THESIS

THE DEVELOPMENT AND DEMONSTRATION OF A MULTIPLE STAGE ANAEROBIC DIGESTER FOR THE TREATMENT OF HIGH SOLIDS WASTES

Submitted by

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ABSTRACT

THE DEVELOPMENT AND DEMONSTRATION OF A MULTIPLE STAGE ANAEROBIC DIGESTER FOR THE TREATMENT OF HIGH SOLIDS WASTES

The semi-arid Great Plains of the central United States is home to numerous high-density, confined animal feeding operations (CAFOs) that utilize outdoor animal pens. These facilities generate a desiccated manure very different from the wastes generated from similar enclosed facilities in other parts of the country. These high-solids wastes present challenges to the conventional digestion systems commonly used on wastes with lower solids contents. Therefore, it was determined that there was a need in the industry for a new technological approach to improve feasibility of the digestion of these challenging wastes.

A first principle design technique was applied to the conceptual design of an innovative technology better suited to such a challenging substrate. This system, named the CSU multiple-stage anaerobic digester (MSAD) technology, is a promising technical alternative to existing AD technologies. The CSU MSAD technology demonstrated the ability to overcome various limitations in previous anaerobic digestion technologies and ultimately demonstrated the ability to be used in the digestion of a wider variety of substrates.

A demonstration-scale CSU MSAD system was constructed and operated for a duration of four months. The demonstration-scale equipment was constructed as a stand-alone mobile pilot lab that could function with various substrates and hydrolysis reactor configurations. In addition to the demonstration of the MSAD system on manure wastes, experiments were conducted on the digestion and inoculation of food wastes. Findings from these experiments

indicated that substrate inoculation became less important as the digestion system operated for a longer duration. Inferring from these findings, it is expected that commercial MSAD digesters will not benefit from substrate inoculation after the system completes a successful startup process.

An analysis of the existing state of the MSAD technology was completed based on review of previous research efforts. To prioritize future research efforts, a modified technology development risk analysis using qualitative scores was applied to development needs of the technology that currently have unknown and potentially risky outcomes. This approach has led to a series of recommended future development efforts for the commercialization of this technology.

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Chapter 1: Introduction

1.1 Research Motivation:

Anaerobic digestion (AD) is a valuable waste management tool for use on various agricultural substrates. Although the technology often requires mechanically complex and capital-intensive equipment, AD can be an energy efficient waste stabilization method. Unlike aerobic stabilization processes, AD generates combustible methane that can be utilized for energy generation. Even so, technical and economic challenges have delayed widespread adoption of this promising technology.

Determining the feasibility of an AD project is a complicated process. A primary factor is the availability of suitable substrates for AD. In many areas of the country, this includes low-solids animal wastes generated on site. A second factor is the market value for the biogas generated from the process. Two common methods of monetizing biogas include 1) gas combustion and conversion to electricity (sold to electricity utilities), and 2) methane enrichment and pipeline injection (sold to natural gas utilities). A third factor that affects project feasibility is the accessibility of suitable methods to dispose of (or treat) the liquid digestate generated from the process. Distribution directly onto farmland is a common disposal strategy. This requires stockpiling the digestate, which can result in odorous emissions.

Although AD is a viable waste management solution for many agricultural producers, there are very few such digesters operating in the semi-arid Great Plains Region of the U.S. This is partially due to unique constraints present in the semi-arid Great Plains, such as climate, cultural practices, and economic considerations which are not present in other areas.

For example, conventional approaches to AD require relatively consistent substrates that have a low solids content (typically <15%). This is a notable issue in the arid Great Plains, where

this technology is poorly suited for treating the prevalent agricultural wastes that are often desiccated and high in solids content. Also, low natural gas and fertilizer values in these areas limit the technology's economic potential.

Although there are numerous approaches to AD that address specific issues, few technologies have effectively addressed the unique challenges present in the semi-arid Great Plains of the U.S. A new technical approach has been proposed that seeks to address the above and other related issues with conventional AD technologies. This approach utilizes a multi-stage reactor system to address each limitation and improve the overall feasibility of AD in the region.

1.2 Research Objectives

Research objectives in this work:

(a) Evaluate the CSU multiple stage AD (MSAD) technology at a demonstration scale.

(b) Compare the MSAD technology to conventional AD technology by assessing key criteria relevant to the digestion of dry-lot manure wastes

(c) Investigate the inoculation of food waste within the leachate bed reactor (LBR) through leachate entrained inoculation or solid substrate inoculation techniques at the pilot/demo scale.

(d) Assess the state of technical readiness of the CSU MSAD technology and prioritize future development activities.

