

THESIS

AEROBIC POST-PROCESSING OF DIGESTATE FROM A MULTI-STAGE ANAEROBIC DIGESTER

Submitted by

Julie N. Sandefur

Department of Civil and Environmental Engineering

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Spring 2017

Master's Committee:

Advisor: Sybil Sharvelle

Susan DeLong
Jessica Davis

Copyright by Julie N. Sandefur 2017

All Rights Reserved

ABSTRACT

AEROBIC POST-PROCESSING OF DIGESTATE FROM A MULTI-STAGE ANAEROBIC DIGESTER

The management of animal waste from feedlots is inconvenient and costly due to the storage and transportation involved in ensuring the waste is utilized appropriately. Anaerobic digestion is a proven method for breaking down waste with low solids content and capturing methane produced to use as renewable energy. Composting is an age-old process in which solid waste retains its nutrients and becomes a suitable, natural soil amendment. By combining these methods within multi-stage anaerobic digestion (MSAD), two valuable by-products are generated – methane and nutrient-laden compost – through a process able to handle high solids material.

A laboratory-scale study was conducted to simulate aerobic composting of high solids cow manure (HSCM) in a leachate bed reactor (LBR) after anaerobic digestion from a MSAD. Analysis of the leachate and solid material were performed after each phase: anaerobic – 21 days, active aerobic – 21 days, and curing - 60 days. The effects of agricultural by-products used as bulking material in the LBRs and of compost inoculum added were also assessed. The bulking material assisted in providing uniform flow of leachate through the LBRs during the anaerobic phase and served as an additional carbon source once aeration began. Inoculum acquired from Colorado State University's (CSU) composter was added at the beginning of the aeration phase via two different methods alongside a control group in order to assess the potential contributions of including already composted organic material still containing active bacteria. Compost quality

parameters monitored consisted of ammonium to nitrate ratio, carbon to nitrogen ratio, pH, soluble salts, sodium absorption ratio (SAR), percent total nitrogen, phosphorus, and potassium, and the Solvita® Maturity Index (SMI).

There was a sizable volatile solids reduction (%VS) observed of the HSCM only in two of the three different bulking material reactor sequences. The bulking material study showed a $41\% \pm 0.12$, $33\% \pm 0.03$ and 55% average reduction in the manure for corn stover, beanstalk, and woodchip reactors respectively. The woodchips most likely contributed to the larger solids reduction due to their larger particle size and more rigid structure allowing leachate and air more pathways to access and breakdown material. VS reduction in the inoculum study showed that there was no solids reduction benefit achieved by including a 1:2 municipal solid waste (MSW)-horse manure combined inoculated compost to the reactors prior to the active aeration phase. The control reactors outperformed the reactors where inoculum was added on top or mixed in with the digestate.

The quality of the matured compost from all the reactors in both studies met or exceeded required specifications. The stability and maturity of the composts were compared to Rocky Mountain Region Classification tables as well as the SMI range. In each case, the analytes measured were below the suggested limits in the classification table and most fell in the “finished compost” range on the SMI scale. The values of the major nutrients assessed were of satisfactory contents as to be useful for land application.

This study seeks to encourage the process of MSAD on feedlots with HSCM in arid to semi-arid regions by demonstrating the usefulness of the by-products achieved from the process. Methane gas produced in the anaerobic phase is a valuable form of renewable energy that can be used

onsite. A mature compost product meeting Class 1 Compost/ Soil Amendment Classification standards can be used onsite or sold for a variety of applications. By generating methane and beginning the composting process in the same LBR, solids are further reduced, weight is minimized and the material is more stable for transportation and storage.

ACKNOWLEDGEMENTS

First, I would like to thank my advisor Dr. Sybil Sharvelle for the opportunity to take part in this research project and for her support along the way. Without her continued guidance and patience I probably would have tossed in the towel long ago. Thanks to Dr. Susan De Long and Dr. Jessica Davis for their invaluable expertise in this field and their willingness to be on my committee.

I would also like to thank Lucas Loetscher for his invaluable insight during the rough patches of the research and for keeping the SimLab running as smoothly as possibly. Thanks to Matthew Lewis and Rongxi Wu for checking in on my reactors when I was away. Most importantly, I would not have made it through without the loving encouragement and support of my parents, David and Kathryn Sandefur.

TABLE OF CONTENTS

ABSTRACT.....	ii
ACKNOWLEDGEMENTS.....	v
LIST OF TABLES.....	viii
LIST OF FIGURES.....	ix
CHAPTER 1: INTRODUCTION.....	1
1.1 Research Motivation.....	1
1.2 Research Objective.....	4
CHAPTER 2: BACKGROUND AND LITERATURE REVIEW.....	5
2.1 Agricultural Solid Waste.....	5
2.2 Anaerobic Digestion.....	5
2.2.1 General Process.....	5
2.2.2 Benefits of Anaerobic Digestion.....	6
2.3 AD Technology.....	7
2.3.1 Current AD Technology.....	7
2.3.2 MSAD Technology.....	8
2.3.3 Advantages of Multi-Stage Reactors.....	9
2.3.4 Advantages of Leachate Recirculation.....	10
2.3.5 Combining MSAD and Leachate Recirculation.....	11
2.4 Post-Anaerobic Processing.....	12
2.4.1 General Benefits.....	12
2.4.2 Conventional Composting Approaches.....	13
2.4.3 Solids Reduction.....	15
2.4.4 Nutrient Transformation.....	15
2.4.5 Effects of Bulking Material.....	15
2.4.6 Effects of Inoculum Addition.....	16
2.4.7 Composting Anaerobically Digested Material.....	17
2.5 Current Land Application Standards.....	17
2.5.1 Composting Standards.....	17

2.5.2 Stability and Maturity	21
2.5.3 Plant Available Nutrients	23
2.6 Summary	24
CHAPTER 3: MATERIALS AND METHODS	26
3.1 Experiment Setup	26
3.2 Substrate Collection and Storage	28
3.3 Reactor Construction and Set-Up	28
3.4 Loading LBRs	31
3.4.1 Bulking Material Study	32
3.4.1.1 Bulking Material	34
3.4.2 Inoculum Study	35
3.5 Curing Method	37
3.6 Sample Collection	38
3.7 Analytical Methods	39
3.7.1 Manure and Inoculum Characterization	39
3.7.2 CSU Soils Laboratory Testing	41
3.7.3 Leachate Characterization	41
CHAPTER 4: RESULTS AND DISCUSSION	43
4.1 Solids Reduction	43
4.1.1 Bulking Material Study	43
4.1.2 Inoculum Study	47
4.1.3 Anaerobic Degradation	51
4.2 Compost Quality	52
4.2.1 Stability & Maturity	52
4.2.2 Nutrient Availability	56
CHAPTER 5: CONCLUSION	58
REFERENCES	60

LIST OF TABLES

Table 1 - Compost / Soil Classification Standards	19
Table 2 - Outline of Experiments Conducted	28
Table 3 - Bulking Material Volatile Solids Percentages by Mass	34
Table 4 - Inoculum Volatile Solids Reduction in another Experiment (Wilson et al., 2016)	37
Table 5 - Averages and Standard Deviations for Post-Aeration Tested Material by Reactor	46
Table 6 - Comparison of NH_4^+ -N: NO_3 -N Before and After Curing Phase	54
Table 7 - Solvita Ratings and Interpretations.....	56
Table 8 – Average Total Nutrient Measurements by Bulking Material.....	56
Table 9 – Averages of the Saline and Sodic Tendency of the Composts.....	57

LIST OF FIGURES

Figure 1 - Renewable Energy Generated Compared with Other Energy Resources (US EIA, 2015)	1
Figure 2 - Renewable Energy Sources Compared by Amount Generated (US EIA, 2015).....	2
Figure 3 - Feedlot Handling Options (“Agricultural Waste Management Systems Part 651 Agricultural Waste Management Field Handbook Chapter 9 Agricultural Waste Management Systems,” 2011).....	3
Figure 4 - Stages of Anaerobic Digestion	6
Figure 5 – Current Low Solids AD Technology Diagrams and Recommended Waste Solids Content	7
Figure 6 - MSAD Process including (1) LM, (2) LST and (3) HRAD	9
Figure 7 - Schematic of biodigesters used in experiments: a) pilot-scale system; and b) bench-scale system (Pandey et al., 2016)	14
Figure 8 - View of the Front of the CSU Demonstration Scale MSAD.....	26
Figure 9 - Empty Reactors and Caps	29
Figure 10 - Flow Diagram of Reactor System	31
Figure 11 - Examples of Bulking Material Used	35
Figure 12 - Curing Containers	38
Figure 13 – Collecting Leachate Samples from Reactors	39
Figure 14 – Initial and Post-Aerobic Total Dry Mass and Total Volatile Mass (Error bars indicate +/- one standard deviation; error bars are not included for the woodchips experiment because the samples were combined before testing).....	44
Figure 15 a & b - Estimated (a)TS% Removal and (b)VS% Removal for Experiments with Different Bulking Material through both the Anaerobic and Aerobic Phases (Error bars indicate +/- one standard deviation; error bars are not included for the woodchips experiment because the samples were combined before testing)	44
Figure 16 - Initial and Post-Aerobic Dry Mass and Volatile Mass of Manure Only (Error bars indicate +/- one standard deviation; error bars are not included for the wood experiment because the samples were combined before testing).....	45
Figure 17 a & b – Estimated (a) TS% Removal and (b) VS% Removal of Manure Only for Experiments with Different Bulking Material through both the Anaerobic and Aerobic Phases (Error bars indicate +/- one standard deviation; error bars are not included for the wood experiment because the samples were combined before testing).....	45
Figure 18 - Percent Volatile Solids Present after each Phase	47
Figure 19 - Initial and Post-Aerobic Total Dry Mass and Total Volatile Mass (Error bars are not included because the samples were combined before testing).....	48
Figure 20 - Initial and Post-Aerobic Dry Mass and Volatile Mass of Manure Only (Error bars are not included because the samples were combined before testing).....	48
Figure 21 – Total Percent Volatile Solids Removal by Inoculum Composition through both the Anaerobic and Aerobic Phases (Error bars are not included because the samples were combined before testing)	49

Figure 22 - Percent Volatile Solids Removal by Inoculum Composition in Manure Only through both the Anaerobic and Aerobic Phases (Error bars are not included because the samples were combined before testing)	49
Figure 23 - Percent Volatile Solids Present after each Phase (Error bars indicate +/- one standard deviation; error bars are not included for the post-aeration experiment because the samples were combined before testing).....	51
Figure 24(a & b) - Initial and Average Chemical Oxygen Demand Measurements during Anaerobic Phase	52
Figure 25 - Bulking Material Study Meeting Class 1 Composting Requirements.....	53
Figure 26 - Inoculum Study Meeting Class 1 Composting Requirements.....	54
Figure 27 - Interpreting Compost Condition with Solvita Ratings (“Guide to Solvita,” 2002).....	55

CHAPTER 1: INTRODUCTION

1.1 Research Motivation

Energy and water are the two most invaluable commodities to sustaining life in the 21st century.

The United States is the largest user of both commodities in the world. Most of the energy used in the US comes from burning fossil fuels. Only in recent years, as awareness of the limitations of fossil fuels has become apparent, a major effort been made to switch to renewable sources of energy. Last year, 11.1% of total energy generation in the U.S. came from renewable sources such as biomass, hydroelectric, wind and solar (U.S. EIA, 2015). While there has been a considerable increase in the last half-century (Figure 1), there is still much more renewable energy potential to be tapped into.

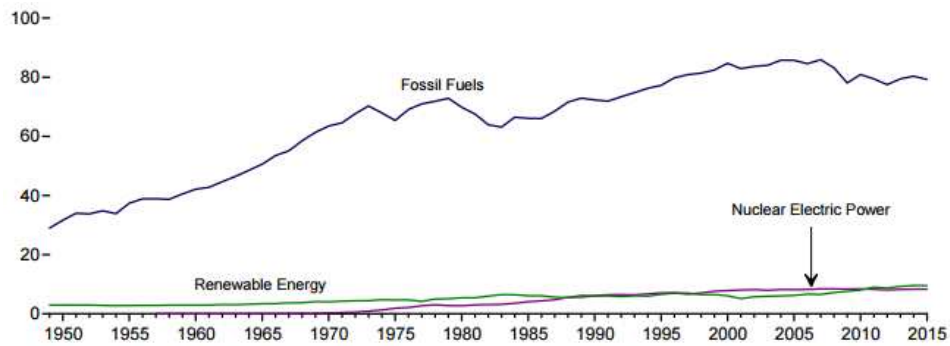


Figure 1 - Renewable Energy Generated Compared with Other Energy Resources (US EIA, 2015)

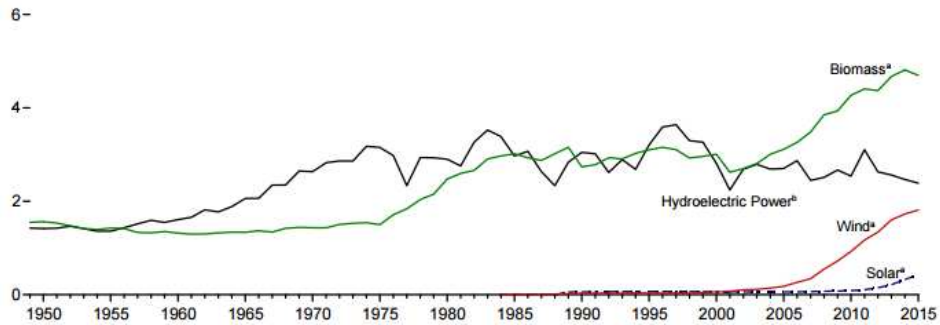


Figure 2 - Renewable Energy Sources Compared by Amount Generated (US EIA, 2015)

Admittedly, the balance between harnessing renewable energy and doing so affordably is difficult. Biomass currently accounts for almost 50% of the total renewable energy produced (Figure 2) and it remains considerably under-utilized. For example, manure from one cow can produce just over 4 Kilowatt-hours per day of methane gas by anaerobic digestion (Sharvelle and Loetscher, Fact Sheet# 1.227). In 2015 the total cattle in U.S. commercial slaughter industry numbered 28.8 million head (USDA ERS, 2016). That equates to a potential 115.2 Gigawatt-hours per day of energy produced nationally compared to the 5 MW-h shown in Figure 2.

Using biomass as a source of energy can illicit other benefits as well. Producing and capturing methane gas in the absence of oxygen prevents high levels of carbon dioxide from forming. Carbon dioxide is a greenhouse gas that is increasing in concentration in the atmosphere. Reducing CO₂ emissions plays a major role in slowing the effects of global warming. Another advantage to biomass degradation is the reduction in solids that need to be handled. Currently, the animal waste generated is used as bedding for livestock or marketed as compost, but mostly land applied as a dry or liquid manure spread (Figure 3) (“Agricultural Waste Management Systems Part 651 Agricultural Waste Management Field Handbook Chapter 9 Agricultural Waste Management Systems,” 2011). However, there is typically not enough nearby demand for compost or land application, and the material is costly to transport long distances. Therefore, the

need for waste utilization should be minimized. AD is one such method that could minimize the amount of waste needing to be utilized.

