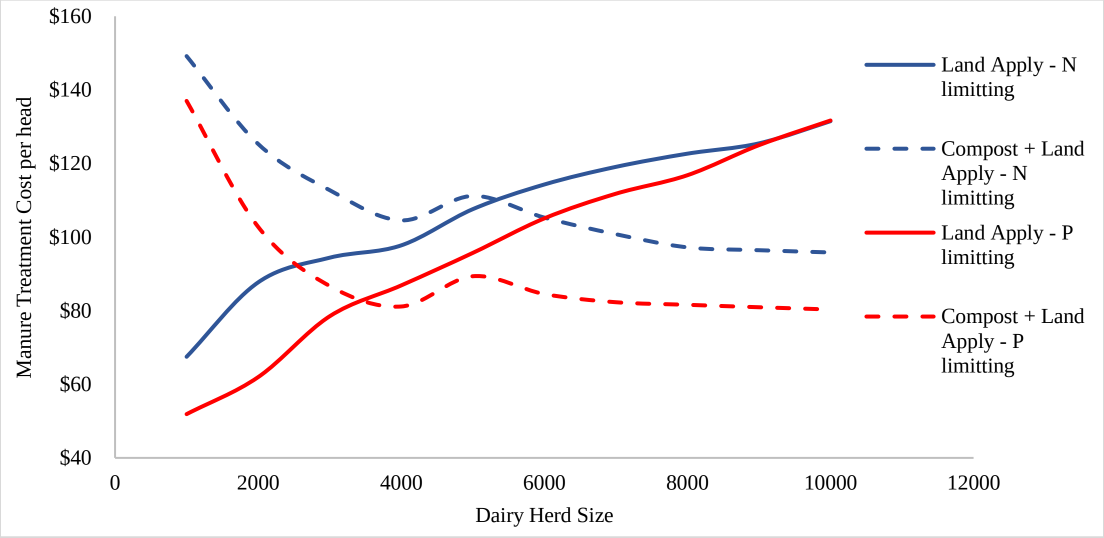

Figure 4. Dairy herds economic comparison between base case land application only scenario and compost + land application scenario at two land application rates.

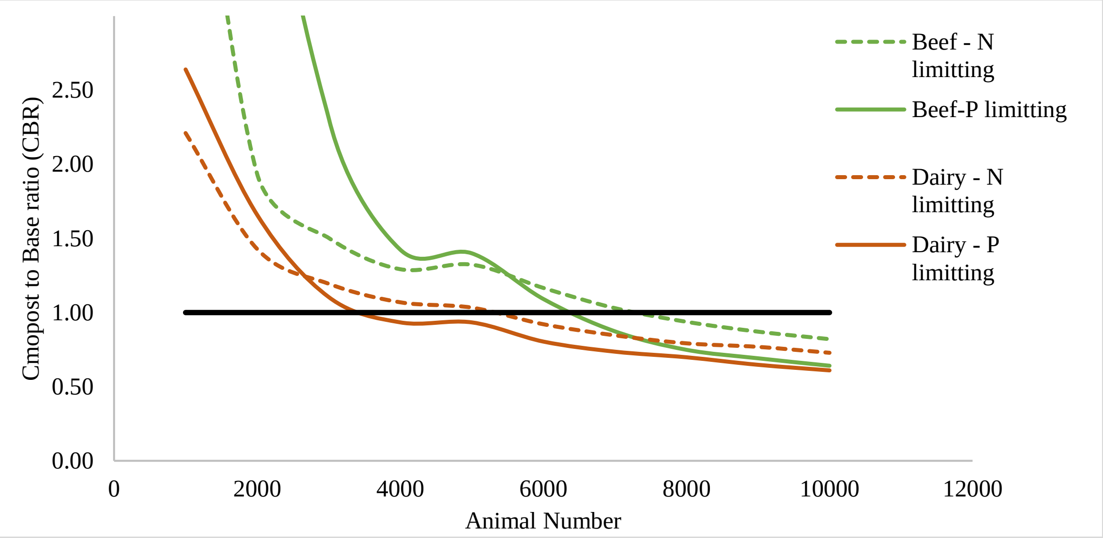

Figure 5. CBR as a function of the number of animals. The horizontal line represents the breakeven number of animals for composting to be economically feasible.

Cost Breakdown

Land application cost follows a diseconomy of scale, whether it is manure or compost applied onto cropland. Composted manure has the benefit of 50% volume reduction, which reduces the amount of manure needed to be managed, hence making savings on land application cost economically significant. Nutrient loss during the composting process may result in the loss of manure value, but the economic benefit of mass reduction outweighs the loss of nutrient value when farm size gets large enough. The facility, machine, and labor costs are collectively exclusive for the composting scenario only. These costs follow an economy of scale pattern where the benefits of capital investment and operating cost can be distributed to more animals as farm size gets larger, as shown in Figure 6. The cost of compost produced per ton based on all the operations is shown in Table 3. This cost of compost can be used as a guideline on the value of compost produced and how much a farmer can sell instead of land applying their own compost.