1.3 Thesis Overview:

Dry-lot animal wastes produced from outdoor animal pens are a challenging substrate to digest with existing digestion technologies (Chapter 3). The CSU MSAD system was developed to address issues encountered in the digestion of these wastes (Chapter 4). As part of this research, the MSAD system was compared to existing AD technologies utilized in the

agricultural waste management industry. These comparisons are based on the suitability of the technology to address the complex issues facing organics recycling in this industry (Chapter 3).

As part of this study, a demonstration-scale MSAD system was designed and constructed to be a mobile experimental platform (Chapter 5-6). This demonstration scale equipment was operated on food waste substrate over a four-month evaluation period. The primary technical questions addressed in this study pertained to the inoculation and digestion of food waste in the MSAD system. A summary of past development efforts to date was also provided in an effort to understand the existing technical state of this technology (Chapter 7).

Chapter 2: Background and Literature Review

2.1 Anaerobic Digestion for Waste Management

AD is a powerful waste management tool for agricultural wastes, producing useful outputs such as combustible methane, stabilized liquid effluent rich in fertilizer nutrients, and soil amendments derived from effluent solids (Nelson 2002). Energy derived from the combustion of biogas can be a carbon-neutral source of energy. It decreases greenhouse gas emissions through the entrapment of methane (a potent greenhouse gas) and through the displacement of carbon positive sources of energy both on and off-farm. For some agricultural producers, the most promising benefit of AD is the reduction of odor by more than 50% (Powers 1999).

AD systems are often installed by agricultural producers to solve key issues with their operations. Commonly desired outcomes include odor mitigation, waste stabilization, and improved farm economics. These specific outcomes are enabled through the use of a sealed system that contains the odorous constituents and that serves to collect the generated biogas. As the process operates without the use of any type of aeration, energy costs are limited. Over the duration of this anaerobic process, many organic wastes are reduced through microbial processes into methane. Ultimately, this methane can be combusted to generate energy to power and heat the digestive process as well as the farm.

Facilities that properly implement AD systems find that the process can supply much or all of their power requirements. The process is remarkably energy efficient, with parasitic loads, or power requirements required to run the process, as low as 1.4% for low solids systems (Banks 2011). AD may also reduce wastewater disposal costs by stabilizing and deodorizing waste product. Even though AD solves key issues with agricultural operations, the process is

operationally complex, and expensive to maintain. Issues can arise that can result in operational problems, so AD is not without considerable challenges and risks.

2.2 Biology of Anaerobic Digesters

AD is a biologically mediated process that is remarkably efficient at converting organic molecules into methane. Four groups of largely interdependent anaerobic organisms participate in a complicated ecology that serves to reduce organic molecules to methane and CO_2. Anaerobic pathways, in general, have low energy available for microbial growth (Gerardi 2003). This results in very long generation times (period of time for cellular biomass to double in mass). Generation times for anaerobic microbes are often greater than three days and can range up to as high as several weeks (Gerardi 2003). This is a much lower growth rate when compared to aerobic microbes that can have generation rates many times faster (Gerardi 2003).

AD relies upon communities of microbes to progress the digestion of putrescible substrates. In a properly functioning AD system, four separate largely interdependent groups of organisms make up an ecological system in which all microbial communities must be operating effectively in order to facilitate the complete digestion of the substrate. This multi-tiered metabolic interaction can be classified as an obligate syntrophic system, which is a mutualistic system where the different organism groups are dependent on the generation and removal of metabolites from the system (Morris 2013). This intercommunity metabolic pathway continues until degradable organic compounds are eventually converted into methane.

The first stage is hydrolysis and is carried out by a diversity of microbes responsible for the solubilization of large organic chain molecules. This solubilization results from the depolymerization of complex polymers into simple, more soluble monomers using hydrolytic enzymes. Example monomers from carbohydrate hydrolysis are simple sugars such as glucose and fructose, while proteins are hydrolyzed into amino acid monomers (Gerardi 2003).

Acidogenesis often follows hydrolysis, and it is responsible for the generation of fatty acids from the monomers generated from hydrolysis. Acetogenesis converts volatile fatty acids (VFAs) into acetic acid. Hydrogen and CO_2 can also be produced as products of acetogenesis (Gerardi 2003).

Methanogenesis is the final stage of AD. In it, methane is generated from either VFAs, or a directly from hydrogen, and carbon dioxide, in either one of the two primary methane pathways. Methane (CH_4), a completely reduced carbon molecule, is an ideal waste product for AD as it is sparingly soluble in water. Once it is generated, it leaves the aqueous system as a gas and does not further impact the microbial ecology.