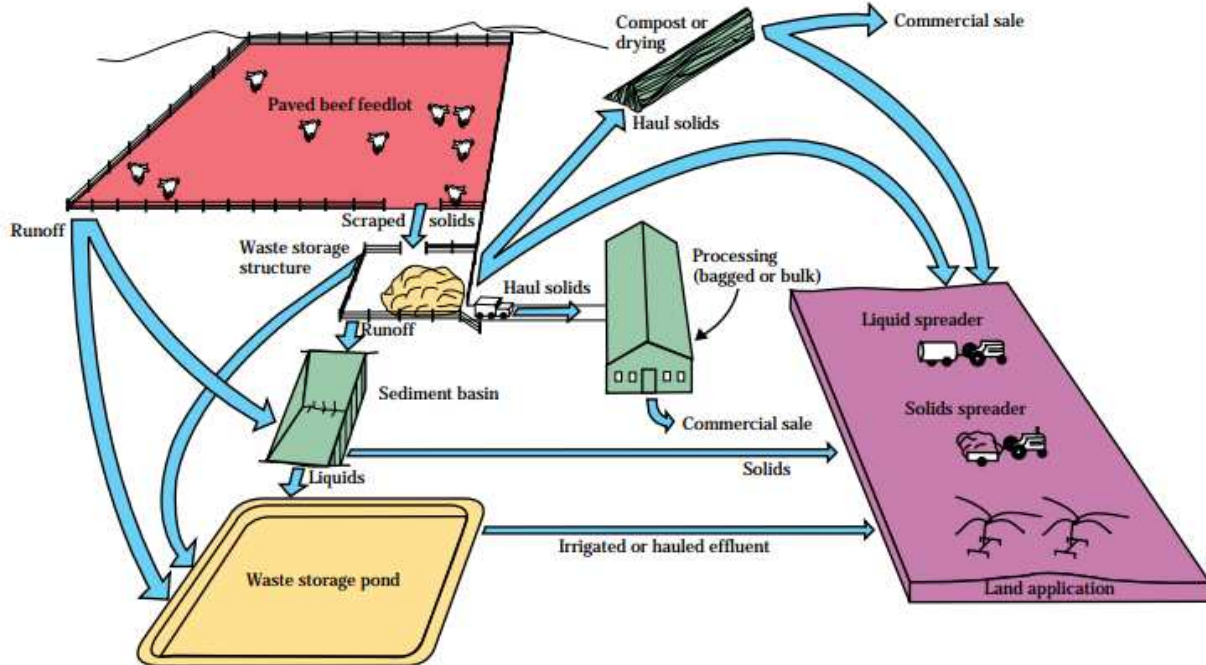


Figure 3 - Feedlot Handling Options (“Agricultural Waste Management Systems Part 651 Agricultural Waste Management Field Handbook Chapter 9 Agricultural Waste Management Systems,” 2011)

There are many reasons AD has not been widely adopted in Colorado animal feeding operations. Two main reasons are lack of proven technologies for anaerobic digestion at high solids loading concentrations and lack of a beneficial by-product of the remaining solids after digestion. Due to water scarcity in the western United States, including Colorado, the animal waste collection process often involves scraping instead of flushing. The difference in these techniques increases the solids content from 10-14% to as high as 90% ((Sharvelle, Keske, Davis, & Lasker, 2011). In recent research studies, Dr. Sharvelle’s group at Colorado State University (CSU) developed a multi-stage anaerobic digester (MSAD) that focus on digesting high solids waste through isolating the rate-limiting stages and recirculating the leachate. After applying MSAD, the remaining digestate could be aerated and converted into compost for land application. Often

there is not a sizable amount of arable land in close proximity to the animal feedlots; therefore, transporting the processed digestate can be cost prohibitive. Composting the remaining solid material can lower the weight and therefore cost less to transport (Sharvelle et al., 2011) Manure composting is a well-described approach for stabilization of nutrients and reduction of pathogens and odors. However, there is very little research assessing the effects of transitioning the material from an anaerobic to an aerobic state in-vessel.

1.2 Research Objective

There is a sense of urgency in continuing to develop cost-effective methods for decomposing biomass by the AD process. This may be possible by maximizing the amount of methane generated and creating a usable final product. The current research project focuses on three main objectives: 1) To study the feasibility of high solids cow manure (HSCM) breakdown during leachate recirculation in MSAD followed by aerobic conditions in-vessel and a further maturing process; 2) To assess the effect of different carbonaceous bulking materials on manure solids breakdown; 3) To evaluate the impact of adding aerobic compost inoculum to the reactors through different methods.

CHAPTER 2: BACKGROUND AND LITERATURE REVIEW

2.1 Agricultural Solid Waste

Livestock production systems, or feedlots, are found in vast numbers all over the US in order to meet the demand for dairy and meat manufacturing. These facilities where a large number of livestock live, eat and, defecate in a small area create some serious environmental risks and challenges. The biggest risk is the potential of pollution through the spread of nitrogen, phosphorous, pathogens, undigested pharmaceuticals, and emission of greenhouse gases. If methods are not developed to contain and dispose of organic solid waste (OSW) properly, the spread of pollution will worsen (Bustamante et al., 2013). One of the biggest challenges in managing the quantities of waste produced is costly. While the storage and transportation costs are noteworthy, there is often much more waste than local places to utilize it. However, anaerobic digestion (AD) is a technology that could be more widely implemented to significantly reduce the risk of pollution if the entire AD process was cost-competitive (Drennan & DiStefano, 2010).

2.2 Anaerobic Digestion

2.2.1 General Process

Anaerobic digestion (AD) has been widely implemented in several parts of the world due to its advantages in managing OSW. There are four major stages of AD: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Figure 4). Microorganisms present during each of these four stages play a key role in the breakdown of OSW and the release of methane for energy production.

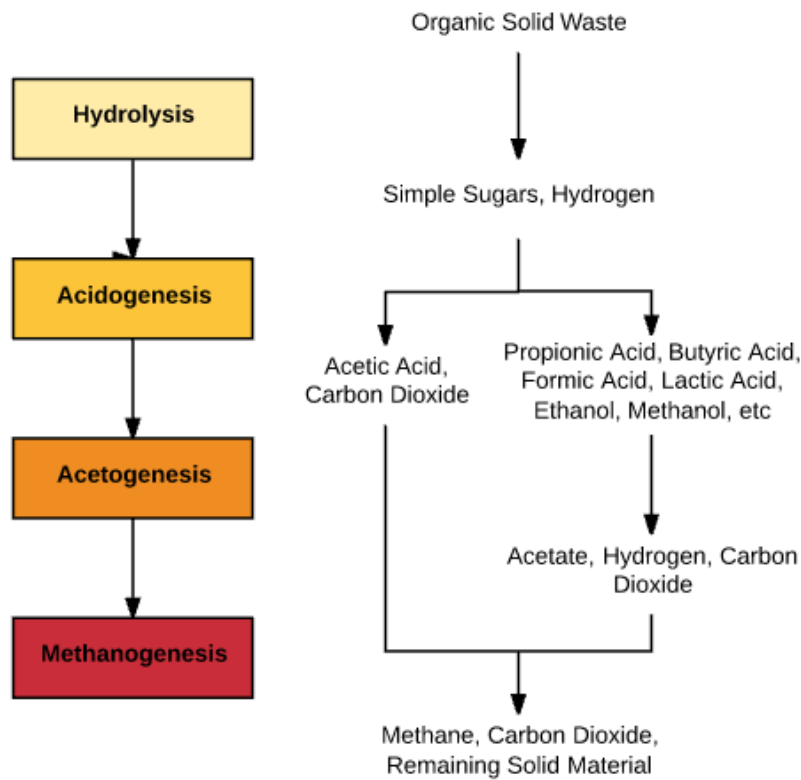


Figure 4 - Stages of Anaerobic Digestion

During the hydrolysis stage, complex organic matter contained in OSW is converted into soluble organic molecules like simple sugars. These simple sugars are then transformed into various acids and alcohols as well as hydrogen and carbon dioxide by acidogenic bacteria through fermentation. The acetogenic bacteria immediately convert the acids and alcohols into a usable form for the methanogenic bacteria, mainly into acetic acid and hydrogen. Methanogenesis is the final stage in the AD process producing methane and carbon dioxide. These four stages are interdependent and the rate of breakdown depends primarily on the type of initial waste and the operating temperature, as well as reactor design and operating scheme (Fox & Pohland, 1994).

2.2.2 Benefits of Anaerobic Digestion

AD is seen as one of the key elements in the current energy transition as it is both a waste treatment technology and a source of renewable energy (Degueurce, Tomas, Le Roux, Martinez,

& Peu, 2016). By restricting oxygen in the breakdown of OSW, the formation of carbon dioxide is minimized and methane generation increases. This methane can be captured and used to reduce or eliminate the energy operating requirements of the system depending on the size.

2.3 AD Technology

2.3.1 Current AD Technology

While the single stage AD process is a good alternative in reducing solids content while releasing energy in the form of methane gas, standard digesters cannot handle high solids loading. The current AD technologies used include covered lagoons, plug flow, complete mix, upflow sludge blanket (USB) and fixed film reactors (FF). Each of these AD technologies has an associated recommended waste solids content shown in Figure 5.

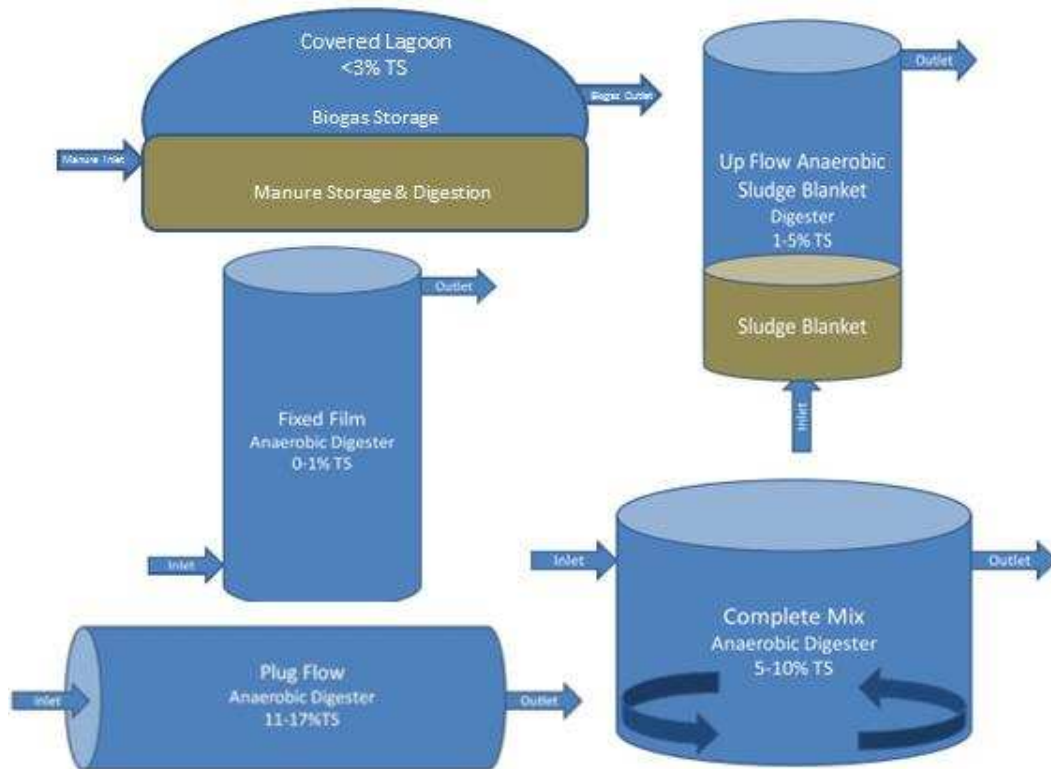


Figure 5 – Current Low Solids AD Technology Diagrams and Recommended Waste Solids Content

(Sharvelle et al., 2011)

Covered lagoons have the lowest capital cost associated with them and quickly eliminate odors. However, there are usually longer retention times associated with lagoons, especially in colder temperatures. This allows for minimal biogas recovery. Plug flow systems are also low in capital cost and are able to handle higher solids content waste because the waste travels down the system as a continuous mass or plug. However, plug flow systems are sensitive to heterogeneous input material resulting in varying biogas production and low volatile (VS) destruction rates. Complete Mix reactors allow for variability in waste input and have more reliable methane production compared to covered lagoons or plug flow reactors. However, they have a high capital cost and require large energy input for mechanical mixing. USB reactors are highly efficient because of high VS destruction leading to high biogas yields in a small volume of space. Unfortunately, they have a longer start up period and are also not conducive to high solids wastes. Finally, FF reactors contain high surface area material for larger colonies of microorganisms. The larger presence of microorganisms correlates to higher methane generation. Unfortunately, potential clogging of the reactor necessitates high water content waste and smaller solid waste particulates (Sharvelle et al., 2011). These conventional technologies have their place; however, by themselves, none of them are capable of handling the high solids percent (upwards of 50%) from cattle waste collected from dry lots without a substantial amount of water being added to the system.

2.3.2 MSAD Technology

Multi-stage anaerobic digestion (MSAD) seeks to address the factors slowing down the digestion process by separating the three stages that take place in AD: (1) hydrolysis, (2) acidogenesis and acetogenesis, and (3) methanogenesis. Hydrolysis occurs in the leachate module (LM: see component (1), Figure 6) where a small amount of water trickles over a bed containing low moisture waste. The leachate (water containing dissolved carbon and other nutrients) is then

stored in the leachate storage tank (LST) where the acidogenic and acetogenic bacteria thrive. From there the high organic content liquid is fed into a high rate anaerobic digester (HRAD) at an appropriate rate for methane generation. The leachate, having released the dissolved carbon, is recirculated back through the LM where hydrolysis occurs until maximum organic content is leached into the liquid.

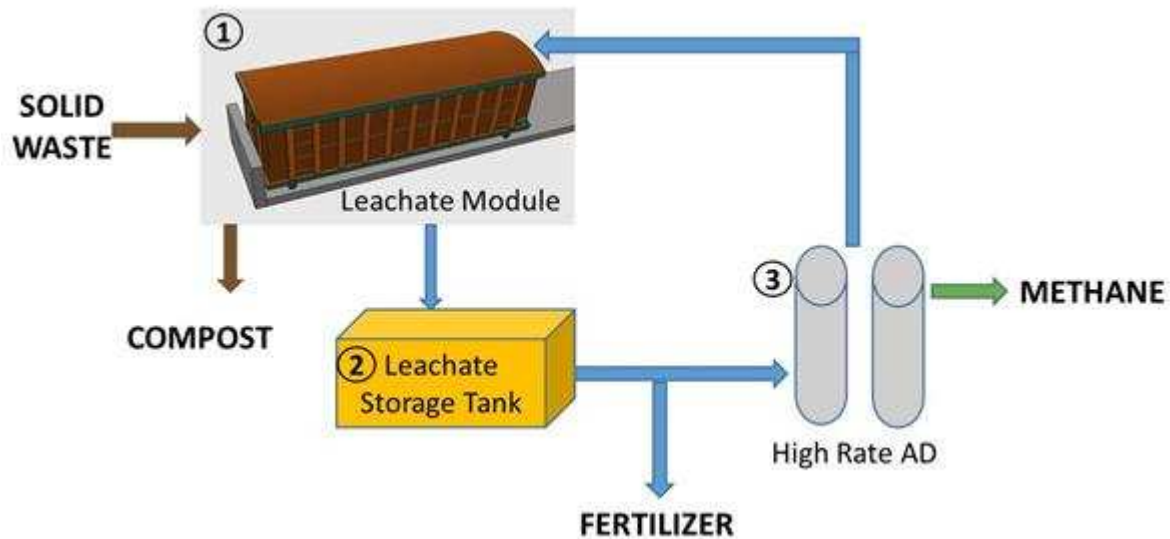


Figure 6 - MSAD Process including (1) LM, (2) LST and (3) HRAD

2.3.3 Advantages of Multi-Stage Reactors

The two stages commonly cited as rate-limiting during the AD process are hydrolysis and methanogenesis (Fox & Pohland, 1994)(Nallathambi Gunaseelan, 1997). Using multiple reactors isolates these rate-limiting stages and enhances each individual process. In the first phase, hydrolysis reactions are enhanced by allowing more contact time between the enzymes and the complex substrates. A reactor containing primarily acidifying organisms can create a higher concentration of enzymes (Fox & Pohland, 1994). In the third reactor, methanogens also become more plentiful because there is no competition from the faster-growing acidogenic organisms.

Also, having the separate reactors allows the pH and temperature preferable to the organisms in each phase to be maintained (Fox & Pohland, 1994).

Using multi-stage reactors also results in a considerable decrease in total digestion time compared to the conventional single stage digestion (Nallathambi Gunaseelan, 1997). This is because by separating the two rate-limiting stages the biological kinetics of the system are improved. Even though the biological reactions that occur during AD are dependent on each other, separating the process into multiple reactors appears to encourage the syntrophic relationship of the bacteria (Fox & Pohland, 1994).

2.3.4 Advantages of Leachate Recirculation

Typical AD systems are unable to handle waste material with total solids above 17%. A few studies have pushed into the 20-30% range by circulating water from a second digester that had already been operating for 40 days (Hall, Hawkes, Hawkes, & Thomas, 1985). However, the average percent total solids of OSM being dry scraped from feedlots in arid to semi-arid regions, like the HSCM obtained from Kersey, Colorado, has been measured as high as 90% total solids (Arikan, Mulbry, & Lansing, 2015)(Sharvelle et al., 2011). Recirculating water in the form of leachate through the MSAD system provides multiple advantages like shorter digestion time, increase methane production, greater VS reduction, and reduced water use.