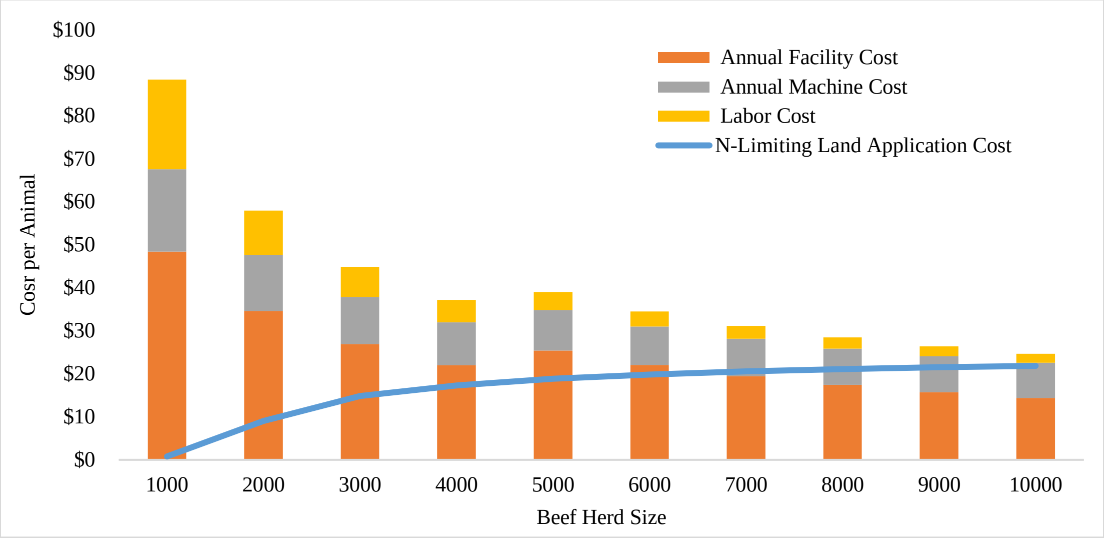

Figure 6. Cost distribution for beef herds composting scenario.

Table 3. Cost of compost production per ton

Number of Animals	Beef compost ($/Ton)	Dairy compost ($/Ton)
1000	16.07	13.31
2000	10.54	9.16
3000	8.15	7.22
4000	6.76	6.07
5000	7.09	6.53
6000	6.27	5.81
7000	5.66	5.26
8000	5.18	4.83
9000	4.80	4.49
10000	4.49	4.21

Sensitivity Analysis

The terms with the highest sensitivity coefficients are shown in Figure 7. Sensitivity coefficients indicate the fractional change in CBR resulting from a 1% (0.01) increase in the variable listed. For example, a 1% increase in the animal farm size from the base case causes a 71% drop in CBR. A positive sensitivity coefficient indicates a higher value of this variable will make composting more economically feasible, while a negative sensitivity coefficient indicates a higher value of this variable will make composting more economically non-feasible. The composting mass loss percentage has the greatest sensitivity coefficient, which illustrates the importance of accurately estimating this term. This shows the importance of good composting practices, as optimizing mass reduction of the compost pile will be the driving factor to make manure composting feasible. Another interesting variable is the composting N loss percentage, as it is almost half less significant in affecting CBR. Unsurprisingly, land application cost and operation size play a significant role in changing the outlook for manure composting.