AD is well known for being a temperamental process, and a common cause of this is when these communities of organisms get out of sync with each other and intermediate products begin to accumulate (Labatut, Monitoring of anaerobic digestion process to optimize performance and prevent system failure 2014). Therefore, it is important to understand the microbial ecology of digesters to reduce the occurrence of process upset. Methanogenic inhibition is a common way that process upset is initiated. In general, methanogenic organisms are more sensitive to inhibition than the other three groups of organisms (Gerardi 2003). Ammonia and salinity are common inhibitory agents that have an outsized inhibitory effect on methanogenesis (Griffin 2012). Due to low methanogenic inhibition thresholds, special emphasis is placed on properly sizing digesters to limit the likelihood and severity of upset conditions.

2.3 Technical Approaches to Anaerobic Digestion

There are a multitude of technical approaches to the digestion of organic substrates. Digestion technologies can be classified based on parameters surrounding substrate type, substrate total solids ranges, reactor loading conditions, temperature ranges, and whether the technology type is single or multi-stage (Lewis 2018). As a full discussion of these varied

approaches would be outside of the scope of this work, priority will be given to single-stage vs. multi-stage digestion approaches, conventional technologies suited to on-farm waste management (Chapter 3), and high-solids digestion systems (Chapter 3).

2.3.1 Single and Multi-Stage AD Systems

Single-stage AD systems are the simplest type of AD reactor system. In single-stage AD technologies, a single reactor is home to all four anerobic microbial communities. This is convenient as it allows microbial metabolites to be generated and consumed in the same reactor. However, it can also lead to process instability due to the lack of control of the production and transfer of these metabolites. A common approach to improving the stability of single-stage AD systems is to simply oversize the reactor by a wide margin. This is often an economically appropriate solution since single-stage approaches to AD minimize the surface area to volume ratio of the tank, thus reducing tank and insulation costs. This way also reduces the capital costs of pumps and controls required by AD systems with multiple-stages. This general approach has led to a plethora of single-stage AD technologies that have been implemented at a commercial level. Single-stage technology examples discussed in detail in Chapter 3 are: complete mix, plug flow, up-flow anerobic sludge blanket, fixed film, and batch digesters.

Multi-Stage AD (MSAD) systems seek to overcome limitations to single-stage digesters by separating the process into two or more stages. The majority of MSAD systems are only two stages, with the hydrolysis/acidification processes separated from the acetogenic/methanogenic stages (Ward 2008). These separate stages aid process stability by protecting the more sensitive methanogens from potential inhibition caused by inconsistent organic loading rates. Multi-stage digesters can be more expensive to build, operate, and maintain than single-stage digesters because of the lack of economies of scale and the relative complexity comparatively.

Chapter 3: Anaerobic Digestion of Dry-lot Wastes in the Great Plains

3.1 On-Farm Digesters

Agricultural producers in many regions of the United States have effectively employed digesters for a variety of wastes substrates. Animal wastes remain a primary substrate though, and the digestion of wastes collected from confined animal rearing facilities remains the most prevalent AD substrate from the agricultural sector. Concentrated animal feeding operations (CAFOs) are ideal sites for AD systems as considerable wastes are generated onsite, and AD can help solve key regulatory issues for CAFO operators. Dairy and hog facilities are the most prevalent sites for digestion systems, which is owed primarily to the manure management practices used at these facilities. Many animal feeding operations in the eastern and western United States utilize either wet scrape or flush type manure collection methods. These methods generate a lower solids content waste, which is suitable for use in conventional digesters. Although there is a multitude of approaches to the implementation of AD, AD is generally best suited for the digestion of low-solids wastes (< 15% total solids). Common substrates utilized by on-farm digesters include diluted pig manure, dairy manure, and chicken manure (Figure 1). Un-diluted manure wastes collected from indoor barns or enclosures are also suitable for digestion (Sharvelle 2012). Frequent waste collection is important in these systems, and produces a wet waste that is suitable for digestion.