Leachate is water containing some of the nutrients and microbes after percolating through solid material. The continual recirculation of these microbes allows the total digestion time be shorter by improving the contact between the biomass and the substrate (El-Mashad, van Loon, Zeeman, Bot, & Lettinga, 2006)(Chan, Chu, & Wong, 2002). Therefore, substrate degradation is positively affected by the frequency and surface area of contact between the substrate and microorganisms during leachate distribution. A second reason for improved degradation is that

the recirculated leachate may contain some inoculum (O'Keefe & Chynoweth, 2000)(Griffin, 2012).

Not only does leachate recirculation enhance the degradation rate, but it also increases the production of methane gas as well (Hall et al., 1985). Experiments performed by El-Mashad et al. (2006) achieved a relatively high methane production rate; an approximately 50% increase in methane production was observed over systems not recirculating leachate. These experiments studying the effect of leachate recirculation on digestion performance were operated at a continuous flow starting day 11 of 60 at 40°C and 50°C (El-Mashad et al., 2006). A greater reduction in VS was also seen in the experiment using leachate recirculation (Degueurce et al., 2016); reporting an overall removal of 26-39% VS. The authors cited favorable conditions by maintaining moisture content in the system as a key parameter in high solid state AD performances. In general, feedstocks containing high total solids (TS) create handling and mixing difficulties making the recirculation of leachate through the OSW necessary to achieve maximum degradation and to improve biogas production (Degueurce et al., 2016).

2.3.5 Combining MSAD and Leachate Recirculation

The MSAD technology has combined the advantages of separate reactor AD and leachate recirculation, thus limiting the need for the addition of water, extensive mixing, and energy needed for heating compared to conventional digestion systems at low solids concentrations (El-Mashad et al., 2006). Systems using multi-stage reactors or leachate recirculation have their individual disadvantages that can be overcome by the advantages of the other.

Separating the hydrolysis and methanogenesis stages of AD can disrupt the syntrophic relationship between the microbes (Fox & Pohland, 1994). However, with leachate recirculation it is sometimes difficult to keep the stages completely separate and therefore, the stages might

overlap, maintaining their natural co-dependence. One disadvantage to leachate recirculation is that unless it is closely monitored, volatile fatty acids (VFAs) can accumulate to unfavorable levels resulting in irreversible acidification. This acidification severely impedes the methanogenic activity (Veeken & Hamelers, 2000). However, acidification is lessened by having a separate methanogenic reactor (Viéitez & Ghosh, 1999), as is the case with the MSAD technology. Accumulating high salinity and ammonia concentrations are also of concern during the recirculation process. However, recent research suggests that inoculation with saline and ammonia-tolerant organisms can help overcome this issue (Griffin, 2012)(Wilson, Sharvelle, & De Long, 2016). While there are some hindrances to separate stage anaerobic digestion and leachate recirculation that need to be overcome, this MSAD technology design is considered an overall operation strategy for the improvement of AD process performance.

2.4 Post-Anaerobic Processing

2.4.1 General Benefits

While AD significantly reduces the total solids to be managed at animal feeding operations and provides methane biogas, there is still a large cost component associated with it. One approach to reduce the remaining operating costs is to create a final product that is biologically stable and economically viable. Aerating the remaining solid material after the anaerobic process could accomplish this. Applying aerobic composting as a post-treatment to AD processes would be attractive as the digested manure still has a high moisture content which contributes to high transport costs. Aerobic composting could produce a stabilized, easy-transferable, useful alternative end product (El-Mashad et al., 2006). For the MSAD technology, aeration is proposed in the LBRs after the anaerobic phase to achieve some initial in-vessel composting.

2.4.2 Conventional Composting Approaches

Several composting methods can be selected and used depending on the investment cost, operation cost, time required to reach compost stability and maturity, space availability, origin of raw material and intended use. Open-air windrow piles are the most simple, but require a lot of space and time, as well as produce a pungent odor. One study compared the compost quality results from three different types of windrowed municipal solid waste (MSW) mixed with woodchips as a bulking agent. A turned pile, a turned pile with forced aeration and a static pile with forced aeration were protected from the elements and monitored closely for three months (Ruggieri, Gea, Mompeó, Sayara, & Sánchez, 2008). The researchers observed that low oxygen concentrations can lead to anaerobic activity in the pile, whereas too much aeration can lead to excessive cooling and ultimately prevent optimal decomposition rates from occurring in thermophilic conditions. Forced aeration was observed to result in a higher internal oxygen content, but that correlated to higher water requirements in order to maintain sufficient moisture content. Also, higher organic matter reduction occurred in the turned piles as well as higher levels of stability and maturity. Their findings ultimately concluded that for heterogeneous solid wastes, such as MSW, turning is essential for windrow composting, therefore making forced air benefits negligible (Ruggieri et al., 2008). However, when assessing multiple stabilization bioprocesses including composting, vermicomposting, static windrows, and anaerobic digestion of beef cattle feedlot manure, the practice of storing it in open fields for an extended period of time for subsequent spreading is the least efficient process for material stabilization (Onica et al., 2016).

Another common composting method is in-vessel composting. In-vessel composting eliminates the need for large operation areas and can speed up the composting process by requiring an energy source investment. One in-vessel composting study using MSW implemented an

accelerated composting process by maintaining high temperatures in the system. They found that an in-vessel composting process, in comparison to windrow composting, was more effective at producing a pathogen-free and nutrient rich soil amendment by frequently measuring pilot-scale and bench-scale samples for *E. coli* and *Salmonella* counts (Pandey et al., 2016). The pilot-scale system and bench-scale system are shown in Figure 7.

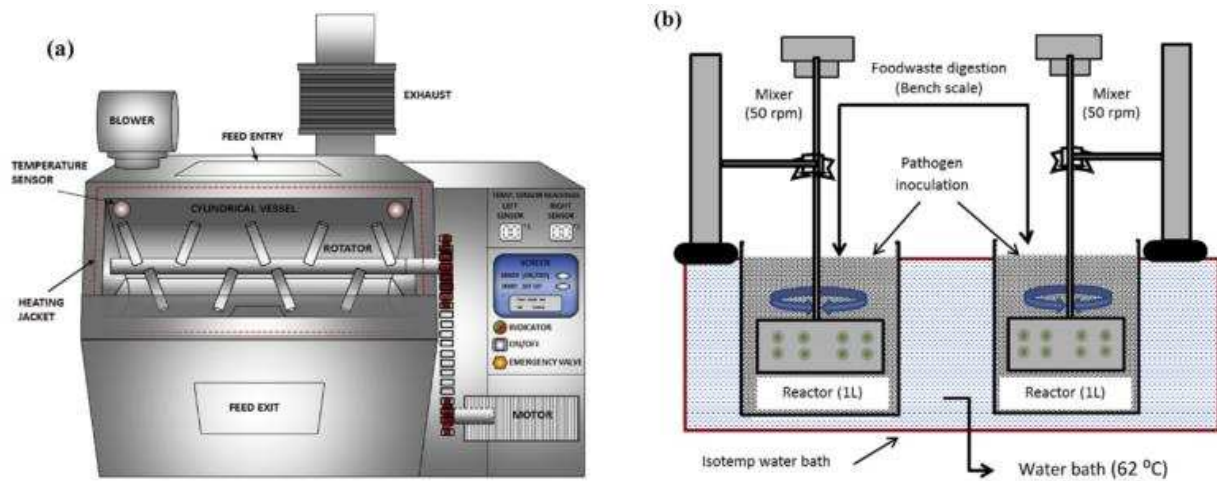


Figure 7 - Schematic of biodigesters used in experiments: a) pilot-scale system; and b) bench-scale system (Pandey et al., 2016)

A second in-vessel study compared the breakdown of solids and stability of the final product of many anaerobic-aerobic scenarios. This was done by using the DiCOM® process to seamlessly switch between anaerobic leachate recirculation and pressurized aeration (Walker, Charles, & Cord-Ruwisch, 2009). They observed that inclusion of an anaerobic phase rather than using aerobic composting solely improved hydrolysis rates, oxidation rates, and product stability. The researchers concluded that the presence of an effective anaerobic phase was more crucial than an extended duration of the aerobic treatment for waste stabilization purposes. However, this process of immediately following an anaerobic phase with an aeration phase in-vessel has not been research further.

2.4.3 Solids Reduction

Further mass reduction during the entire composting process is ideal, but research conducted by Tang, et al. (2006) showed mass reduction of 12-30% after 12-18 months, and most of this reduction was observed in the first month. Therefore, the authors concluded that the maturing process is not an effective means of mass reduction, but more useful for achieving quality instead. Another study combining anaerobic and aerobic digestion of OSW showed total volatile solids destruction of 26% of feedstock. This was seen over the course of a 30 day retention time for the combined system (Kayhanian & Tchobanoglous, 1993). Most solids decomposition was seen in the anaerobic phase and the beginning of the aerobic phase. This is beneficial because most of the organic material gets transformed and released as usable biogas instead of harmful greenhouse gases.

2.4.4 Nutrient Transformation

Organic waste material contains a substantial amount of nutrients; however those nutrients are often in a form that can be inhibiting to plant growth (e.g. ammonia) and are considered contaminants when dissolved in water. There is a lot of biological activity that takes place in the aeration stage aside from breakdown of organic solid material. In fact, the curing phase is crucial for the compost product to be beneficial to plants. During the curing phase an important transition that occurs is nitrification – the process of converting ammonium into nitrate which is a usable form for plant uptake. Properties of compost products can be affected by the conditions prevailing during the maturing process (Tang et al., 2006).

2.4.5 Effects of Bulking Material

The addition of bulking material can have positive effects on the anaerobic degradation process as well as the aerobic composting process. The introduction of bulking material into the hydrolysis reactor with the HSCM achieves a dual purpose. During the anaerobic phase, liquid

flow through solid material is enhanced. In a MSAD with the substrates having >35% TS, digestion during leachate recirculation is difficult to maintain due to the lack of free moving water (Ten Brummeler, 1993). However, adding bulking material to the reactor containing high total solid concentrations assisted in maintaining pathways for leachate flow.

Secondly, during the aerobic composting process, for most of the biological and chemical transformations to take place, the presence of a carbon source is necessary. Addition of bulking materials high in organic matter to the HSCM can assure that a carbon source is present during maturation (Ten Brummeler, 1993). Another study also found the selection of co-composting agents crucial in optimizing the process and improving the quality of the final compost. This study analyzed the solids breakdown and quantity of methane released in a manure-straw mixture. Over the course of a 70 day retention time, a volatile solids reduction of 31.2% was achieved as well as an 18% increase in gas product over batch digesters not containing straw material (Hall et al., 1985).

2.4.6 Effects of Inoculum Addition

While introducing carbonaceous agents to the reactors drastically influences the evolution of the composting process and the final characteristics of the compost obtained, adding an inoculum may have similar benefits. Inoculation is the addition of material containing active biomass acclimated to degradation of the desired material. Inoculated material is an agent by which active microorganisms are introduced to the system. The same manure-straw mixture experiment discussed above also evaluated the addition of inoculum to the system (Hall et al., 1985).

Numerous studies have applied inoculum to the AD phase of solid decomposition and seen higher percentages of hydrolysis and methanogenesis occur, encouraging greater methane production at a faster rate (Hall et al., 1985)(El-Mashad et al., 2006)(Wilson, 2016). However,

little to no research has been conducted on the effects of inoculum addition during the aeration phase.

2.4.7 Composting Anaerobically Digested Material

While there seems to be a significant gap in the literature concerning composting digestate, one research study examined the stability and maturity of compost derived from pig manure (Bustamante et al., 2013). The researchers acquired a solid fraction of the digestate from an industrial digester and placed the material – mixed with different bulking materials - into 350L thermo-composters. The material was turned twice in the 40 day duration of the experiment based on monitored temperature and moisture content. While they discovered that high salinity and the abundance of copper and zinc were the most limiting factors for the use of the compost in agriculture, Bustamante et al. (2013) concluded that composting digestate is a viable method to manage wastes and reduce potential contamination when land applied.

2.5 Current Land Application Standards

2.5.1 Composting Standards

The process of determining what makes high quality, non-toxic compost has developed rapidly over the last few years. While many European government agencies have clearly defined standards for compost products and their use, the United States does not. The only government document stipulating requirements to be met is the Environmental Protection Agency's (EPA) Code of Federal Regulations Title 40, Part 503, Appendix B, Section B that defines the process to further reduce pathogens in compost-quality products. However, the US Composting Council has a publication containing a list of acceptable compost test methods called the "Test Method for the Examination of Composting and Compost" (TMECC). It was created to assist industrial compost producers and purchasers in determining the suitability of the compost in question.

Despite the lack of federal government regulations, state governments have stepped in with requirements and the industry itself has developed its own acceptable guidelines. A group of stakeholders in the Rocky Mountain region developed a “Compost/ Soil Amendment Classification” table a few years ago (Table 1; Adriane Elliot, personal communication, October 18, 2016). These classification standards are a result of evaluating three basic areas: analytical indicators, manufacturing process, and appropriate application based on risk of use. While no certification is produced, the clear answers outlined in response to these three areas offer a lot of insight on how to best use the compost product at hand.

Table 1 - Compost / Soil Classification Standards

Rocky Mountain Region COMPOST/SOIL AMENDMENT CLASSIFICATIONS

There is no implied warranty or product performance guarantee associated with this Classification System

	CLASS I Fully composted, stable, mature product	CLASS II Fully composted, stable mature product	CLASS III Semi-composted dehydrated product	CLASS IV Non-composted feedstock product
Minimum Stability Indicator (Respirometry)	Stable to Very Stable	Stable	Unstable to Moderately Unstable	Unstable
Maturity Indicator Expressed as AmmoniaN / NitrateN Ratio	< 4	< 6	N/A	N/A
Maturity Indicator Expressed as Carbon to Nitrogen Ratio	< 12	< 18	< 25	N/A
Maturity Indicator Expressed as Percentage of Germination / Vigor	80+ / 80+	N/A	N/A	N/A
pH – Acceptable Range (1:5 by weight)	6.0 - 8.4	6.0 - 8.4	6.0 – 9.0	N/A
Soluble Salts – Acceptable Range (1:5 by weight)	0 - 5 mmhos/cm	5 - 10 mmhos/cm	< 30 mmhos/cm	N/A
Testing and Test Report Submittal Requirement	STA / TMECC	STA / TMECC	STA / TMECC	Primary & Secondary Nutrient Testing
Chemical Contaminants	Meet or exceed US EPA Class A standard, 40 CFR 503.13, Tables 1& 3 levels	Meet or exceed US EPA Class A standard, 40 CFR 503.13, Tables 1& 3 levels	Meet or exceed US EPA Class A standard, 40 CFR 503.13, Tables 1& 3 levels	N/A
Bulk Density; % Inorganics; % Moisture; Particle Size Distribution, Primary, Secondary Nutrients; Trace Elements; Organic Matter Expressed in Percentage and Pounds Per CY	Must Report	Must Report	Must Report	Must Report
Pathogens	Meet or exceed US EPA Class A standard, 40 CFR 503.32(a) levels	Meet or exceed US EPA Class A standard, 40 CFR 503.32(a) levels	Meet or exceed US EPA Class A standard, 40 CFR 503.32(a) levels	N/A
Minimum Manufacturing Production Requirement	Each composting facility must be fully permitted by the Colorado Department of Public Health and Environment or their appropriate state agency. If it is exempt from state permitting requirements, it will certify that it follows all guidelines and procedures for production of compost meeting EPA 40 CFR 503.13 requirements for production and marketing of Class A material for unrestricted use and distribution. Written certification from manufacturer is required.			
Applications <i>Note: The listed applications for the various compost class designations are intended for general consideration purposes. The actual use or application of any class of material can be subjective depending on the soil characteristics, quantity used, the method of incorporation, and other factors utilized by the buyer or user.</i>	Horticultural, Nursery, Container Mixes, Turf, Sod, Seed Bed Preparation, Raised Garden, Vegetable Gardens, Top Soil Blends, Backfill, Erosion Control. Watering to leach excess salts not required. Can be applied at high volume. Incorporation can be at shallower depths.	Turf, Sod, Seed Bed Preparation, Raised Garden, Vegetable Gardens, Top Soil Blends, Backfill, Erosion Control. If possible, incorporate at least 60 days prior to planting and water thoroughly before and after planting. Incorporation is important.	Crop production, Turf and Top Soil blends with limitations. Backfill, Erosion Control, Mulch. If possible, incorporate at least 90 days prior to planting. Deep incorporation and thorough mixing very important.	Agriculture
Best Management Practices (BMP) <i>(How the compost is applied and incorporated; effect on performance of product.)</i>	The BMP used by the buyer, user, or applicator will effect the performance of products and also the applications for any product. BMP's will also affect the risks regarding plant germination and vigor associated with the use of soil amendments and compost			
Incorporation Notes	Can be used as a high percentage of the soil profile. Incorporation not critical (top 4" recommended).	Should not be used as a high percentage of the soil profile (30% max). Incorporation in top 6" recommended.	Cannot be used as a high percentage of the soil profile (15% max). Incorporation in top 8" or more recommended.	Cannot be used as a high percentage of the soil profile. Incorporation in top 10" or more recommended.