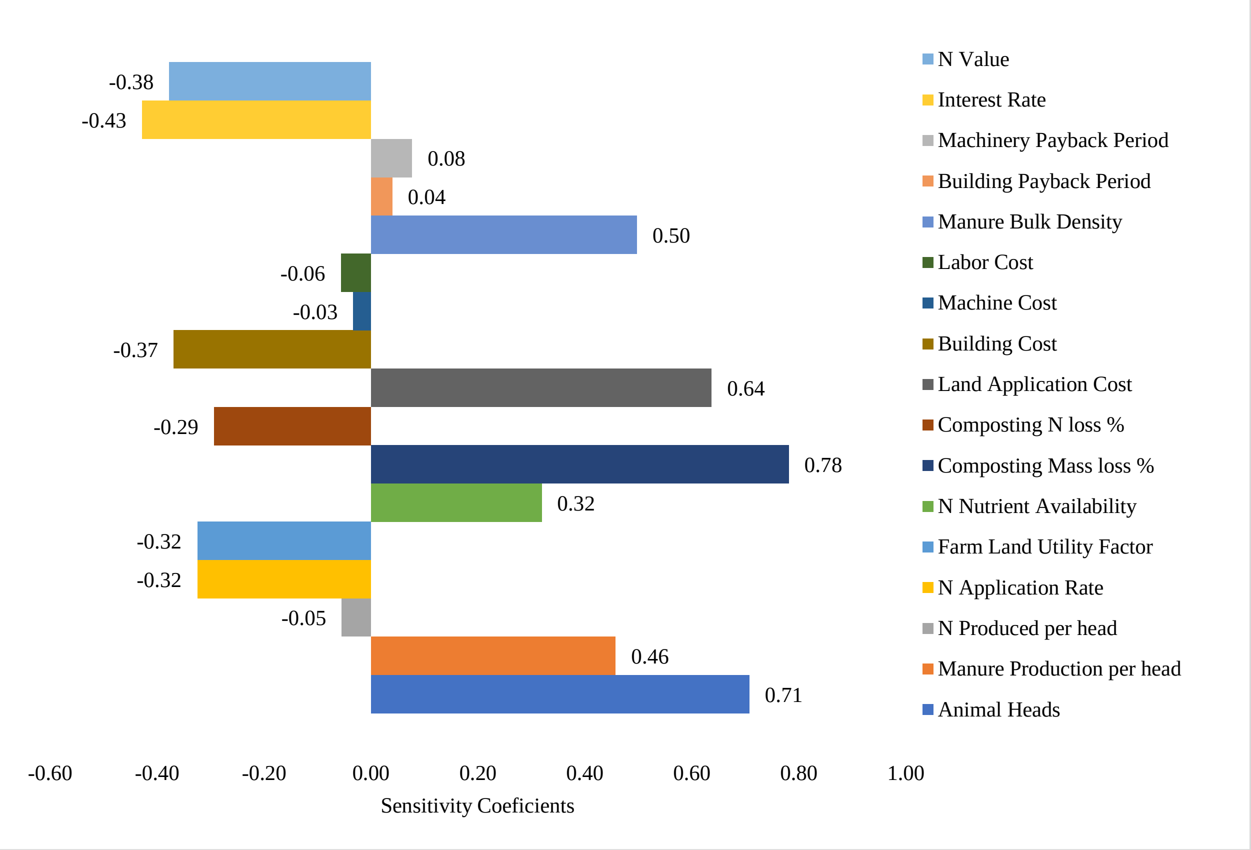

Figure 7. Sensitivity analysis results. Sensitivity coefficients represent the fractional change in CBR with a 1% increase in the variable listed.

Conclusion

Beef and dairy farm need to be relatively large (> 6000 animals) for composting to be economically competitive compared to direct land application. This economic model showed composting efficiency based on mass reduction is the most important factor in evaluating the efficacy of solid manure composting. Hence, more focus must be placed on the proper management of compost to ensure maximum carbon mass reduction.

References

Bernal, M. P., Alburquerque, J. A., & Moral, R. (2009). Composting of animal manures and chemical criteria for compost maturity assessment. A review. *Bioresource Technology*, 5444-5453.

Eghball, B., Power, J. F., Gilley, J. E., & Doran, J. W. (1997). Nutrient, Carbon, and Mass Loss during Composting of Beef Cattle Feedlot Manure. *Journal of Environmental Quality*, 189-193.

Hamby, D. (1994). A Review of Techniques for Parameter Sensitivity Analysis of Environmental Models. *Environmental Monitoring and Assessment*, 135-154.

Iowa Farm Bureau. (2019). Retrieved from https://www.iowafarmbureau.com/About

Larney, F. J., Buckley, K. E., Hao, X., & MaCaughey, W. (2006). Fresh, Stockpiled, and Composted Beef Cattle Feedlot Manure. *Journal of Environmental Quality*, 1844-1854.

Larney, F., Sullivan, D., Buckley, K., & Eghball, B. (2006). The role of composting in recycling manure nutrients. *Canadian Journal of Soil Science, 86*(4), 597-611.

Manure Management Plan Form Appendix A. (2021). Retrieved from Iowa Manure Management Action Group.

North American Meat Institute. (2017). Retrieved from North American Meat Institute: https://www.meatinstitute.org/index.php?ht=d/sp/i/47465/pid/47465

Parkinson, R., Gibbs, P., Burchett, S., & Misselbrook, T. (2004). Effect of turning regime and seasonal weather conditions on nitrogen and phosphorus losses during aerobic composting of cattle manure. *Bioresource Technology*, 171-178.

Pecchia, J. A., Michel, F. C., Rigot, J., & Keener, H. M. (2004). Mass and Nutrient Losses During the Composting of Dairy Manure Amended with Sawdust and Straw. *Compost Science and Utilization*, 323-334.

Peng, X., Zhu, Q., XIe, Z., Darboux, F., & Holden, N. (2016). The impact of manure, straw and biochar amendments on aggregation and erosion in a hillslope Ultisol. *CATENA, 138*, 30-37.