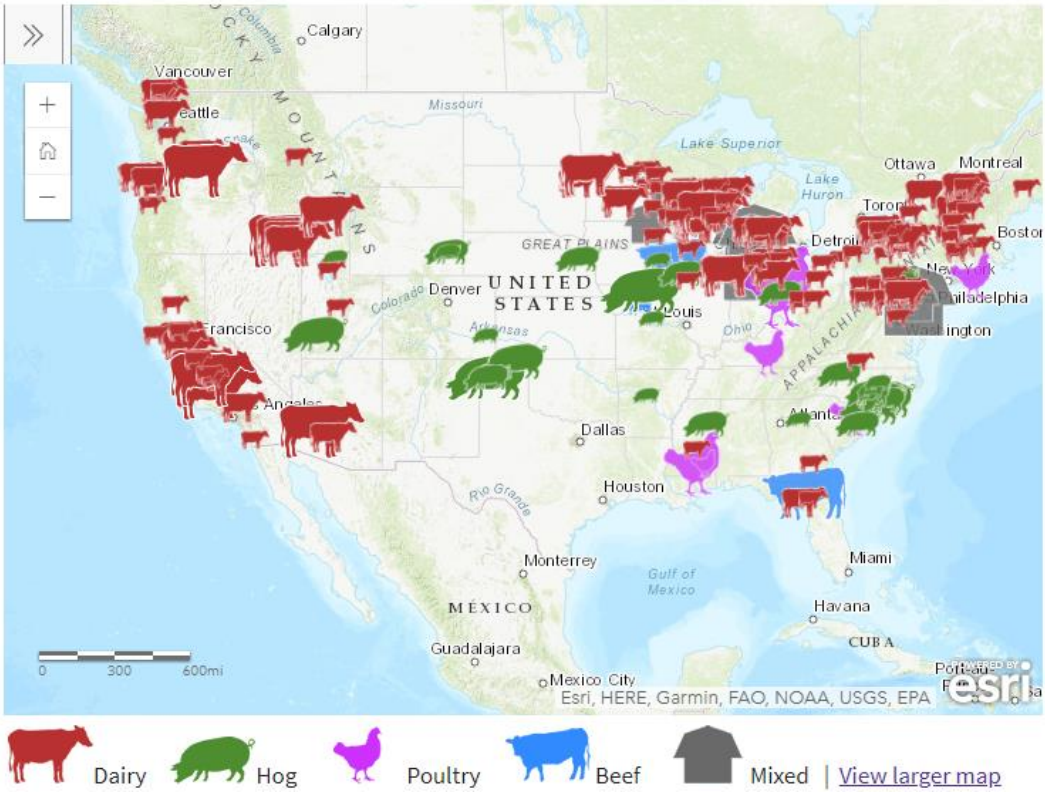

Figure 1: Map of on-farm digesters (EPA 2018).

3.2 Manure Management in the Great Plains Region

It is notable that there are relatively few digesters in the semi-arid Great Plains even though this area is home to many sizable CAFOs. Most of these facilities are cattle feedlots (Figure 2) and outdoor dry-lot dairies.

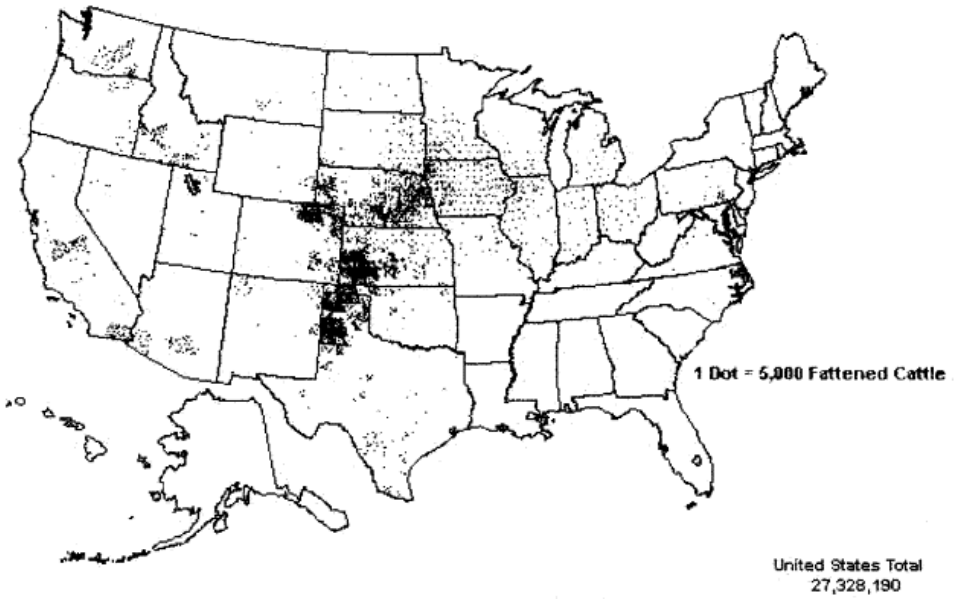

Figure 2: Map of Feedlot Density (National Academies Press 2003).