R.2.16.D6

The Rocky Mountain Region “Compost/ Soil Amendment Classifications” lists five maturity and stability indicators as being the top parameters of interest when classifying compost – ammonia as nitrogen : nitrate as nitrogen ratio ($\text{NH}_4\text{-N}:\text{NO}_3\text{-N}$), carbon : nitrogen ratio (C:N), soluble salts, pH and percentage of germination / vigor. The ratio of $\text{NH}_4\text{-N}:\text{NO}_3\text{-N}$ should decrease substantially as the compost matures, especially if digestate from an anaerobic process is the starting material, because in the presence of excess oxygen, the reduced forms of nitrogen are quickly oxidized into nitrate; a form of nitrogen that plants can uptake. A ratio of less than 4, and ideally less than 1, is an indication that the material has reached the end of the composting process (USDA NRCS, 2011). The C:N ratio is a parameter used to determine if compost is nitrogen stable. Having a lower C:N ratio is also important in providing nutrients to the soil for plant uptake (USDA NRCS, 2011).

Soluble nutrients such as potassium and calcium account for most of the salinity in compost products; however, high levels of sodium are detrimental to plant growth. Maintaining a soluble salt content below 5 mmhos/cm keeps various salts ions at a favorable level for plant growth (see table 1 above). The sodicity of soils and composts is measured by the sodium adsorption ratio (SAR). The SAR is the ratio of sodium to calcium and magnesium. Soils exhibiting greater than 13 SAR are considered high in sodium. Colorado soils average around 1.5 SAR (Azar, Carlson, Durnford, & Stromberger, 2012). Compost high in sodium needs to be managed carefully to avoid over application to the soil. Compost microorganisms operate best under neutral to slightly acidic conditions which correlate to a pH range of 6-8.4 (see table 1). The percentage of germination / vigor reports optimal conditions for growing seedlings. The Solvita Maturity Index (SMI) test can be conducted to evaluate the CO_2 respiration and NH_3 volatility which indicating the maturity of the compost (Woods End Research, 2002). The state of Colorado has also

officially recognized the SMI as an appropriate quick, on-site evaluation of compost. Also, a research assessment of various stability tests, including Solvita, determined that all of the ‘quick tests’ of compost maturity provide suitable results for compost producers and buyers (Brewer & Sullivan, 2008).

2.5.2 Stability and Maturity

For waste material to be applied to land, it should be of high quality. It must be safe for contact with humans, animals, plants and the environment, and it should also be beneficial for soil health. The ideal compost product should be free from pathogens, contain acceptable levels of trace elements, and have limited amounts of organic contaminants. In other words, it must be sufficiently stable and mature. While the terms ‘stability’ and ‘maturity’ are often used interchangeably in literature, a slight distinction can be made and applied to the parameters that define each term. Stability refers to the degree of organic matter decomposition; so a stable compost material would resist further decomposition (Wichuk & McCartney, 2010). Maturity, on the other hand, refers to the readiness of the compost for a particular end use. A mature compost will not cause adverse effects when applied to plant-growing media (Wang et al., n.d.; Wichuk & McCartney, 2010).

A variety of issues may arise if the compost is unstable or immature. Instability may lead to large temperature fluctuations in the material and continued production of flammable gases, such as CO₂ and NH₃. Continued decomposition is a sign of an immature product and results in odors and potential toxicity to plants from high levels of ammonia that can lead to oxygen depletion of the soil. Ultimately unstable, immature compost is capable of carrying pathogens and contaminating ground and surface water, while having adverse effects on plant growth (Wichuk

& McCartney, 2010). For these reasons it is necessary to reliably evaluate compost samples for maturity and stability.

The tests associated with measuring the stability and maturity of compost varies greatly. There are a number of analytical methods that are widely accepted and used. One published study set out to predict the potential for plant growth in compost-amended potting mixes by performing compost characterizations and bioassays on windrow composting samples consisting of dairy manure with wheat straw compared to dairy manure with sawdust (Wang et al., 2004). This study considered a variety of parameters including temperature, pH, moisture content, conductivity (EC), percent volatile solids (VS%), organic carbon (C), C:N, total nitrogen (N_{tot}), $NH_4-N:NO_3-N$ and SMI. They determined that the most useful compost characteristics to predict plant growth for the dairy manure with wheat straw compost were (in decreasing order) C:N, EC, SMI, Solvita CO₂ index (part of the SMI test), ash content, N_{tot} , and organic C. For the dairy manure with sawdust compost the most useful characteristics were EC, SMI, and total nitrogen (Wang et al., 2004).

A recent study set out to determine the best methods for measuring compost stability and maturity while considering whether an acceptable stand-alone test exists (Wichuk & McCartney, 2010). The parameters the researchers assessed in detail included all of those mentioned above in the work of Wang et al. (2004), as well as a wide range of respiration measurement techniques: oxygen uptake, carbon dioxide evolution, Dewar self-heating, and Solvita. Their conclusion was that if a single method had to be chosen for stability, a respirometric test would be recommended because respiration indices are well-established and not dependent on feedstock materials (Wichuk & McCartney, 2010). For maturity evaluation, Wichuk & McCartney (2010) encouraged bioassays – the process of growing a species of plant with the compost in particular

types of soil - as the most effective, but recognized that this method takes more time and resources. Ammonium values and the $\text{NH}_4\text{-N}:\text{NO}_3\text{-N}$ can be very telling as well.

Therefore, there is not one stand-alone parameter that can predict the stability and maturity of a compost product. There are a number of variables that come into play like type of waste material, the inclusion of other organic materials, time, and intended use. However, it seems that a measurement of respiration as well as noting the change in concentration and form of carbon and nitrogen in the material can be very useful in predicting how stable and mature a compost product is.

2.5.3 Plant Available Nutrients

The end purpose of composting is to have a useful product to apply to the land that will improve soil quality and stimulate plant growth. Making sure the compost is stable and mature is one way to ensure useful application, but being aware of the amount of nutrients it contains is just as important. While some plants are more particular than others, most desire large amounts of nutrients present in specific forms and low amounts of salt. Having an understanding of the nutrient content in the compost and the most efficient form of uptake can promote maximum benefit to the plants and surrounding soil.

The three nutrients plants need in the greatest quantities are nitrogen, phosphorous and potassium. Nitrogen is an essential component of amino acids, nucleic acids and chlorophyll; therefore, plants receiving a sufficient amount of nitrogen will grow more quickly and exhibit a higher rate of photosynthesis. While there are many forms of nitrogen that exist naturally, plants up-take nitrogen in the forms of ammonium (NH_4^+) and nitrate (NO_3^-) (R. M. Waskom & Bauder, n.d.). In general plants absorb phosphorus in the form of orthophosphates (H_2PO_4^- and

HPO_4^{-2}), but they can also use certain forms of organic phosphorous. Phosphorous is primarily necessary for energy transfer reactions within plant cells (R. Waskom & Bauder, n.d.). Potassium is involved in many enzymatic reactions resulting in transpiration and plant growth. Soluble forms of potassium can be directly removed from the soil by plants.

Conditions of high pH, salinity and sodicity can have adverse effects on the ability of plants to uptake nutrients even if the nutrients are present in sufficient amounts. High pH indicates a basic soil and begins to cause concern at $\text{pH} > 7.8$. A soluble salts measurement can be substituted for EC according to CSU Extension's Fact Sheet No. 0.521, and this measurement of salinity refers to the cumulative presence of various salts ions in the soil (R. Waskom, Bauder, Davis, & Andales, n.d.). A reading of 2-4 mmhos/cm indicates a slightly saline soil, whereas a reading >4 means the soil is saline. The sodicity describes the amount of sodium present in composts and is measured by the sodium adsorption ratio (SAR). The SAR is the ratio of sodium to calcium and magnesium. Soils exhibiting greater than 13 SAR are considered to be high in sodium. Colorado soils average around 1.5 SAR (Azar et al., 2012). Compost high in sodium needs to be managed carefully to avoid over application to the soil.

2.6 Summary

The means and cost of managing animal waste material is causing increasing concern. Anaerobic digestion helps address these concerns by minimizing the solids needing to be disposed of and creating usable energy in the form of biogas as opposed to releasing a large quantity of greenhouse gases. While AD is a widely used method, the required low solids content is often a limiting factor. By using MSAD technology, wastes consisting of a higher solids loading rate can be processed in a shorter amount of time. Introducing a bulking material into the hydrolysis reactor maintains pathways for leachate flow, allowing the enzymes to interact with a greater

amount of substrate material. The presence of inoculum may also play a part in the quantity and rate at which methane is produced (research objective 3, section 1.2).

Aerating the digestate from the MSAD produces other benefits. Introducing oxygen to an oxygen-deficient system encourages different bacteria to thrive and continue to break down solids. It also allows for nitrogen and other nutrients to be converted into a useful form for plant uptake. The amounts of these useful nutrients as well as the absence of pathogens define the stability and maturity of the compost product which is measured best through respiration techniques and bioassays where time and money allow. This compost product can then be land applied according to the classification standards the product meets. The addition of bulking material to the substrate not only assists in consistent leachate flow during the anaerobic stage, but also provides an additional carbon source during compost maturation (research objective 2, section 1.2).

Current methods of composting include windrow composting where the material is open to the elements, with occasional turning, and in-vessel composting where all of the external factors are controlled. If these composting techniques are combined with AD to provide improved waste processing and methane generation, a complete resource recovery could be achieved. MSAD has been demonstrated to be an effective degradation of high solids manure in an LBR; however, immediately transitioning the digestate to an aerobic composting stage has not been well studied. Our primary research objective is to study the feasibility and benefits of this transition in-vessel (section 1.2).

CHAPTER 3: MATERIALS AND METHODS

3.1 Experiment Setup

The purpose of this research was to evaluate the efficacy of an aerobic phase subsequent to the anaerobic phase of digestion in the MSAD technology. The impact of several bulking materials was evaluated in addition to incorporating compost inoculum. To accomplish this, a system was constructed connecting six LBRs to the MSAD in the mobile unit. The MSAD mobile unit is a demonstration of the multi-stage digestion technology fitted in a 8' by 48' insulated transport trailer. It houses one 300 gallon LST, one 300 gallon FF with 30ft³ of BioPortz media (Entex Technologies), a control room, pumps, a gas flare, and two small rooms in the back where the LBRs were set up (Loetscher & Sharvelle, 2016).



Figure 8 - View of the Front of the CSU Demonstration Scale MSAD

Six LBRs were run in triplicate during 'Run 1' and in duplicate for 'Run 2' in order to try more inoculated varieties. Known amounts of representative manure samples and bulking material

were combined and loaded into each LBR. After loading and sealing the LBRs, the material underwent three phases of breakdown: anaerobic digestion (AD), aerobic and curing. During the first 3-week phase, AD, leachate was pumped into the LBRs and distributed along the top. Each column was purged with nitrogen before leachate entered the system. Dissolved organic molecules broken down by hydrolytic bacteria were carried out of the LBRs in the leachate and measured periodically by chemical oxygen demand (COD) testing. The leachate was recycled back through the LST and the FF in the MSAD trailer in order for the methanogenic bacteria to convert the dissolved organic molecules into methane biogas and release it from the system.

For the second phase of the experiment, pressurized air was pushed up into the LBRs. Core samples were taken weekly from each LBR over the course of three weeks. The top cap of the LBRs was removed permanently after week one. The caps were not removed early in case methane gas built up in the room during the transition between phases. Upon completion of three weeks, the LBRs were weighed, sampled, and transferred to a bucket system for the final curing phase. The bucket system was designed to isolate the material and promote the curing process. Curing would not take place in vessel in full scale implementation of the MSAD technology, but ideally in covered windrows. However, given the time and space available, it was not suitable to perform the curing process this way during the study.

For the inoculum study, two runs reported differed in bulking material used and overall purpose (see table 1). The purpose of “Run 1” was to compare the different bulking materials used through all three phases of the experiment and how it assisted or hindered the breakdown of the HSCM. The objective of “Run 2” was to determine the impact inoculum had in the decomposition of material in the aerobic and curing phases. Two LBRs were left unaltered as controls (similar to Run 1), two LBRs had composted inoculum added on top of the

anaerobically digested material and the same amount of inoculum was mixed into the last two LBRs.

Table 2 - Outline of Experiments Conducted

Experiment	Dates of Reactor Operation	Bulking Material in Reactors	Inoculation Method
Run 1	02/29/16 – 04/21/16	Corn Stover (3)	None
		Beanstalk (3)	
Run 2	05/12/16 – 06/26/16	Woodchips (6)	None (2)
			Top (2)
			Mixed (2)

3.2 Substrate Collection and Storage

The cow manure assessed during this digestion analysis was collected from JBS Five Rivers Feedlot (Kersey, Colorado) in early February of 2016. JBS Five Rivers regularly scrapes the HSCM from the sod outdoor pens and piles it into windrows. This means that soil, feed and bedding could be mixed in with the manure. A fairly fresh truck load of HSCM was acquired, dumped outside the Atmospheric Simulation Lab, and covered with a tarp. It was from this pile that the starting material was taken.

3.3 Reactor Construction and Set-Up

The focus of the reactor studies was to evaluate the efficacy of material processing when switching columns to an aerobic phase after the anaerobic phase of operation. Therefore, the columns included only the LBR component of the MSAD and not a fully linked MSAD system. However, if leachate were continuously recirculated through the LBRs, volatile fatty acids would build up hindering process performance. Therefore, leachate for the reactors was pulled from the

leachate storage tank of the mobile MSAD unit (section 3.1). This setup provided a simple way to focus on the LBR components in the columns study without building a completely linked MSAD system for the column study.

Six identical reactor columns were built using clear tubes and plastic caps on either end. The tubes were made of an acrylic plastic and were 2' 8" long with an 8 inch diameter. With the caps in place, there was approximately 2' of space for the material. Each cap, also 8 inches in diameter, consisted of two plastic pieces sandwiching a rubber O-ring (see figure 9 below). Once the cap was put in place and bolted tight, the rubber O-ring created an air-tight seal. The caps used on the top of the columns had five small ports that allowed leachate to distribute evenly over the top of the column and one large port to allow gas to escape the column. The bottom cap had numerous holes on the inside with two main ports on the outside. One port allowed the leachate to drain to the sump and the other allowed pressurized air into the system. Only one of these ports was open at a time. Two different mesh pieces with different size pores were stacked on top of the bottom cap inside the column to prevent the drain holes from clogging.



Figure 9 - Empty Reactors and Caps

Wooden frames were built for each of the six columns and once they were filled with material they were hung on the wall in a small 10' x 3 ½' insulated room in the MSAD trailer. The room in the trailer was chosen because of its close proximity to the already operating fixed film reactor, which the leachate was cycled through. Insulating Styrofoam sheets lined 3 of the 4 walls, thus temperature regulated at 35°C ± 2°C with an industrial space heater. Maintaining the temperature in this range was important to support microbial activity by preventing excess heat loss (Molnar & Bartha, 1988).