Ritchie , H., & Roser , M. (2017, August). *Meat and Dairy Production*. Retrieved from Our World in Data: https://ourworldindata.org/meat-production#citation

Russelle, M. P., Blanchet, K. M., Randall, G. W., & Everett, L. A. (2009). Characteristics and Nitrogen Value of Stratified Bedded Pack Dairy Manure. *Crop Management*.

Sawyer, J., & Mallarino, A. (2016). *Using Manure Nutrients for Crop Production.* Iowa State University Extension and Outreach.

Tiquia, S. M., Richard, T. L., & Honeyman, M. S. (2000). Effect of Windrow Turning and Seasonal Temperatures on Composting of Hog Manure from Hoop Structures. *Environmental Technology*, 1037-1046.

USDA. (2014). *Fertilizer use and price*. Retrieved September 2, 2021, from Economic Research Service United States Department of Agriculture: https://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx

Viaene, J., Van Lancker, J., Vandecasteele, B., Willekens, K., Bijttebier, J., Ruysschaert, G., . . . Reubens, B. (2016). Opportunities and barriers to on-farm composting and compost application: A case study from northwestern Europe. *Waste Management, 48*, 181-192.

Zhang, Z., Liu, D., Qiao, Y., Li, S., Chen, Y., & Hu, C. (2021). Mitigation of carbon and nitrogen losses during pig manure composting; A meta-analysis. *Science of The Total Environment, 783*, 147103.

Zingore, S., Delve, R., Nyamangara, J., & Giller, K. (2007). Multiple benefits of manure: The key to maintenance of soil fertility and restoration of depleted sandy soils on African smallholder farms. *Nutrient Cycling in Agroecosystems, 80*, 267-282.

CHAPTER 5. DESIGN AND CONSTRUCTION OF MESOPHILIC PLUG FLOW ANAEROBIC DIGESTERS

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Introduction

Anaerobic digestion (AD) is one of the popular technologies employed for manure treatment, especially with recent government Renewable Natural Gas (RNG) incentives on energy produced from AD have encouraged the rapid increase in adoption of such technologies (EPA). Biochar addition in anaerobic digestion is a proven means of improving anaerobic digestion while reducing the risk of process failure (Masebinu, Akinlabi, Muzenda, & Aboyade, 2019). A 750 mL lab-scale semi-continuous batch anaerobic digestion experiment was conducted by Xu et al. (2021) showed that 1% biochar addition at 20-day HRT has the highest methane yield. Another study by Sanchez et al. (2021) suggested that biochar only significantly increases methane yield and biogas after HRT increases beyond seven days in a 3-L continuous CSTR. There are many similar biochar anaerobic digestion studies in the literature that are conducted in the range of 250 mL serum bottles to 2 L flasks and most consistently proven the benefits of biochar addition for process optimization.

To date, no literature on biochar addition in pilot-scale plug-flow systems has been identified. This study aimed to design, construct, and test six 100-L plug-flow anaerobic digesters for subsequent swine manure anaerobic digestion experiments.

Materials and Methods

Digester Design and Construction

The goal of this study was to design and build six plug-flow anaerobic digesters, which supports a working volume of 100 liters, based on a modified design by Sells, et al. (2011). The digester body was built with a 6-foot long 1-foot diameter high-density polyethylene (HDPE) pipe with (polyvinyl chloride) PVC slip end caps, as shown in Figure 1. The six digesters were placed in a wooden structure made of 2 inches by 4 inches wood struts pieced together to form a structure, as shown in Figure 2. Digesters were heated with electric heating cables while insulated with bubble rolls (Reflectix Insulation; Markleville, Indiana) and fiberglass insulation (United States Gypsum; Chicago, Illinois) to maintain the temperature at 35 °C. The inlets and outlets are made of 2-inch PVC pipes with inlets connected to a 90-degree tee PVC pipe while the outlet is connected to a ball valve connected at the ends. The plug flow system works by manually removing a known amount of substrate from the outlet then filling on with the same amount that has been taken out. The "dump and fill" volume is calculated based on a 110-L digester working volume and will vary by HRT, as shown in Table 1.