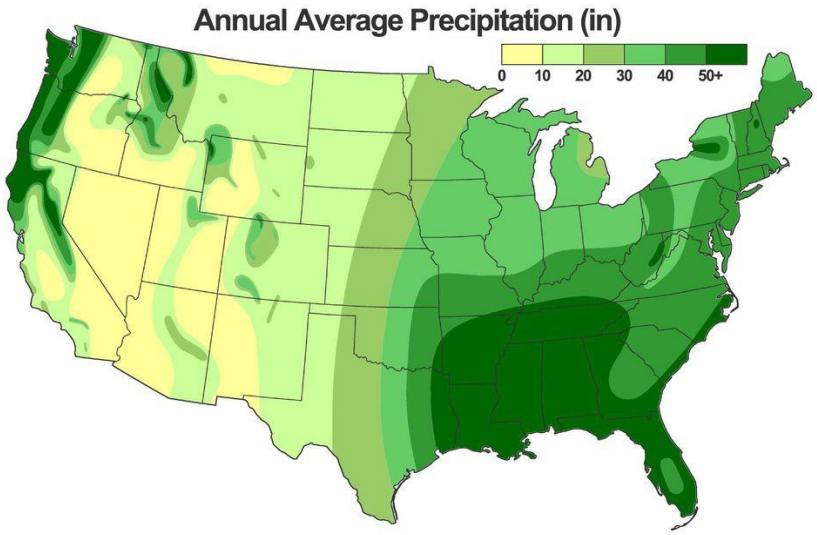

Figure 3: Map of annual precipitation in the US (Renzulli 2018).

The semi-arid Great Plains area of the U.S. is home to a multitude of outdoor dry-lot dairies and feedlots due to its semi-arid climate (Figure 3). The majority of this area experiences less than 30 inches of precipitation per year (NCA 2018). It resides in an area with high solar insolation, with generally mild summers and winters. These climatic conditions facilitate the use of outdoor open lot feeding operations. In these outdoor dry-lot systems, wastes are

predominantly deposited outdoors and desiccated on site. In such a state, wastes are often allowed to accumulate, which allows dry-lot operators to infrequently collect the wastes. The use of heavy equipment such as front-end loaders made for the construction industry expedites the process. The ease of waste collection and the low collection frequencies are obvious benefits to operators as they enable lower labor requirements.

Figure 4. Dry-lot Colorado dairy, dry-lots in the backgrounds, and manure composting windrows in the foreground (photo curtesy of Colorado Correctional Industries)

Outdoor dry-lot wastes are also exposed to the elements such as precipitation events and varying temperatures. Due to these factors, wastes may spend weeks to months in variable states of decay. As such, the original organic matter within the wastes is reduced through:

- Leaching from the waste into runoff from precipitation,
- Biological oxidization into CO_2,
- Low-temperature fermentation producing various organic acids that are volatile as well as readily oxidized by aerobic microbes on the waste's surface,

- And low-temperature AD producing traces of reduced gasses such as H_2S, H_2, NH_3, and CH_4.

These factors reduce the methane potential of each unit of dry matter. However, even with substantial degradation in this process, the desiccation of manure wastes may reduce its weight and yield a manure with a comparatively high methane potential per unit of total mass. Data collected from Colorado facilities show that the desiccated waste still maintains a high energy density (Table 1).

Table 1: Total Solids (TS) and Biochemical Methane Potential (BMP) of Dry-lot Wastes (methods documented in Chapter 5).

Colorado Manure Wastes	% TS	BMP (L CH_4/kg Waste)
Dry scrape dairy manure	53.1	23.2
Fresh collected horse manure	29.9	35.2
Dairy/horse manure	31.3	15.6
Wet scrape manure	18.7	14.0
Dry scrape manure	88.7	15.9
Dry scrape manure w/ straw	78.8	49.5
Diluted Dry scrape	30.9	13.7

3.3 Digestion of High Solids Manure Wastes

In addition to issues encountered with high-solids wastes, dry-lot manure wastes pose additional complexities that may impact project feasibility. Notably, dry-lot wastes are collected from outdoor confinement areas, which leads to a host of variable waste conditions depending on weather and regionally related conditions. Additionally, on-farm manure management practices also may also lead to additional variations in manure quality. These complexities include:

Climate/Regional Related Issues:

- Manure has variable qualities due to seasonal weather patterns,
- Wet manure is much heavier, leading to higher transport costs,

- Dry Manure is challenging to digest,
- Frozen manure leads to collection and handling issues,
- Outdoor wastes can be contaminated with blow sand and silts from neighboring land.

Management and Site-specific Issues:

- During manure collection, gravel and soil can be disturbed from the subgrade soil,
- Collection frequency can be highly inconsistent,
- Precipitation drainage can be variable among feedlots.

These factors lead to the generation of a waste substrate of unpredictable solids contents, methane potentials, and contamination levels. Furthermore, the waste may be collected in frequencies that may overwhelm the capabilities of a digestion system. Based on interviews with animal feeding operations there was considerable unwillingness to modify existing manure management practices to facilitate AD. Waste needs to be moved out when operators see fit. Waste stockpiling is not an attractive option due to site-related capital costs, the operational costs of double loading of the waste, as well as odor generation issues.