During the anaerobic phase of the experiment, leachate was cycled through each reactor column by a Colman-Palmer peristaltic pump at a rate of 20 mL/min (figure 10). Neoprene #18 tubing was used in conjunction with #18 pump heads on one pump and Neoprene #20 tubing was used in conjunction with #20 pump heads on the other pump. The pumps had programmable settings that adjusted to the different diameters of the tubes to maintain identical flow rates. The leachate was pumped out of an operating fixed film reactor from the MSAD and into the top of the LBRs every day, 24 hours a day for three weeks. After passing through the composite material in LBRs, the leachate drained out the bottom and underneath the trailer into the leachate storage tank including a sump (Loetscher & Sharvelle, 2016). From the sump it was pumped back up into the leachate storage tank and through the fixed film reactor completing the circuit.

After the anaerobic phase was complete, the system was switched over to the aerobic phase. This phase transition was determined from a previous set of experiments to be approximately 3 weeks. This optimal time frame was based on COD trends in the leachate as well as previous research. To make the switch to an aerobic system, the pumps were shut off and the leachate already in the LBRs was allowed to drain for 24hrs. After that time, all drain and gas valves were closed, except the top gas out line. The air-in lines were attached and pressurized air from a

compressor in a nearby building was pushed into the bottom of the LBRs at a rate of 5 psi. This aeration phase continued for three weeks. Choosing to run the aeration phase for three weeks was a conservative estimate of time. Organisms work more quickly in the presence of oxygen; however, since the process of switching from anaerobic to aerobic in-vessel is not well studied, three weeks seemed more than sufficient for the full transition. Further studies would determine a more efficient time period for the aeration phase. The lids of the LBRs were left on for the first week to allow proper ventilation of residual methane gas, but were eventually removed.

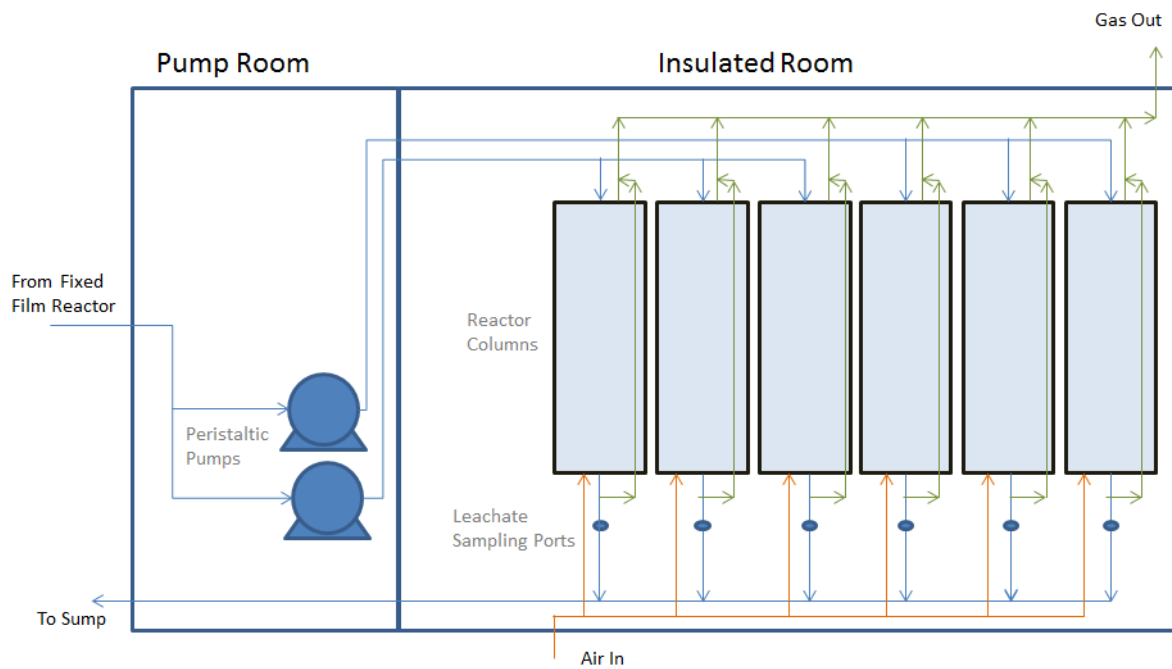


Figure 10 - Flow Diagram of Reactor System

3.4 Loading LBRs

A representative sample of manure exceeding the amount able to fit in all 6 columns was gathered in a large, plastic trough. It was mixed and broken into golf ball size pieces or smaller. Each LBR was filled with 10 kilograms of sample.

3.4.1 Bulking Material Study

Run 1 and the non-inoculated reactors of Run 2 were assessed in the bulking material study (see table 2). Both the corn stover and beanstalk materials were obtained as agricultural by-products (see section 3.4.1.1) and fed through a standard commercial wood chipper (Earthquake, Viper 212cc) prior to mixing with the manure samples. In each reactor column, 5% of the sample by weight consisted of one of two agriculture by-products; meaning 500 grams was thoroughly mixed with 9500 grams of manure by hand and dumped into the reactor column.

The total mass of the material in the reactors were weighed before the anaerobic phase and after the active aeration phase; A cumulative time of approximately 42 days. The mass of reactor material was then multiplied by its respective TS value to obtain its total dry mass (equation 1).

The total dry mass of the bulking material was subtracted from the total dry mass value so that an estimate of TS reduction of the manure material alone could be made (equation 2). Where M_{total} is the total mass of the material, $TS\%_{total}$ is the average measured TS after aeration, M_{bm} is the initial mass of the bulking material added, and $TS\%_{bm}$ is the average measured TS of the bulking material after aeration.

Equation 1

$$\text{Total Dry Mass} = (M_{total} * TS\%_{total})$$

Equation 2

$$\text{Dry Mass of Manure Only} = (M_{total} * TS\%_{total}) - (M_{bm} * TS\%_{bm})$$

To acquire the total volatile mass the total dry mass value was multiplied by the respective VS fraction (equation 3). To calculate the volatile mass of the manure only the dry mass of the bulking material was multiplied by its VS% and subtracted from the volatile mass (equation 4).

Where $M_{total\ dry}$ is the total dry mass calculated in equation 1, $VS\%_{total}$ is the average measured

VS post-aeration, $M_{bm\ dry}$ is total dry mass of the bulking material calculated in the second part of equation 2, and $VS\%_{bm}$ is the average measured VS post-aeration.

Equation 3

$$Total\ Volatile\ Mass = (M_{total\ dry} * VS\%_{total})$$

Equation 4

$$Volatile\ Mass\ of\ Manure\ Only = (M_{total\ dry} * VS\%_{total}) - (M_{bm\ dry} * VS\%_{bm})$$

Calculating the dry and volatile mass of the manure only was important in order to estimate degradation that may have occurred in the manure phase (excluding bulking material) and also to have values to compare to literature. Because minimal research has been conducted on the in-vessel transition between anaerobic and aerobic phases, subtracting the effects of the bulking material from the composition would provide comparable data. However, it is possible that the manure only values calculated led to an over-estimate in the TS% removal values. By subtracting the total TS of the bulking material, it is implying that the entire solids breakdown that occurred was by the HSCM. This is uncertain because a control without bulking material was unable to be run. In calculating the manure only VS% removal, the assumption that all of the bulking material volatile solids (VS_{bm}) were removed in each combined sample might lead to a conservative result. Because of the uncertainty of the VS breakdown for each bulking material in combination with HSCM, subtracting the whole of the VS_{bm} may include VS breakdown that occurred in the manure. Therefore, the actual VS% removal may be higher than reported values, but would lie somewhere between the manure only VS% removal and the total VS% removal.

To obtain the TS and VS% removal values, the total volatile mass of the material post-aeration ($M_{total\ volatile}$) was subtracted from the initial volatile mass ($M_{i, total\ volatile}$) and then divided by the

initial volatile mass (equation 5). This was also done to determine the VS% removal for the volatile mass of the manure only (equation 6).

Equation 5

$$VS\% \text{ Removal} = \frac{M_{i, \text{ total volatile}} - M_{\text{ total volatile}}}{M_{i, \text{ total volatile}}}$$

Equation 6

$$VS\% \text{ Removal of Manure Only} = \frac{M_{i, \text{ volatile}} - M_{\text{ volatile}}}{M_{i, \text{ volatile}}}$$

In order to calculate the dry and volatile mass of the manure only, the assumption was made that there was little to no mass reduction of the bulking material during the anaerobic and active aeration phases. This assumption was based on VS analyses that were performed on isolated pieces of bulking material at each phase. The volatile percent of the material measured is shown in table 3 below.

Table 3 - Bulking Material Volatile Solids Percentages by Mass

	Pre-Anaerobic	Post-Anaerobic	Post-Active Aeration
Corn Stover	84%	85%	83%
Beanstalk	85%	85%	86%
Woodchips	90%	87%	91%

3.4.1.1 Bulking Material

In preliminary experiments no bulking material was mixed in with the manure sample and the leachate pooled at the top of the LBRs as the manure degraded and clumped together. An inch of sand was added to the top of the samples in the next run to help maintain pathways through the

material for leachate to flow, but pooling still occurred. At this point the decision was made to add the bulking material prior to the anaerobic phase to facilitate liquid flow through the LBRs. Most of the bulking material does not substantially degrade during the anaerobic phase (see table 3), so it can still serve as an additional carbon source during the aerobic phase. While this was not the original intent, it seemed to be advantageous to evaluate bulking material addition at the stage of LBR loading as well as during in vessel composting.

The beanstalk and corn stover material were donated to the project by the Agricultural Research Development and Education Center (ARDEC) at Colorado State University (CSU) and the wood chips were donated by Morgan Timber Products (Fort Collins, CO) (see figure 11). However, if used long-term on a larger scale these materials would need to be available locally and at minimal cost.



Figure 11 - Examples of Bulking Material Used

3.4.2 Inoculum Study

Run 2 in table 2 was the inoculum study where all six columns started off identical with 5% by weight of woodchips. After three weeks running anaerobically, the reactor columns were

transitioned to the aerobic phase, but with slight differences. Two reactor columns were left unaltered as controls. A layer of 1000 grams of inoculum was added to the top of the second two columns and a liter of water poured over it to encourage distribution of the active microbial organisms present. The last two columns were dumped out into a plastic trough and 1000 grams of inoculum was intermixed as thoroughly as possible with the anaerobically digested manure samples and returned to the column to be aerated. The inoculum sample mentioned above was obtained from “Oscar”, Colorado State University’s composter in May of 2016. Oscar receives 1200lbs of pulped food waste from CSU dining facilities and horse manure in the ratio of 1:2 respectively each day.

Similar to the previous study, the material in the reactors was weighed before the anaerobic phase and after the active aerobic phase. The total dry mass and total volatile mass were calculated similarly to the bulking material study (see equations 1&3). The dry mass and volatile mass of the manure only was also calculated in a similar manner, except the inoculum material was also subtracted (see equations 7 & 8 below). The VS% removal was calculated using equations 5 & 6 above.

Equation 7

$$\text{Dry Mass of Manure Only} = (M_{total} * TS\%_{total}) - (M_{bm} * TS\%_{bm}) - (M_{inoc} * TS\%_{inoc})$$

Equation 8

$$\begin{aligned} \text{Volatile Mass of Manure Only} \\ = (M_{total\ dry} * VS\%_{total}) - (M_{bm\ dry} * VS\%_{bm}) - (M_{inoc\ dry} * VS\%_{inoc}) \end{aligned}$$

Similar to the bulking material study, the inoculum that was added to the LBRs after the anaerobic phase was assumed not to have substantially degraded over the course of the active aeration phase. This assumption was based on research from similar reactor studies including

food waste that a doctorate student shared via email correspondence (Wilson et al., 2016). The average measured values are shown in the table below.

Table 4 - Inoculum Volatile Solids Reduction in another Experiment (Wilson et al., 2016)

	Pre-Digestion	Post-Digestion
TS	24%	22%
VS	79%	72%

3.5 Curing Method

After the aerobic phase, the digested material was weighed, sampled, and set up to mature further. The samples were placed into a 5-gallon paint bucket (Home Depot) which was then stacked inside a second 5-gallon paint bucket. Both buckets had holes a quarter inch in diameter drilled into the sides at various heights around their perimeter in order to allow air to flow to all parts of the sample (see figure 12). The top bucket with the sample also had holes in the bottom to allow moisture from the bucket below which contained an inch of water. Lids were lightly placed on top rather than securely fastened.



Figure 12 - Curing Containers

These 6 stacks of buckets stood in a small warehouse room for approximately 60 days. The room maintained a temperature of $27^{\circ} \pm 2^{\circ}$ during the curing process. If the curing material was noticeably drying out, water was lightly sprayed on top.

3.6 Sample Collection

Leachate samples and solid material samples were taken regularly throughout the duration of the experiments. Approximately 30 mL of leachate was sampled every 2-3 days during the 3 weeks of anaerobic digestion from the drainage ports of each LBR as well as directly from the fixed film reactor (figure 13). Approximately 100g of solid composite sample was taken from each reactor before the anaerobic phase, during the transition between the anaerobic and aerobic phases, each week during the aerobic phase, and then at the end of the aerobic phase. A $\frac{3}{4}$ " diameter tubular soil sampler (Forestry Suppliers) was used to extract these core samples while the material was in the reactors. Larger samples, approximately 1kg, were taken after the aerobic

phase and after the curing phase. Each of these larger samples was a composite from different area of the reactor or bucket.



Figure 13 – Collecting Leachate Samples from Reactors

3.7 Analytical Methods

Constant laboratory analyses were conducted on leachate and solid samples throughout each stage of the experiment. Leachate analysis, in the form of chemical oxygen demand (COD) testing, was performed on samples from the fixed film reactor as well as the reactor columns throughout the analysis. Total solids (TS) and volatile solids (VS) testing were performed in house throughout the experiment. From each composite solid sample four TS and VS tests were performed. Further extensive compost analysis testing on initial, intermediate and final samples was performed by the Soil, Water and Plant Testing Laboratory at Colorado State University.

3.7.1 Manure and Inoculum Characterization

The analytical characterization for the fresh and digested manure, as well as the inoculum used in run 2, consisted of total solids and volatile solids testing. Both tests were run according to the

standard methods (APHA, 1995). At least four representative samples of each material were tested and averaged.

3.7.1.1 Total Solids

Aluminum dishes were pre-weighed on an analytical balance, and 10-15 grams of material were added to each dish and recorded. The dish with the sample was then placed inside an electric oven to dry at 110°C for 1-2 hours and allowed to cool until the weight stabilized. The final mass of the dish was recorded. The percent mass of total solids (TS%) present per gram of material was determined by the equation below.

Equation 9

$$TS\% = \frac{\text{Weight of sample and dish after drying} - \text{Weight of empty dish}}{\text{Initial weight of sample in dish} - \text{Weight of empty dish}} * 100$$

3.7.1.2 Volatile Solids

The term volatile solids refers to the weight loss of a sample after ignition. The same samples measured for total solids were used in determining the volatile solids of the material. Once the total solid samples were cooled and weighed, they were placed in a 550°C oven for 2 hours.

After the ignition, the remaining fixed solids were weighed and the equation below was used to determine the percent of volatile solids (VS%) of the sample.

Equation 10

$$VS\% = \frac{\text{Weight of sample and dish after drying} - \text{Weight of sample and dish after ignition}}{\text{Weight of sample and dish after drying} - \text{Weight of empty dish}} * 100$$

A representative sample of the bulking material was separated and analyzed for TS and VS at each stage as well; following the same TS and VS procedures above (equations 9 and 10).

3.7.2 CSU Soils Laboratory Testing

Compost quality tests were performed by the Colorado State University Soil, Water and Plant Testing Laboratory. The CSU Soil Lab performed their extensive composting analysis on the HSCM at each stage of the experiment for both runs. The major results of interest include pH, C:N, $\text{NH}_4^+:\text{NO}_3^-$, SMI, percent N_{tot} , percent total phosphorous and percent total potassium as well as soluble salts and SAR.

3.7.2.1 Solvita Maturity Index

Carbon dioxide production and ammonia levels were estimated using Solvita compost test kits (Woods End Laboratory). Solvita is a colorimetric method wherein gel paddles are inserted into a sieved (0.95 cm), enclosed sample. After 4 h of exposure to headspace gases, gel paddle colors are compared to a color chart to determine CO_2 and NH_3 levels. The individual CO_2 and NH_3 levels are used to identify the Solvita Maturity Index, which may range from a value of 1, indicating “raw compost” to 8, or “finished compost” (Woods End Laboratory, 2004).