Table 1: Dump and fill volume required with various HRT

HRT (days)	Dump and fill volume (L)
10	38.50
20	19.25
30	12.83

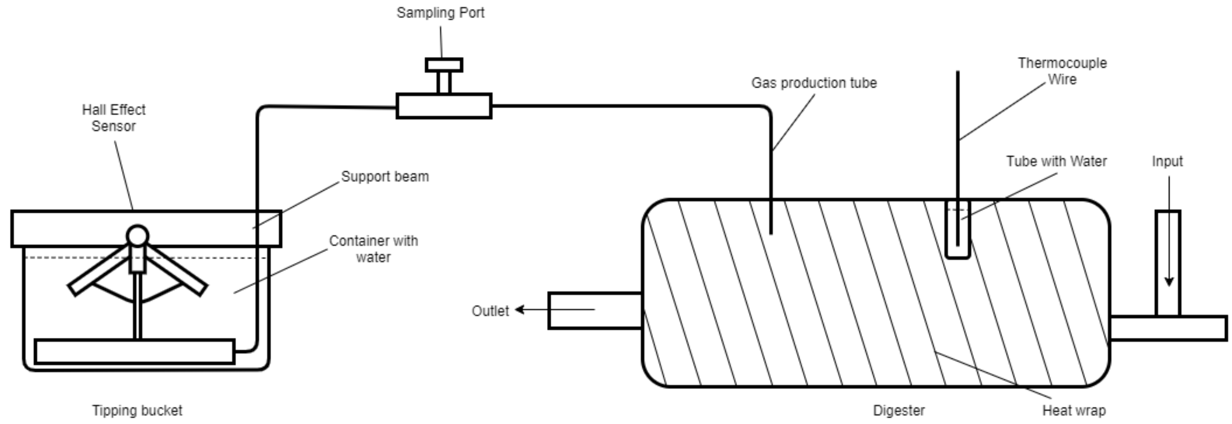


Figure 1. Diagram of sub-pilot-scale, 100-L plug flow anaerobic digester.

Figure 2. Picture of six 100-L anaerobic digesters in placed

Thermocouple wires (Omega Engineering, Inc.; Stamford, Connecticut) measured the inner temperature of the digester via a 0.5-inch PVC tube filled with water inserted into the digester through a threaded fitting. The purpose of the water filled tube is to prevent huge fluctuations in temperature which will create noise in temperature measurements. Biogas produced is channeled out from the digester through a ¼ inch rubber tubing via a threaded to barb brass fitting to the inverted tipping bucket. The gas production is measured by a submerged inverted tipping bucket that calibrates to 30 mL of biogas per tip. A sample port, as shown in

Figure 3 is assembled halfway through the gas line for methane concentration measurement. Periodic samples are collected for measuring methane content with an infrared gas analyzer (Sensor Inc, Germany).

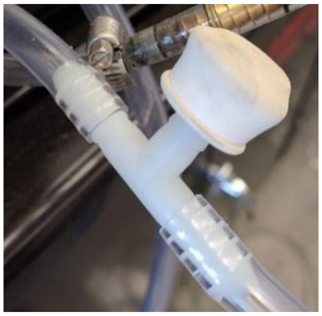
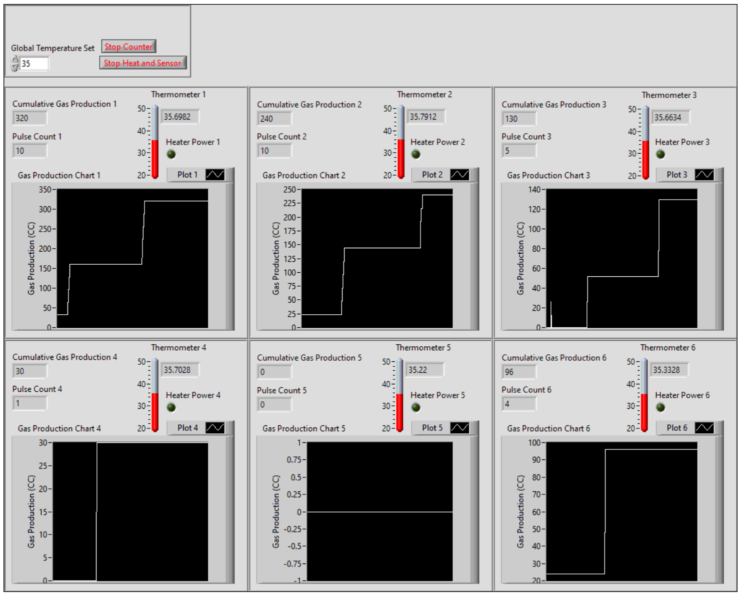


Figure 3: Sample port connected in the gas line

Controls System and Circuit Layout

The controls system was set up using LabVIEW software (National Instrument Corporation; Austin, Texas). The LabView graphical user interface (GUI) is shown in Figure 4, where users can set the digesters' operation temperature while monitoring actual digester temperature and cumulative gas production. USB 1208LS and USB-TC (Measurement Computing Corporation; Norton, Massachusetts) were the analog and digital I/O data acquisition devices used. The hall effect sensor attached to the tipping bucket and electric heating cables were connected to the USB 1208LS while the thermocouple wires were connected to the USB-TC, as shown in Figure 5. Gas production measurement and time are also recorded on an excel file real-time utilizing the "Write to measurement file" function within LabVIEW for easy data processing. Temperature is set at 35 °C by default but could be changed to any temperature desired. When the temperature falls below the set point in this GUI, the heater power turn "on" until the temperature is met; when the temperature rises above the set point, the heater power turns "off". More details on the LabVIEW coding can be found in the appendix.