The problem of high-solids contents is not easily solved through the addition of dilution water. First, in the semi-arid Great Plains region, ground and surface waters are a precious resource. This creates a complicated societal debate about the dilution of waste substrates with freshwater solely for treatment. Additionally, wastewater generation is a major concern due to the high cost of treating large volumes of dilute wastewater. Additionally, wastewater storage may also lead to odor generation, which can lead to reduced project feasibility due to odor complaints. Lastly, dilution water decreases the viscosity of waste substrates, leading to the settling of sands and gravels within the digester tanks. These settled inert materials require additional machinery to facilitate removal from the process.

Manure management at dry lot dairies and feedlots results in the generation of a desiccated manure, which has lost a portion of its original biogas potential as well as accumulated inert sand and soil. Due to the outdoor source of the collected waste, it has variable characteristics that limit its usefulness. This leads to challenges which restrict the ability to efficiently process this substrate with AD.

3.4 Conventional AD Technologies used for On-Farm Waste Management

AD is utilized on a multitude of farms throughout the world. As of 2018, there are more than 230 operating digesters used to manage on-farm wastes i (EPA 2018). The technologies utilized in these locations are generally operated as single-stage digesters, which means that all four of the AD biological processes happen in the same vessel.

Complete mix digesters are a common digestion technology in wastewater treatment plants. These systems utilize a mixing method (either a motorized paddle, or biogas injection) to stir the reactor, effectively distributing metabolites throughout the reactor, as well as keeping solids in suspension. This strategy is an effective way to improve process reliability, but it requires the process operate at a low solids ranges, often below 10%TS (Sharvelle 2012). Complete mix digesters require significant dilution to be able to process high solids dry-lot wastes, but with sufficient access to low-cost dilution water (and a method to remove settleable inert particles), they can most appropriate digester.

Plug flow digesters are low-rate digesters that rely upon the addition of high viscosity waste substrate to push solids through an elongated (often horizontal) reactor. These systems require consistent substrate viscosity as well as frequent reactor loadings to ensure the system operates at peak performance. With dry-lot wastes, plug flow digesters will struggle to manage the high level of inorganic solids contents and to manage the highly variable nature of the incoming wastes.

High rate single stage reactors, such as the sludge blanket and fixed film digesters, are optimized for maintaining very long microbial retention times. This enables the reactors to accumulate large concentrations of active microbes that serve to enhance digestion rates. However, these high rate digesters all operate at very low solids levels, often this relegates these reactor systems to only being appropriate for the digestion of very dilute agricultural wastewaters.

Conventional AD technologies are utilized by many agricultural operations throughout the world. These technologies, however, are optimized for use with low solids digestion substrates, which are significantly different than dry-lot wastes. When these technologies are applied to the challenging application of dry-lot high-solids wastes, existing technologies are found to be lacking (Sharvelle 2012). Based on these factors a qualitative scoring system for existing technologies was compiled which aided technology comparison (Table 2).

Agricultural producers in the semi-arid Great Plains generally use direct field application, or managed composting, as primary methods of waste disposal. Due to challenges currently found in existing AD technologies, these methods are currently the most appropriate ways to dispose of dry-lot manures (Sharvelle 2012). To further investigate the application of AD for the digestion of dry-lot wastes, other technical approaches used in related industries were investigated.

Table 2: Summarized Results of AD Technology Scoring for the Treatment of Agricultural Wastes

Criteria	Plug Flow	Complete Mix	Fixed Film	Covered Lagoon	Sludge Blanket	Batch Digesters	High Solids MSAD
Digestion of Very Low Solids Wastes (<5%TS)	Non-Feasible	Ideal	Ideal	Ideal	Ideal	Non-Ideal	Ideal
Digestion of Low Solids Wastes (5-10%TS)	Non-Ideal	Ideal	Non-Feasible	Non-Feasible	Non-Feasible	Non-Ideal	Ideal
Digestion of Moderate High Solids Wastes (10-15%TS)	Ideal	Non-Ideal	Non-Feasible	Non-Feasible	Non-Feasible	Ideal	Ideal
Digestion of High Solids Wastes (>15%TS)	Non-Ideal	Non-Feasible	Non-Feasible	Non-Feasible	Non-Feasible	Ideal	Ideal
Digestion Rates at Optimal Solids Ratio	Low	Moderate	High	Low	High	Low	High
Substrate Composition Flexibility	Low	Moderate	Low	Low	Low	High	High
Microbial Retention	Low	Moderate	High	Moderate	High	Low	High
Resilience to Process Upset	Low	Moderate	High	Moderate	High	High	High
System Complexity	Moderate	Moderate	Moderate	Low	Moderate	Low	High

3.5 Relevant Technical Approaches for the Digestion of Dry-Lot Wastes

Conventional AD systems are not appropriate to treat dry-lot wastes. Therefore, high-solids wastes remain a readily available and underutilized resource. High-solids wastes are interesting due to their high energy density and their ability to be transported from offsite locations. This resource potential enables the development of new technology approaches, including implementing technological solutions used in other industries that show promise.