3.7.3 Leachate Characterization

During the anaerobic phase of the experiment, leachate trickled into the LBRs at a constant rate. Samples of this leachate were taken before and after the LBRs every other day and analyzed for organic content via COD. This is the oxygen equivalent of the soluble organic matter that can be oxidized using a strong chemical oxidizing agent in an acidic medium. The “test N tube kit” from Hach Company – a colorimetric test - was used to determine the COD content of the leachate samples. The accurate values associated with this specific test ranged from 20-1500 mg/L, therefore a manual dilution of 1:10 or 1:20 was often necessary. A blank (DI water) and a 1000mg/L COD standard (Hach COD standard solution, cat. 2253929) were included in each run performed. A 2mL sample was added to each of the Hach vials and inverted several times. The vials were then incubated in a Hach COD Reactor at 150°C for 2 hours. After heating the vials,

they were cooled to room temperature and read using program 435 COD HR on the Hach DR 3900 spectrophotometer. The blank sample was used to zero the instrument before reading the remaining samples. The dilution factor was applied to the subsequent recorded COD values.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Solids Reduction

4.1.1 Bulking Material Study

The bulking material study consisted of two types of agricultural by-products, corn stover and beanstalk, as well as woodchips, each run in triplicate. However, the TS and VS experiments for the woodchip sample had to be rerun at a later date due to equipment malfunctions. Only combined samples had been stored. For this reason there is no standard deviation accompanying the woodchip data in Figures 14-18 below. The reactors containing beanstalk and corn stover had the same initial material, while the woodchips had a separate initial value for the starting material because it was a later run.

The dry and volatile masses were calculated both with the estimated remaining bulking material and without. Figure 14 shows the total dry mass and total volatile mass; this includes the weight of the bulking material in each reactor. Figure 15 hones in on the %TS and %VS removal for each material. All three material compositions show a dramatic decrease in solid material. The %TS removal is relatively even among the three bulking materials, while the woodchips show the greatest %VS removal.

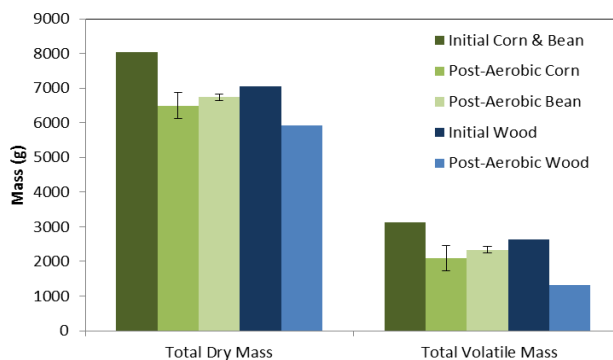


Figure 14 – Initial and Post-Aerobic Total Dry Mass and Total Volatile Mass (Error bars indicate +/- one standard deviation; error bars are not included for the woodchips experiment because the samples were combined before testing)

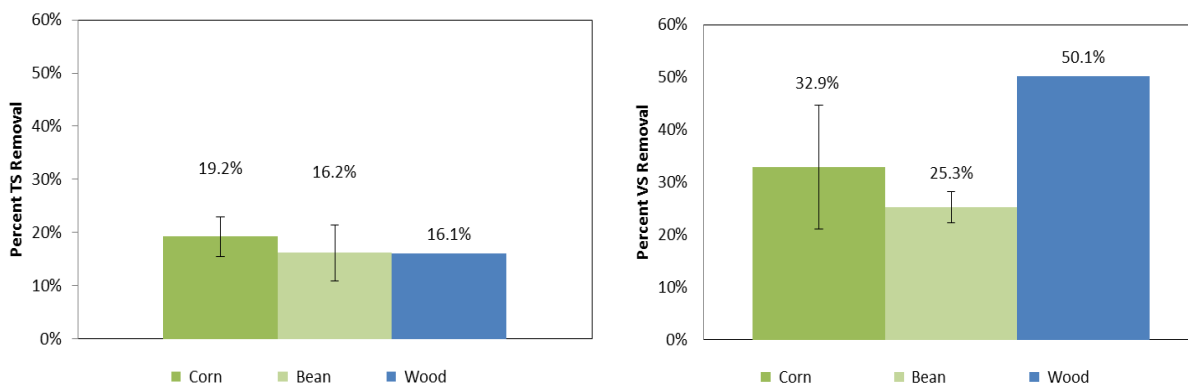


Figure 15 a & b - Estimated (a)TS% Removal and (b)VS% Removal for Experiments with Different Bulking Material through both the Anaerobic and Aerobic Phases (Error bars indicate +/- one standard deviation; error bars are not included for the woodchips experiment because the samples were combined before testing)

Figure 16 below displays the estimated dry mass and volatile mass of the HSCM only for the different bulking materials and Figure 17 displays the TS% and VS% removal. To estimate the total and volatile solids reduction within the manure material only, it was assumed that there was little to no mass reduction of the bulking material during the anaerobic and active aeration phases (see section 3.4.1 for details of this assumption). This assumption resulted in a probable over-estimation of the TS% removal and a conservative estimate for VS% removal. Assuming the bulking material contributed no mass reduction is a best possible estimate for obtaining a manure only value. However, the actual VS% removal may lie somewhere in the middle of the values displayed in Figures 15b and 17b, or higher.

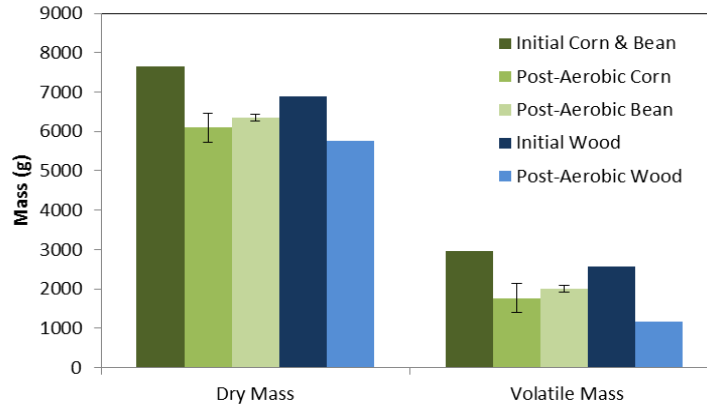


Figure 16 - Initial and Post-Aerobic Dry Mass and Volatile Mass of Manure Only (Error bars indicate +/- one standard deviation; error bars are not included for the wood experiment because the samples were combined before testing)

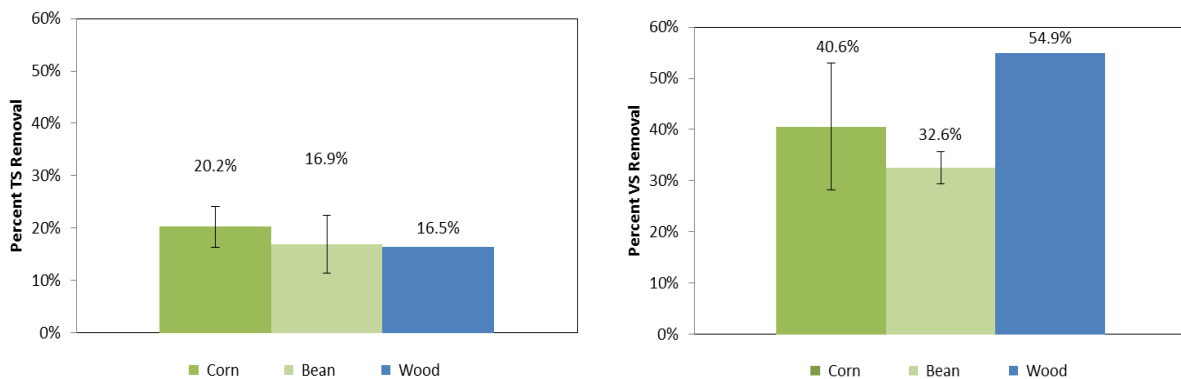


Figure 17 a & b – Estimated (a) TS% Removal and (b) VS% Removal of Manure Only for Experiments with Different Bulking Material through both the Anaerobic and Aerobic Phases (Error bars indicate +/- one standard deviation; error bars are not included for the wood experiment because the samples were combined before testing)

While a notable decrease in VS was observed for all three bulking materials, the reactor with the woodchips showed the greatest removal. One physical reason for this may be because the woodchips were slightly larger in size therefore creating larger pathways for leachate and forced air to flow through. Another could be that the initial HSCM sample contained slightly different biological properties than the sample used in the beanstalk and corn stover run. Also, the chemical composition of the woodchips varies greatly from the other two bulking materials and could have played a role in increasing the degradation of the HSCM. More detailed analysis

would need to be performed to determine the reason the woodchips performed better. Table 5 shows the standard deviation among the numerous replicate samples from each reactor.

Table 5 - Averages and Standard Deviations for Post-Aeration Tested Material by Reactor

	Corn Stover			Beanstalk			Woodchips
	LBR 1	LBR 2	LBR 3	LBR 4	LBR 5	LBR 6	LBR 1 & 2 Composite
Number of Replicates	8	7	12	8	8	8	5
Average TS	0.5137	0.5192	0.5489	0.6687	0.6934	0.6939	0.6647
TS Standard Deviation	0.0426	0.0429	0.0332	0.0397	0.0404	0.0588	0.0063
Average VS	0.3689	0.2947	0.2990	0.4932	0.3800	0.3930	0.2220
VS Standard Deviation	0.0425	0.0559	0.0727	0.0737	0.0574	0.0472	0.0062

A t-test was performed on the total VS% removal values for the corn stover and beanstalk bulking material reactors. Based on the 1-sided equal variance t-test it does appear that mass removal is higher for corn stover at the 95% significance level, $P=0.05$. However, there is nothing in the data that would point to the assumption of using equal variance and 2-sided is needed if detection of corn stover always having greater reduction than beanstalk or beanstalk having greater reduction than corn stover is desired. Therefore, the 2-sided unequal variance t-test performed did not reveal any statistically significant results. This is mostly because the sample size was small. More research is needed before a statistically significant result could be determined reliably.

To gain a better understanding of the process volatile solids reduction throughout the three phases, the VS fraction of material was measured after each phase (see Figure 18). While there is no consistent trend among the three bulking agents, in general, the VS fraction declined steadily from the initial raw sample to the cured compost material. The removal of fixed solids as well as volatile solids through nutrient recirculation could account for some of the inconsistencies in the general trend.

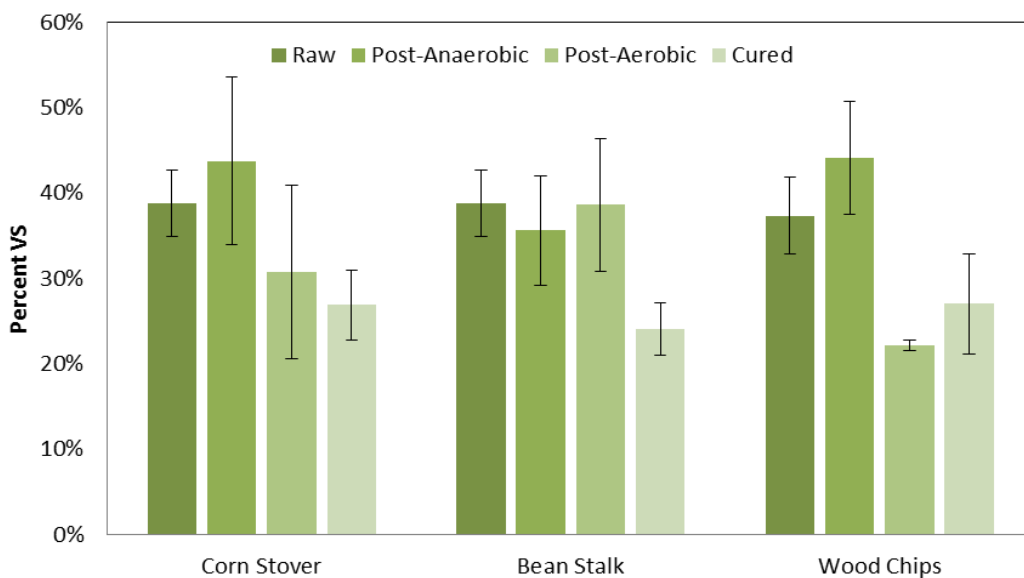


Figure 18 - Percent Volatile Solids Present after each Phase

4.1.2 Inoculum Study

The inoculum study was performed to see if active aerobic bacteria from a previously composted sample, containing 1:2 of pulped food waste from CSU dining facilities and horse manure, would make any significant contribution to mass degradation during the active aerobic phase and overall quality of the cured material. A duplicate run of three different inoculum compositions was performed: control (no inoculum), top (inoculum placed on top of digestate), and mixed (inoculum mixed throughout reactor). The total dry and volatile masses calculated are displayed in Figure 19, and the dry and volatile masses of the manure material only are shown in Figure 20.

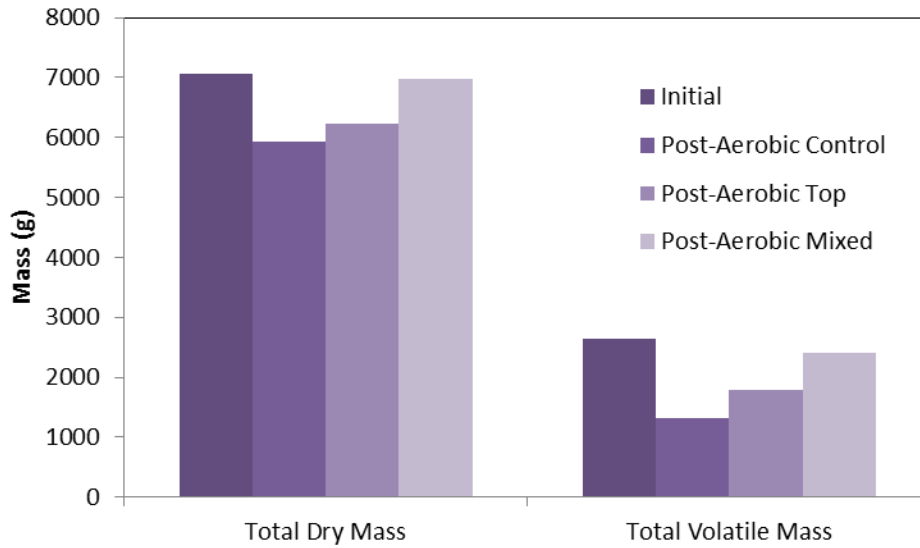


Figure 19 - Initial and Post-Aerobic Total Dry Mass and Total Volatile Mass (Error bars are not included because the samples were combined before testing)

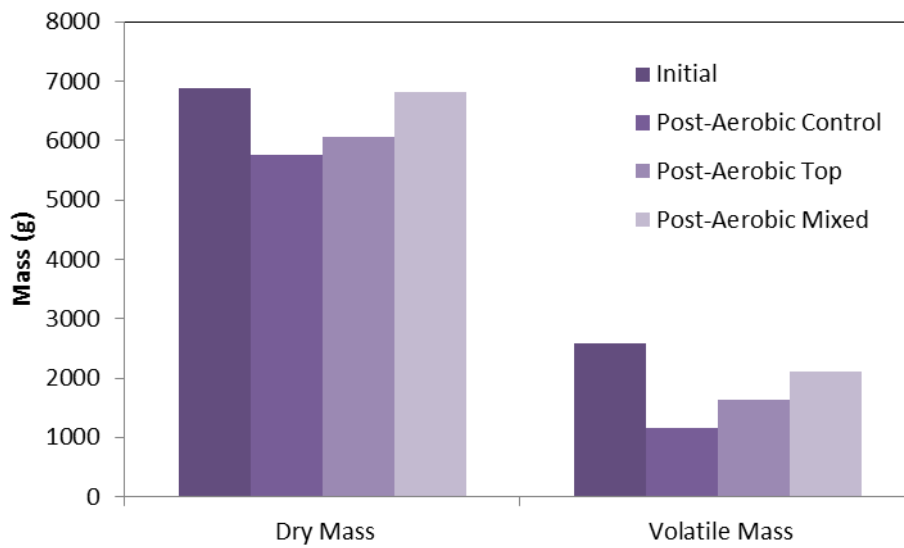


Figure 20 - Initial and Post-Aerobic Dry Mass and Volatile Mass of Manure Only (Error bars are not included because the samples were combined before testing)

The total volatile reduction averages for each reactor type are shown in Figures 21 & 22. While it is clear that inoculum did not assist in the aerobic degradation of solid material, in addition it may have had a negative effect. More reactor studies would need to be run in order to determine

if that is the case. The woodchips bulking material had an expected 5% difference when subtracted; exhibiting no contributing degradation.