Global Temperature Set: 35

Cumulative Gas Production 1: 320
Pulse Count 1: 10
Thermometer 1: 35.6982

Cumulative Gas Production 2: 240
Pulse Count 2: 10
Thermometer 2: 35.7912

Cumulative Gas Production 3: 130
Pulse Count 3: 5
Thermometer 3: 35.6634

Cumulative Gas Production 4: 30
Pulse Count 4: 1
Thermometer 4: 35.7028

Cumulative Gas Production 5: 0
Pulse Count 5: 0
Thermometer 5: 35.22

Cumulative Gas Production 6: 96
Pulse Count 6: 4
Thermometer 6: 35.3328

Figure 4. GUI from LabVIEW for six digesters

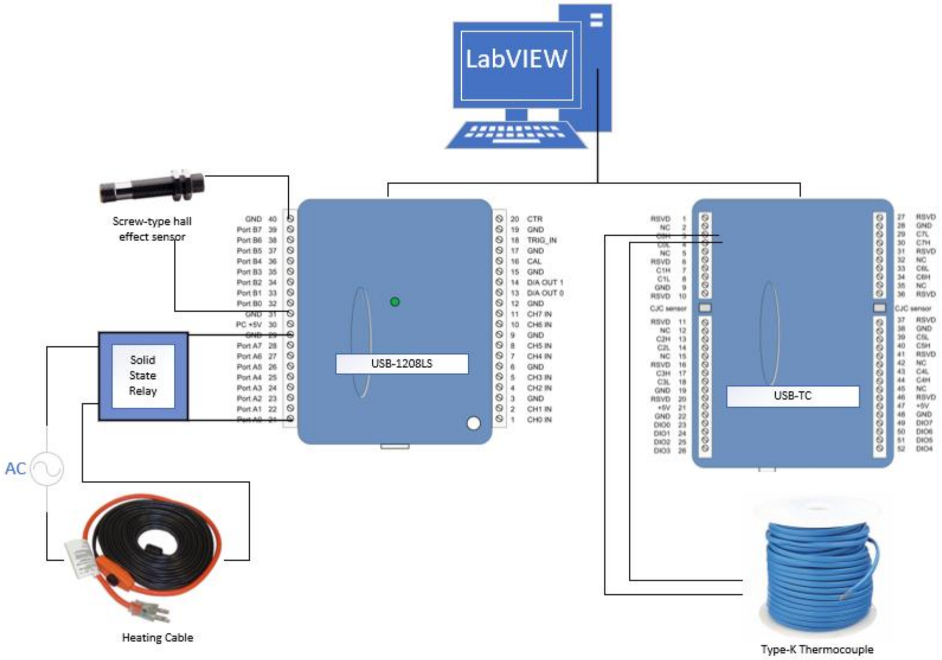


Figure 5. Schematic of circuit diagram anaerobic digesters and tipping buckets

Substrate

The manure was obtained directly from a deep-pit swine facility in central Iowa for digester testing purposes. Corn stover biochar, which underwent autothermal pyrolysis pretreated with ferric sulfide, is co-digested with manure.

Table 2. Substrate characteristics of substrate

	Swine Manure	Biochar
Total Solids (TS)	7.75 %	97.10%
Volatile Solids (VS)	6.14 %	48.20%
Chemical Oxygen Demand, COD (mg/L)	102 900	-

Results and Discussion

Testing

Digesters were loaded with 100-L of swine manure with 3% biochar for digesters A, B, C. Heaters were able to heat and maintain digesters at 35 °C throughout the digestion period. Inverted tipping buckets were able to capture biogas production throughout the period without problems. Even though periodic fluctuations are observed in biogas production from the digesters, general biogas production rate patterns are similar among the three digesters, as shown in Figure 6. Methane content within biogas is constantly at 65%, with a total biogas production of the three digesters ranging from 3460 L to 4840 L over the range of 70 days.