3.5.1 High-Solids Digestion

High-solids wastes are wastes which are generally considered to be outside the range of conventional digestion systems such as complete mix and plug flow digesters. These wastes are classified in this work as greater than 20% total solids by weight, examples of which could be agricultural crop byproducts, dry-lot collected manure (Chapter 4), or the organic fraction of municipal solid wastes (discussed below).

Due to their inherently low water content, these substrates can be more energy dense than low solids digestion substrate. Additionally, the increased viscosity of high-solids wastes facilitates the use of conventional solid waste containment equipment such as uncovered roll-off dumpsters and dump trucks. This leads to high-solids wastes being transported more readily and more economically than low solids wastes, allowing AD facilities catering to high-solids wastes to potentially import wastes from offsite (Fagbohungbe 2015).

AD is a complicated microbial process that involves multiple product/reactant exchanges between different communities of organisms. In a low solids digestion system, these exchanges are facilitated by water that acts as a readily available solvent thereby aiding solution transport within the system (Gerardi 2003). However, in high-solids digestion, the removal of microbial metabolites is limited by lower solution transport. This leads to higher localized metabolite concentrations, lower hydrolysis rates, as well as overall digestion rates (Abbassi-Guendouz

2012). The effect of low solution transport on high-solids digestion rates is well evidenced by its direct impact on hydrolysis rates. This effect can have a pronounced impact on digestion rates of recalcitrant substrates where hydrolysis is already a limiting factor (Noike 1985).

3.5.2 High Solids Digestion Technologies

High solids digestion can take several forms. The simplest form of digestion, batch digestion or dry fermentation is conducted when wastes are simply stored under anaerobic conditions and allowed to ferment. Other more actively managed high solids digestion technologies are seek to improve rates through increased solution transport and microbial inoculation. One such high solids digestion approach is to use mechanical mixers and pumps to mix high-solids wastes within digestion reactors. Another method is to distribute a recycled process liquid called leachate on top of wastes in a percolation-based reactor method.

Batch digesters are digesters that utilize multiple vessels to hold waste substrates during the digestion process. Water can be added to the wastes at the beginning, or wastes can be processed without water addition. In this simplistic process, high-solids wastes can be digested. However, this process is inefficient due to suboptimal digestion rates. At the beginning of the batch digestion process, hydrolytic and acidogenic microbes will dominate. This can cause an overabundance of metabolites toxic to methanogens. In such a sub-optimal condition, anaerobic digestion can often progress, albeit slowly, and methanogenic biomass will increase as the substrate is digested. In batch systems, this valuable biomass is discarded at the end of the process, and the process is restarted with new batches (Fernández 2008). This cyclical growth pattern leads to batch digesters having low hydrolysis and overall digestion rates. Thus, unmodified batch digestion systems are rarely a practical option for the digestion of high-solids wastes, and in the preparation of this document no current technology providers for this technology were able to be found.

Low-solids digesters utilize conventional methods to increase solution transport within the reactor including biogas mixing, hydraulic mixing, and low-power mechanical mixing. However, in a high-solids AD system, water, the primary solvent, is less available. This leads to even greater rate limitations due to poor solution transport. Conventional methods to increase mixing are not appropriate. Due to increased viscosities within the reactor, biogas mixing and hydraulic mixing are often infeasible. Mechanical mixing is still possible, but mixers must be designed to endure the substantial forces that these viscous substrates apply to the mixing shaft (Karim 2005). The DRANCO (DRy ANaerobic COmposting) technology is an AD system provider which markets a high solids mechanically mixed digester utilizing a vertical silo type digester which uses high solids pumps to mix the reactor vessel. Another technology provider, Kompogas, uses a horizontal digester, with a colinear horizontal mixer shaft within it. It is unknown how high-solids mechanically mixed AD systems would operate with the high levels of sand and gravel contaminates within dry-lot manure. These inert contaminates may pose significant challenges for mixing equipment in these digesters.

In addition to mechanical mixing, another method, leachate recirculation, can be utilized to improve solution transport within specially designed reactors (Vavilin 2002). This approach has predominantly been utilized for the digestion of high-solids food wastes and municipal solids wastes, but it has been difficult to implement in the digestion of animal manures wastes due to low hydraulic conductivity of these wastes (Demirer 2008) (Rico 2015).

Leachate recirculation can be an effective way to improve solution transport within porous high-solids waste substrates, like many food wastes. In this method water, or leachate, is distributed onto the top surface of high-solids waste beds where it percolates down through the

waste bed. This percolated liquid, termed as leachate, is used as a solvent to extract and distribute microbial metabolites throughout the reactor.