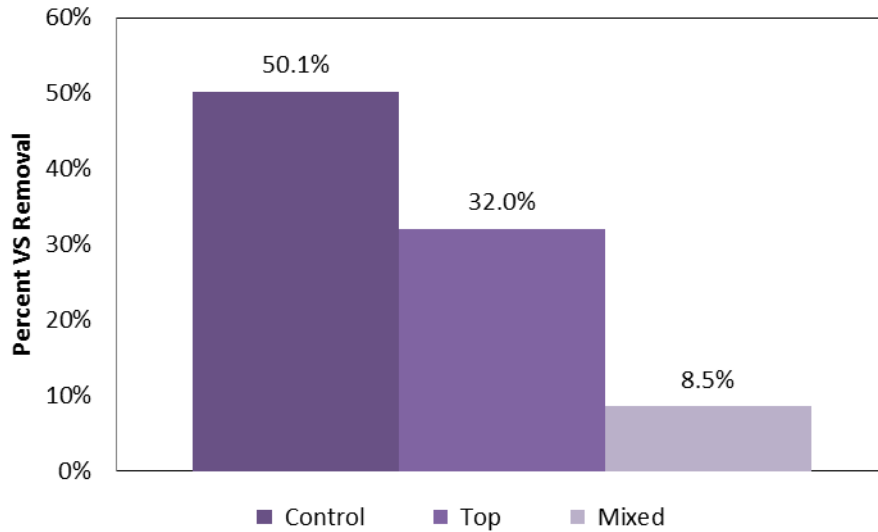


Figure 21 – Total Percent Volatile Solids Removal by Inoculum Composition through both the Anaerobic and Aerobic Phases (Error bars are not included because the samples were combined before testing)

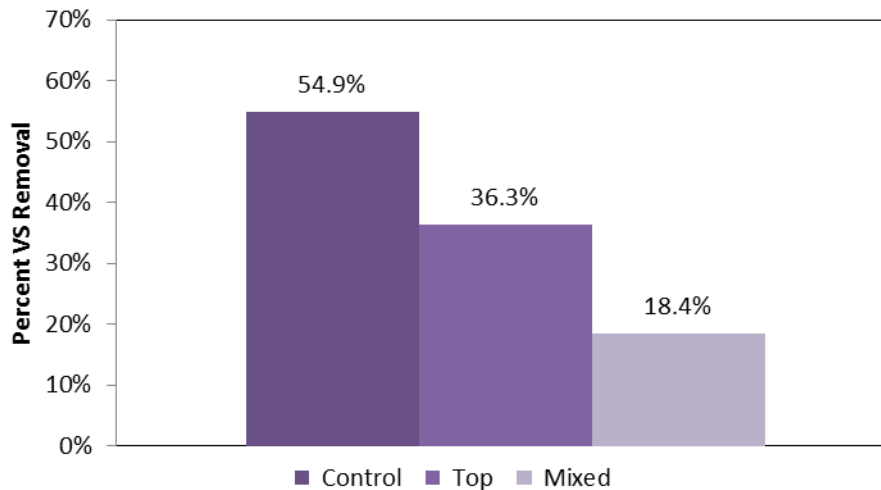


Figure 22 - Percent Volatile Solids Removal by Inoculum Composition in Manure Only through both the Anaerobic and Aerobic Phases (Error bars are not included because the samples were combined before testing)

While in most scientific literature the addition of inoculum plays a significant role in the breakdown of organic material during the anaerobic phase, in this study the inoculum did not seem to make a difference in the degradation of solids during the active aeration phase. One

reason for this may be the type of inoculum that was used. Combined MSW and horse manure compost was readily available so it was used as the inoculum source. However, one study found that it took MSW inoculated bacteria longer to adjust to HSCM material than did inoculated bacteria from the same source (Hall et al., 1985). Another reason could be that compost inoculation has little overall effect on solid degradation, but more research should be conducted before this can be concluded.

Also similar to the bulking material study, the VS fraction of material at each phase was sampled and analyzed as shown in the figure below. Again, there is no consistent trend among the three inoculum treatments, but in general the VS fraction declined steadily from the initial raw sample to the cured compost material; this trend is best seen in the reactors with inoculum on the top in Figure 23. The post-aerobic phase for each composition does not have a standard deviation associated with it because these samples had to be re-run at a later date due to inaccurate temperature settings on the ovens. The aerated material had been composited based on inoculum composition and kept in a sealed container at 4°C.

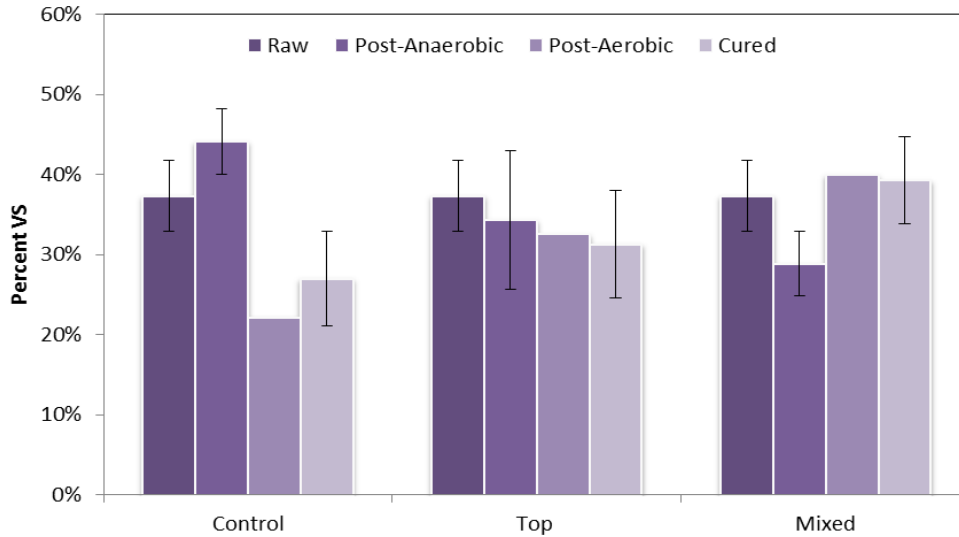


Figure 23 - Percent Volatile Solids Present after each Phase (Error bars indicate +/- one standard deviation; error bars are not included for the post-aeration experiment because the samples were combined before testing)

4.1.3 Anaerobic Degradation

Unfortunately, due to the nature of the reactor setup, weighing the material in the LBRs between the anaerobic and active aeration phase was not feasible. Therefore, in order to make sure that degradation was taking place during the anaerobic phase, COD values were analyzed on the leachate leaving the LBRs and leaving the FF reactor (just before being pumped into the LBRs). These COD values indicated the amount of soluble organics in the system. Figures 24a and 24b show the initial leachate COD levels (sampled post-FF reactor) and the averages for each LBR correlating to different bulking material (sampled post-LBR). The COD averages of each bulking material spiked early on in the run indicating that there was more available organic material able to be broken down and solubilized than at the end of the three week run where the initial and average were about the same. This shows that there was indeed some break down of material during the anaerobic phase even though the total dry and volatile mass of the digestate was not able to be calculated.

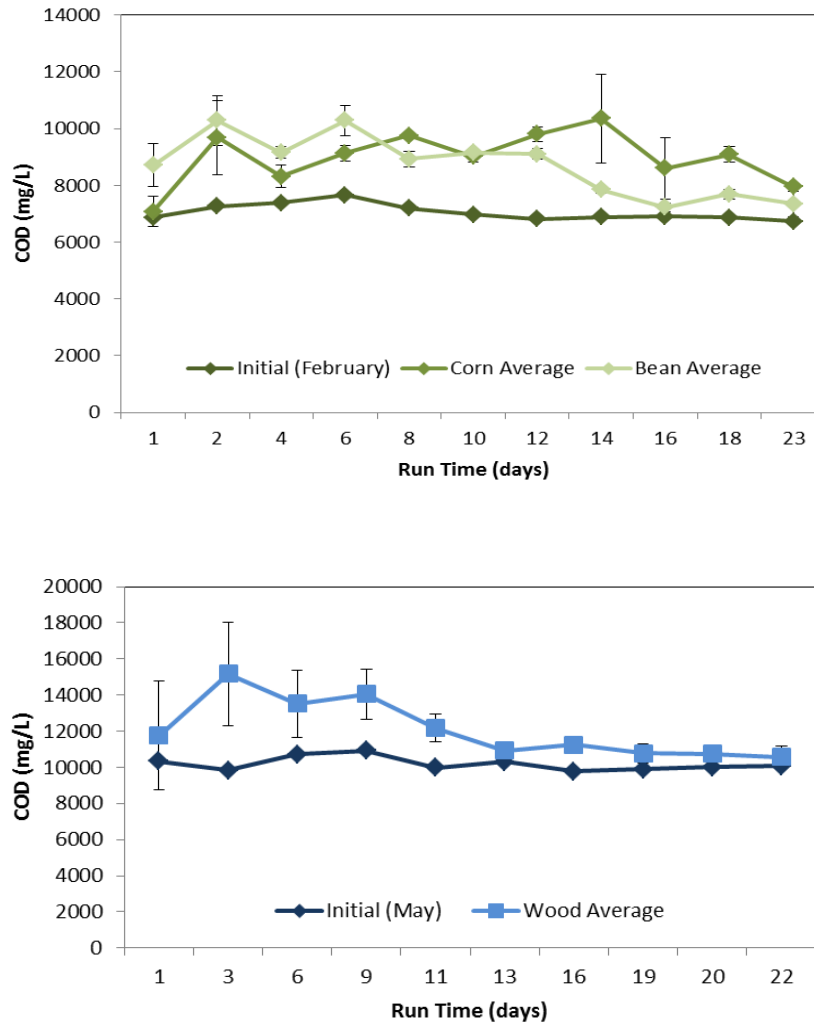


Figure 24(a & b) - Initial and Average Chemical Oxygen Demand Measurements during Anaerobic Phase

4.2 Compost Quality

4.2.1 Stability & Maturity

Knowing the quality of compost product produced is imperative to determining its use. The Rocky Mountain Region “Compost/ Soil Amendment Classifications” table (section 2.5.2) lists three maturity indicators - ammonia-N : nitrate-N ratio, C:N, and percentage of germination / vigor – as well as pH and soluble salts as being the top parameters of interest when classifying compost. Four of the five parameter results from the bulking material study are displayed in Figure 25 below. The upper limits of the analytes are indicated by a solid line and the pH range

is boxed. All three cured materials consisting of different bulking materials met the range requirements for all four parameters – $\text{NH}_4^+\text{-N}$: NO_3^-N , C:N, pH and soluble salts. Meeting the Class I requirements demonstrates a fully composted, stable and mature product.

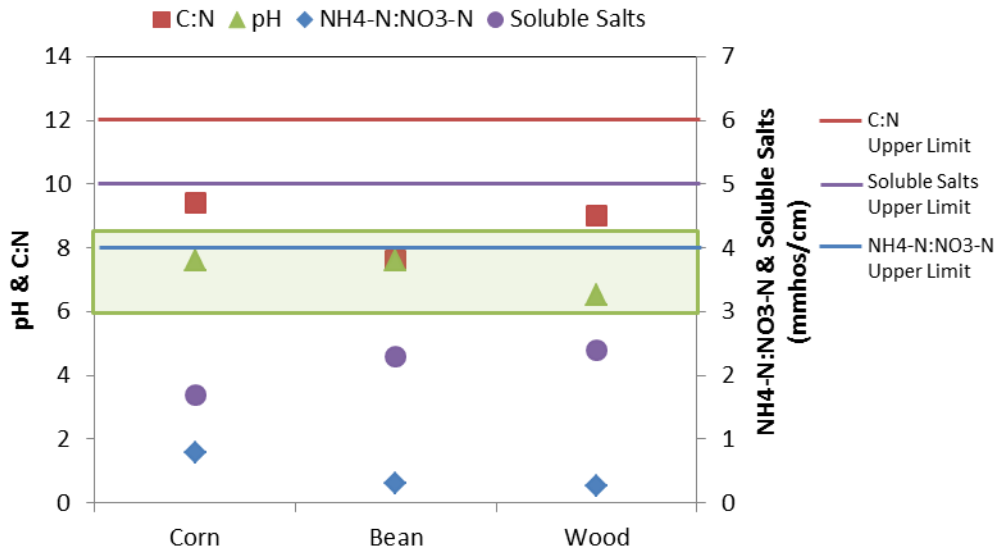


Figure 25 - Bulking Material Study Meeting Class 1 Composting Requirements

A similar figure (Figure 26) was constructed for the inoculum study. In this study all three inoculum treatments met the ceiling limit or range requirement for a fully, composted, stable and mature product.

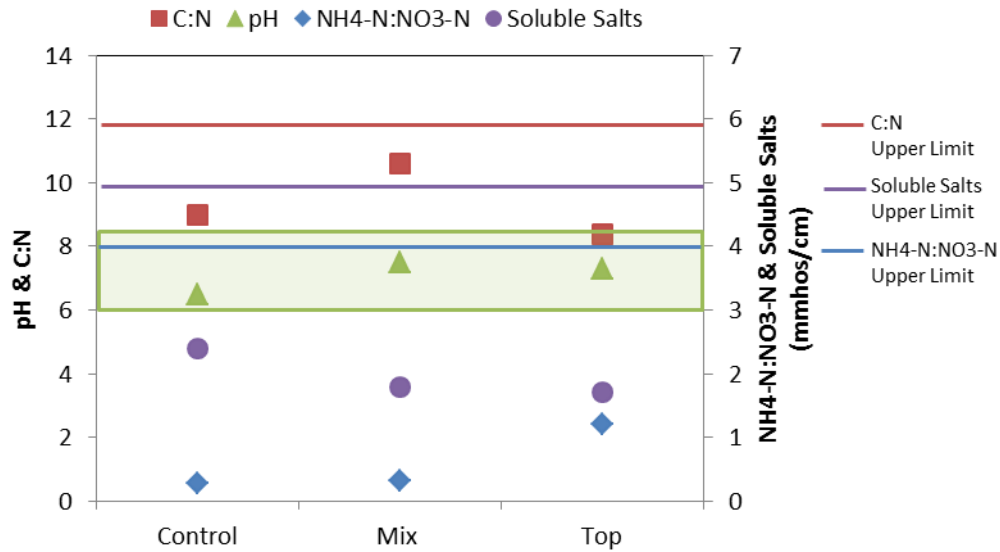


Figure 26 - Inoculum Study Meeting Class 1 Composting Requirements

With the Rocky Mountain Region “Compost/ Soil Amendment Classifications” upper limit of $\text{NH}_4^+\text{-N: NO}_3^-\text{N}$ being 4, Table 6 shows the necessity of the curing phase. During the curing phase, nitrification continues to take place oxidizing the ammonium to nitrate as the material was open to the air.

Table 6 - Comparison of $\text{NH}_4^+\text{-N: NO}_3^-\text{N}$ Before and After Curing Phase

	Corn Stover	Beanstalk	Woodchips Control	Woodchips Top	Woodchips Mix
Pre-Curing	29.20	11.64	12.10	11.34	11.86
Post-Curing	0.78	0.31	0.27	0.32	1.20

The fifth parameter was measured by the Solvita® Maturity Index (SMI) instead of the germination / vigor percentage. The SMI is a combination of the Solvita ammonia test result and the Solvita carbon dioxide test results. Figure 27 below, courtesy of Wood Ends Research Lab,

shows where composts may fall based on the measurements in Table 6 (“Guide to Solvita,” 2002).