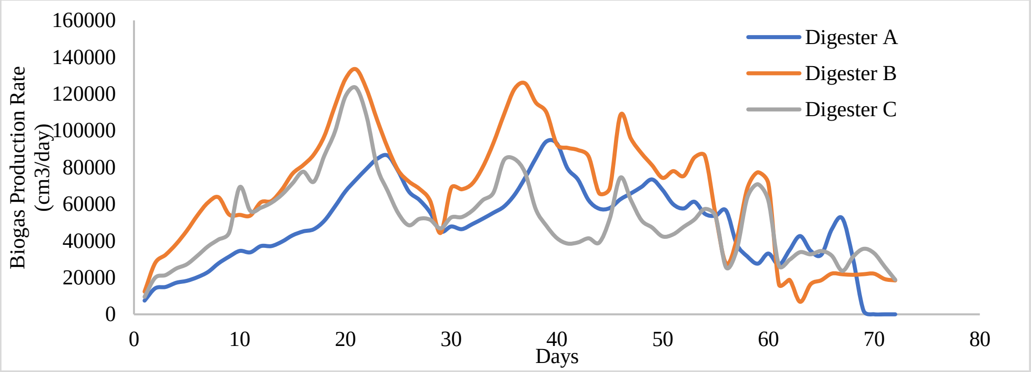


Figure 6. Gas production rate from digesters as a function of time

Validation

TS reduction achieved range from 51.3% to 56.0%, while VS destruction ranges from 55.1% to 69.4%, as shown in Table 3. Methane production for the three digesters is between 482 to 675 mL of CH_4 / g of VS destroyed, comparable to the 500 mL of CH_4 / g of VS destroyed (Sweeten, Fulhage, & Humenik, 1981).

Theoretical CH_4 production per COD destroyed is 350 mL of CH_4 / COD destroyed (Hill, 1983), while the actual yield in this testing ranges from 450 – 600 mL of CH_4 / COD destroyed. The discrepancy in these values may be attributed to manure's high solids nature, which poses challenges in COD measurements.

Table 3. Initial and final TS, VS, and COD for each digester

	Digester A			Digester B			Digester C		
	Initial	Final	Reduction	Initial	Final	Reduction	Initial	Final	Reduction
TS (Kg)	11.83	5.76	51.3%	11.83	5.63	52.4%	11.83	5.20	56.0%
VS (Kg)	8.35	3.74	55.2%	8.35	3.75	55.1%	8.35	3.39	59.4%
COD (mg/L)	104000	41100	60.5%	104000	76200	26.7%	104000	54800	47.3%

Conclusion and recommendations for future work

Plug flow anaerobic digesters were designed, constructed, and tested with 110 Kg of swine manure digested with 3% biochar for 70 days. Biogas production is captured via the tipping bucket system flawlessly over the entire period. In future experiments involving these digesters, gas leaks need to be addressed in some of the digesters.

References

EPA. (n.d.). *Renewable Natural Gas from Agricultural-based AD/Biogas systems*. Retrieved September 16, 2021, from United States Environmental Protection Agency: https://www.epa.gov/agstar/renewable-natural-gas-agricultural-based-adbiogas-systems#why-interest-rng

Hill, D. (1983). Simplified Monod Kinetics of Methane Fermentation of Animal Wastes. *Agricultural Wastes, 5*, 1-16.

Masebinu, S., Akinlabi, E., Muzenda, E., & Aboyade, A. (2019). A review of biochar properties and their roles in mitigating challenges with anaerobic digestion. *Renewable and Sustainable Energy Reviews, 103*, 291-307.

Queck-Matzie, T. (2019). *An Overview of Pork Production in the US*. Retrieved from Successful Farming: https://www.agriculture.com/livestock/hogs/an-overview-of-pork-production-in-the-us

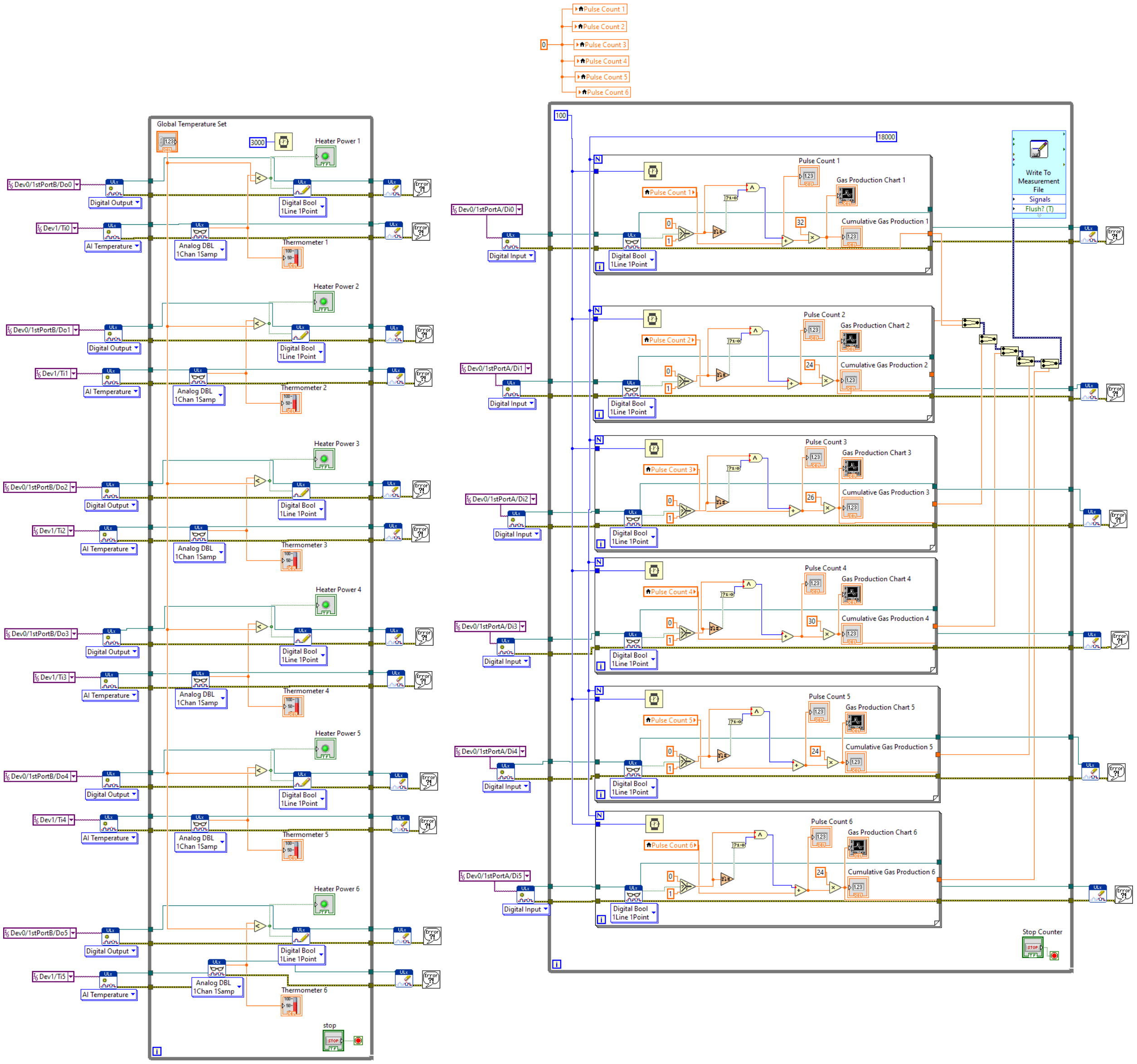
Sanchez, E., Herrmann, C., Maja, W., & Borja, R. (2021). Effect of organic loading rate on the anaerobic digestion of swine waste with biochar addition. *Environmental Science and Pollution Research, 28*, 38455-38465.

Sells, S., Burns, R., Moody, L., & Raman, D. (2011). Comparison of Methane Production from Bench- and Sub Pilot-Scale Anaerobic Digesters. *Applied Engineeering in Agriculture, 27*(5), 821-825.

Sweeten, J., Fulhage, C., & Humenik, F. (1981). Methane Gas from Swine Manure. *Waste Management*, L-1860.

Xu, M., Uludag-Demirer, S., Fang, D., Zhou, L., Liu, Y., & Liao, W. (2021). Effects of pyrogenic carbonaceous materials on anaerobic digestion of a nitrogen-rich organic waste - swine manure. *Energy & Fuels, 35*, 2282-2292.

Appendix: LabVIEW code for Anaerobic Digesters' Controls System



CHAPTER 6. GENERAL CONCLUSION

Manure processing and management remains a challenge for large-scale farmers especially with the rising global demands of animal protein. Composting and anaerobic digestion are promising methods of manure treatment if the issue of scalability can be overcome. This thesis's objective was to investigate economic feasibility of solid manure composting and evaluate methods and treatments for efficient manure anaerobic digestion.

The first study, the techno-economic analysis conducted on solid manure composting showed beef and dairy farms need to be relatively large (> 6000 animals) for composting to be economically competitive compared to direct land application. This model also showed composting efficiency expressed as volume and mass reduction is the most important factor in evaluating the efficacy of solid manure composting. This means extensive monitoring and care on composting process will pose the greatest benefit on making composting efficient. Methods of increasing more efficient composting processes like aeration and manipulating C:N ratio might be worthwhile.

The second study designed, constructed, and tested pilot -scale plug-flow anaerobic digesters with built-in automated data collection and controls systems. The digesters successfully handled 100 kg of manure with 3% biochar addition. Gas production data are collected with LabVIEW software and the resulting methane production and COD reduction are close to the values reported in literature.

Future work has the potential to build on the research from this thesis. The economic model for manure composting could be further refined and more holistic with the inclusion of various composting methods discussed in Chapter 2 of this thesis. The model can also be expanded by the including more manure types particularly for poultry and account for the effect of co-composting multiple substrates. With the sub-pilot scale anaerobic digesters being constructed, a wide range of AD experiments can be conducted and not limited to co-digestion of manure with biomass or biochar, manipulation of HRT, temperature and even investigate effect of multiple substrate pre-treatment methods.