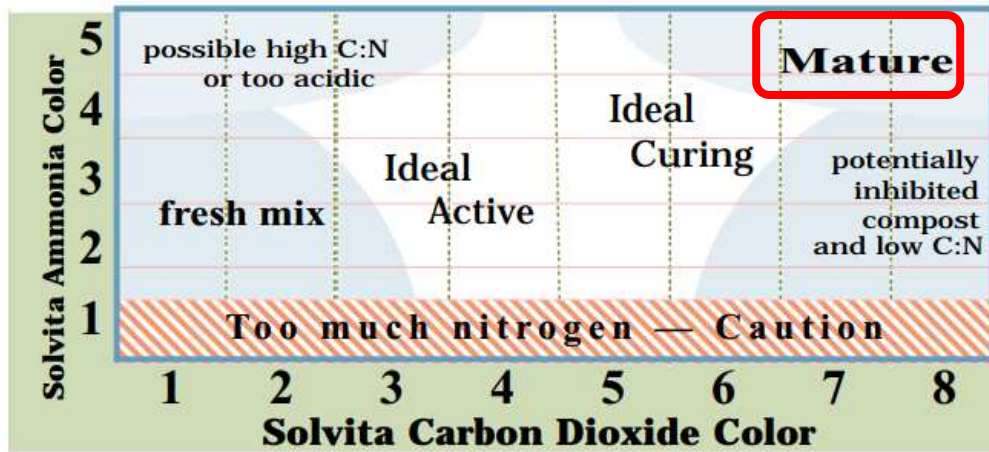


Figure 27 - Interpreting Compost Condition with Solvita Ratings (“Guide to Solvita,” 2002)

Based on the SMI, the Wood Ends Research Lab provides a qualitative description of the compost as well as suggested uses. Table 7 below shows the Solvita ratings of the cured product from each run of the bulking material and inoculum assessments measured. Three of the five cured samples fell in the “finished compost” range and are suggested to be used as a soil mix. The other two cured samples were considered “active/finished” so a different recommended use was given. However, the curing phase could also be extended until these two samples reached a “finished” rating. All fell within the mature region on the SMI range (note the red box on Figure 27).

Table 7 - Solvita Ratings and Interpretations

	Solvita Ammonia Test Result	Solvita Carbon Dioxide Test Result	Solvita Maturity Index (SMI)	Qualitative Description of Compost	Best Use of Compost Based on SMI
Corn Stover	5.00	6.96	7	Finished	Soil mixes
Bean Stalk	5.00	6.85	7	Active / Finished	Compost-soil blends
Woodchips - Control	5.00	7.82	8	Finished	Soil & peat-based mixes
Woodchips - Top	5.00	6.85	7	Active / Finished	Compost-soil blends
Woodchips - Mixed	5.00	7.15	7	Finished	Soil mixes

4.2.2 Nutrient Availability

The three nutrients that plants need in the greatest quantities are nitrogen, phosphorus and potassium. All three of these nutrients were measured in the cured samples for each bulking material and are displayed in Table 8. Producers would need to determine the appropriate application of the compost based on these total nitrogen and total phosphorus percentages. The soil type, aquifer depth and irrigation method used play key roles in minimizing the leaching of nitrates and maximizing crop uptake efficiency (Waskom & Bauder, n.d.).

Table 8 – Average Total Nutrient Measurements by Bulking Material

	Corn Stover	Beanstalk	Woodchips
Total Nitrogen (%)	0.61	0.82	0.66
Total Phosphorous as P (%)	0.29	0.24	0.49
Total Potassium as K (%)	0.37	0.24	0.59

Conditions of high pH, salinity and sodicity can have adverse effects on plants' ability to uptake nutrients even if the nutrients are present in sufficient amounts. High pH indicates a basic soil and begins to cause concern at pH > 7.8. A soluble salts measurement was performed instead of EC and according to CSU Extension's Fact Sheet No. 0.521 the readings are directly

proportional to each other (Waskom et al., n.d.). This measurement of salinity refers to the cumulative presence of various salt ions in the soil. A reading of 2-4 mmhos/cm indicates a slightly saline soil, whereas a reading >4 means the soil is saline. The sodicity of soils and composts is measured by the sodium adsorption ratio (SAR). The SAR is the ratio of sodium to calcium and magnesium. Soils exhibiting greater than 13 SAR are considered high in sodium. Colorado soils average around 1.5 SAR (Azar et al., 2012). Compost high in sodium needs to be managed carefully to avoid over application to the soil. Based on the measured parameters in Table 9, these composts would be considered slightly saline, but overall have a normal physical soil condition (Waskom et al., n.d.).

Table 9 – Averages of the Saline and Sodic Tendency of the Composts

	Corn Stover	Beanstalk	Woodchips
pH	7.6	7.6	6.5
Soluble Salts (1:5, mmhos/cm)	1.7	2.3	2.4
Sodium Adsorption Ratio (SAR)	9.8	7.7	1.8

The woodchips SAR value is so much lower than the SAR value for the corn stover or beanstalk samples. This is concerning because the bulking materials do not contribute a significant source of sodium to the material. It is primarily found in the HSCM in large quantities. This uncharacteristically lower value could be due to physical or chemical affects the woodchips had on the HSCM or a testing error. Further testing would be needed to determine conclusively.

CHAPTER 5: CONCLUSION

The feasibility of degrading and composting HSCM was successfully assessed in this research study. Monitoring the decomposing solid material through three stages provided valuable insight as to how efficiently this process takes place. In the anaerobic phase organic material was successfully digested based on monitoring COD. A period of forced aeration allowed for a faster transition between stages, and the curing phase was necessary for nutrient transformation into a plant-usable form. The length of each of these phases was chosen based on previous research and system feasibility. Optimizing the length of the aeration phase before large scale implementation is necessary to maximize the efficiency of the process and to reduce the amount of energy consumed.

The bulking material mixed in with the HSCM in the LBRs played a crucial role throughout the experiment. During the anaerobic and active aeration phases, the material prevented the HSCM from clumping together in the anaerobic phase and provided air transfer in the aerobic phase. During the curing phase, the bulking material served as an additional carbon source for the oxidation process. The general benefits of bulking material addition were known prior to the experiments above, which is why a control without bulking material was not run. Instead, the objective was to compare the effectiveness of different bulking materials (Section 1.2).

Substantial reduction in total dry and volatile mass during the anaerobic and active aeration phases was seen throughout the different bulking materials, however, the LBRs containing woodchips showed the greatest reduction in VS% (~50%) with corn stalk right behind at just above 40%. In the inoculum study, the reactors without inoculum added at the start of the

aeration phase were perceived to have higher VS reduction than their inoculated counterparts. Early results do not indicate substantial benefit from adding an aerobic inoculum after the anaerobic digestion phase. Based on the widely accepted compost amendment classifications, all of the cured material met the requirements for mature and stable Class 1 compost.

There are some important improvements that could be applied in the future to make this research more relevant. With additional funding and more time, testing for the presence of coliform bacteria at the end of each phase would be informative. Also, running the Solvita maturity index analysis on a weekly basis during the curing phase may result in shortening the time needed for that process. Further research is necessary to determine which crops or plants would adapt well to this type of compost and at what soil-mixture composition.

As the demand for renewable energy sources becomes greater, the more efficient use of water becomes necessary and the need for better animal waste utilization increases, this research technique of aerating HSCM digestate will become more accepted. The additional methane generated by MSAD and bulking material addition offsets energy operation costs. Recirculation of leachate in the system saves on the amount of water needed to encourage solids breakdown and the amount of wastewater needing to be treated post-process. By aerating and curing the remaining inorganic solid material, a land-applied product is manufactured; benefitting not only the plants it supplies nutrients to, but society with better waste management. Environmental benefits include preventing greenhouse gases from being generated and released as well as preventing groundwater contamination from open-air windrowing. While there are still some aspects of the process needing further research, being able to transform HSCM into usable compost by beginning aeration in-vessel is a significant contribution to the environment, to society and to the world.

REFERENCES

- Agricultural Waste Management Systems Part 651 Agricultural Waste Management Field Handbook Chapter 9 Agricultural Waste Management Systems. (2011).
- Arikan, O. A., Mulbry, W., & Lansing, S. (2015). Effect of temperature on methane production from field-scale anaerobic digesters treating dairy manure. *Waste Management*, *43*, 108–113. <http://doi.org/10.1016/j.wasman.2015.06.005>
- APHA. (1995). *Standard methods for the examination of water and wastewater. 19th ed.* American Public Health Association, Washington, DC, USA.
- Azar, M. N., Carlson, K., Durnford, D., & Stromberger, M. (2012). Dissertation Effect of Graywater Irrigation on Soil Quality and Fate and Transport of Surfactants in Soil.
- Brewer, L. J., & Sullivan, D. M. (2008). A Quick Look at Quick Compost Stability Tests.
- Bustamante, M. A., Restrepo, A. P., Albuquerque, J. A., Pérez-Murcia, M. D., Paredes, C., Moral, R., & Bernal, M. P. (2013). Recycling of anaerobic digestates by composting: effect of the bulking agent used. *Journal of Cleaner Production*, *47*, 61–69. <http://doi.org/10.1016/j.jclepro.2012.07.018>
- Chan, G. Y. S., Chu, L. M., & Wong, M. H. (2002). Effects of leachate recirculation on biogas production from landfill co-disposal of municipal solid waste, sewage sludge and marine sediment. *Environmental Pollution*, *118*(3), 393–399. [http://doi.org/10.1016/S0269-7491\(01\)00286-X](http://doi.org/10.1016/S0269-7491(01)00286-X)
- Degueurce, A., Tomas, N., Le Roux, S., Martinez, J., & Peu, P. (2016). Biotic and abiotic roles of leachate recirculation in batch mode solid-state anaerobic digestion of cattle manure. *Bioresour. Technology*, *200*, 388–95. <http://doi.org/10.1016/j.biortech.2015.10.060>
- Drennan, M. F., & DiStefano, T. D. (2010). Characterization of the curing process from high-solids anaerobic digestion. *Bioresour. Technology*, *101*(2), 537–544. <http://doi.org/10.1016/j.biortech.2009.08.029>
- El-Mashad, H. M., van Loon, W. K. P., Zeeman, G., Bot, G. P. A., & Lettinga, G. (2006). Effect of Inoculum Addition Modes and Leachate Recirculation on Anaerobic Digestion of Solid Cattle Manure in an Accumulation System. *Biosystems Engineering*, *95*(2), 245–254. <http://doi.org/10.1016/j.biosystemseng.2006.06.006>
- Fox, P., & Pohland, F. G. (1994). Anaerobic treatment applications and fundamentals: Substrate specificity during phase separation. *Water Environment Research*, *66*(5), 716–724. <http://doi.org/10.2175/WER.66.5.8>
- Guide to Solvita® Testing for Compost Maturity Index. (2002, April). Woods End Research Laboratory, Inc (3.7). http://www.solvita.com/pdf-files/solvita_man3.7.pdf

- Griffin, L. P. (2012). Anaerobic Digestion of Organic Waste: The Impact of Operating Conditions on Hydrolysis Efficiency and Microbial Community Composition, 103.
- Hall, S. J., Hawkes, D. L., Hawkes, F. R., & Thomas, A. (1985). Mesophilic anaerobic digestion of high solids cattle waste in a packed bed digester. *Journal of Agricultural Engineering Research*, 32(2), 153–162. [http://doi.org/10.1016/0021-8634\(85\)90075-7](http://doi.org/10.1016/0021-8634(85)90075-7)
- Kayhanian, M., & Tchobanoglous, G. (1993). Innovative Two-Stage Process for the Recovery of Energy and Compost from the Organic Fraction of Municipal Solid Waste (MSW). *Water Science and Technology*, 27(2).
- Molnar, L., & Bartha, I. (1988). High solids anaerobic fermentation for biogas and compost production. *Biomass*. [http://doi.org/10.1016/0144-4565\(88\)90090-X](http://doi.org/10.1016/0144-4565(88)90090-X)
- Nallathambi Gunaseelan, V. (1997). Anaerobic digestion of biomass for methane production: A review. *Biomass and Bioenergy*, 13(1), 83–114. [http://doi.org/10.1016/S0961-9534\(97\)00020-2](http://doi.org/10.1016/S0961-9534(97)00020-2)
- O’Keefe, D. ., & Chynoweth, D. . (2000). Influence of phase separation, leachate recycle and aeration on treatment of municipal solid waste in simulated landfill cells. *Bioresource Technology*, 72(1), 55–66. [http://doi.org/10.1016/S0960-8524\(99\)00089-9](http://doi.org/10.1016/S0960-8524(99)00089-9)
- Onica, M. ^, Silva De Mendonça Costa, S., Francisconi Lorin, H. E., De Mendonça Costa, A., Cestonaro, T., Pereira, D. C., & Bernardi, F. H. (2016). Performance of four stabilization bioprocesses of beef cattle feedlot manure. <http://doi.org/10.1016/j.jenvman.2016.07.003>
- Pandey, P. K., 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. <http://doi.org/10.1016/j.jclepro.2016.08.034>
- Ruggieri, L., Gea, T., Mompeó, M., Sayara, T., & Sánchez, A. (2008). Performance of different systems for the composting of the source-selected organic fraction of municipal solid waste. *Biosystems Engineering*, 101(1), 78–86. <http://doi.org/10.1016/j.biosystemseng.2008.05.014>
- Sharvelle, S., Keske, C., Davis, J., & Lasker, J. (2011). Guide for Assessing Feasibility of On-Farm AD at Cattle Operations in Colorado. <http://extension.colostate.edu/topic-areas/agriculture/?target=publications#crops>
- Tang, J.-C., Maie, N., Tada, Y., & Katayama, A. (2006). Characterization of the maturing process of cattle manure compost. *Process Biochemistry*, 41(2), 380–389. <http://doi.org/10.1016/j.procbio.2005.06.022>
- Ten Brummeler, E. (1993). Dry Anaerobic Digestion of the Organic Fration of Municipal Solid Waste. *PhD Thesis, Wageningen Agricultural University, Wageningen, The Netherlands*.
- United States Department of Agriculture, Economic Research Service. (2016). <http://www.ers.usda.gov/data-products/>

- United States Department of Agriculture, Natural Resources Conservation Service. (2011). Agricultural Waste Management Field Handbook. <https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/ecoscience/mnm/?cid=stelprdb1045935>
- United States Energy Information Administration, U.S. Department of Energy. (2015). Annual Energy Outlook 2015 with Projections to 2040. [http://www.eia.gov/forecasts/aeo/pdf/0383\(2015\).pdf](http://www.eia.gov/forecasts/aeo/pdf/0383(2015).pdf)
- Veeken, A. H. M., & Hamelers, B. V. M. (2000). Effect of substrate-seed mixing and leachate recirculation on solid state digestion of biowaste. *Water Science and Technology*, 41(3).
- Viéitez, E. ., & Ghosh, S. (1999). Biogasification of solid wastes by two-phase anaerobic fermentation. *Biomass and Bioenergy*, 16(5), 299–309. [http://doi.org/10.1016/S0961-9534\(99\)00002-1](http://doi.org/10.1016/S0961-9534(99)00002-1)
- Walker, L., Charles, W., & Cord-Ruwisch, R. (2009). Comparison of static, in-vessel composting of MSW with thermophilic anaerobic digestion and combinations of the two processes. *Bioresource Technology*, 100(16), 3799–3807. <http://doi.org/10.1016/j.biortech.2009.02.015>
- Wang, P., Changa, C. M., Watson, M. E., Dick, W. A., Chen, Y., & Hoitink, H. A. J. (2004). Maturity indices for composted dairy and pig manures. <http://doi.org/10.1016/j.soilbio.2003.12.012>
- Waskom, R., & Bauder, T. (n.d.). Best Management Practices for Phosphorus Fertilization.
- Waskom, R., Bauder, T., Davis, J., & Andales, A. (n.d.). Diagnosing Saline and Sodic Soil Problems.
- Waskom, R. M., & Bauder, T. A. (n.d.). *Best Management Practices for Nitrogen Fertilization to Protect Water Quality. Colorado State University Extension.*
- Wichuk, K. M., & McCartney, D. (2010). Compost stability and maturity evaluation-a literature review A paper submitted to the Journal of Environmental Engineering and Science. *Canadian Journal of Civil Engineering*, 37(11), 1505–1523. <http://doi.org/10.1139/L10-101>
- Wilson, L. P., Sharvelle, S. E., & De Long, S. K. (2016). Enhanced anaerobic digestion performance via combined solids- and leachate-based hydrolysis reactor inoculation. *Bioresource Technology*, 220, 94–103. <http://doi.org/10.1016/j.biortech.2016.08.024>