There are two primary configurations that leachate recirculation technologies take: landfill cell-type systems and garage-style loading bays. Landfill cell loading bays utilize a large outdoor landfill basin that is lined and filled with high-solids wastes. These basins are enclosed with a gas tight cover. Once enclosed, leachate is distributed onto the surface of the waste where it is allowed to percolate through the waste mass. Once the leachate reaches the lowest point in the basin, it is recovered from the bottom of the mass using a pumping system. This pump returns the leachate to the surface of the leachate where it continues the leaching process. Gas is collected within the gas tight cover as it is produced. Variations of the landfill-type digestion system can utilize leachate heating, and pH adjustment of the leachate. Landfill systems which maximize the potential for AD are typically not provided by single companies, but instead are engineered and constructed from components from multiple technology providers.

Garage-style leachate systems utilize an enclosed garage-type bay, which is fitted with a gas tight door. Leachate, typically collected from mature or leachate bays, is distributed through a network of sprayers onto the surface of the substrate. These systems also utilize a pump to recirculate collected leachate to the top of the enclosure (Li 2011). Bioferm and Gicon are two technology providers who offer high solids food waste digestion systems which use leachate recirculation.

Leachate-based systems have notable advantages over other high-solids systems. These systems are less operationally complicated than mechanically mixed digesters and have higher digestion rates than batch-type digesters. Even so, his technology is not without significant issues for the digestion of dry-lot and other manure wastes. Most notably, there are multiple issues

related to hydraulic distribution within the leach bed reactor (Demirer 2008). Waste substrates placed within leach bed systems must be able to conduct flow consistently over the duration of the digestion period. Inconsistent flow, or worse, complete hydraulic failure results in the creation of localized pockets of VFA accumulation that limits further digestion of digestion substrates. With substrates prone to poor flow distribution, such as dry-lot manure, lignocellulosic bulking materials such as wood chips, are added to improve hydraulic flow characteristics. This can add costs to the process without an associated increase of methane potential due to the low degradability of the lignocellulose bulking material. Another limitation with leach bed systems, as noted above for batch systems, is that the valuable methanogenic biomass is ultimately disposed at the end of the cycle.

3.6 Summary

Although AD is an accepted and relatively common waste treatment method for CAFO's in other areas of the country, it is currently a rarity in the semi-arid Great Plains region of the United States. This area is host to a clear majority of the feedlots in the United States, and also contains many outdoor dry-lot dairies. There is, therefore, an opportunity for this waste to be used as an anaerobic digestion substrate. However, these substrates are highly desiccated, degraded, and often contain high levels of inert contaminants. This makes the wastes physically unlike many other substrates utilized by conventional digestion technologies and often poses significant challenges for these systems.

Based on these factors, it was determined that dry-lot manure wastes generated in the semi-arid western United States are poorly suited for use in existing conventional AD technologies, and that non-conventional high solids technologies should be investigated. High solids AD approaches, although developed primarily for high-solids food waste substrates, may be appropriate for the digestion of dry-lot wastes, but these approaches are not without their own

risks and limitations. Batch digesters, the simplest of high-solids digesters, are highly tolerant to inorganic contaminates, and are generally low capital costs, but these systems have low treatment rates, and may require dilution to process dry-lot wastes. Mechanically mixed high solids digesters have much higher rates than batch digesters but are more complex and have higher capital costs. Mechanically mixed digesters require highly robust mixing paddles or pumps which may not be appropriate for the high levels of sand and gravel contained in dry-lot wastes. Leachate based AD systems are also possible alternatives for the digestion of dry-lot wastes, but these systems have not been shown to operate reliably on manure wastes.

Traditionally, aerobic composting or direct field application is the best solution for agricultural producers (Sharvelle 2012). With these understanding in mind, a first-principle approach was applied to design a new AD system to address the limitations of existing legacy and high solids digestion systems.

Chapter 4: CSU Multistage Anaerobic Digestion System

4.1 Technical Development

Based on previous analysis, it was determined that existing technologies were inappropriate for the task of digesting dry lot manures. From a qualitative perspective, it was determined that existing technologies were developed and tested on primarily low solids wastes. It was not surprising that they were unsuitable to process significantly different waste products. Accordingly, it was surmised that these technical limitations may have been related to the technologies themselves rather than inherent physical/chemical limitations of the involved microbes. Thus, an effort was undertaken to apply design principles to the formation of a purpose designed technology suitable for the digestion of challenging high-solids wastes such as dry-lot manures.

4.2 CSU Multi-Stage Anaerobic Digestion System

The CSU Multi-Stage Anaerobic Digestion System (MSAD) uses dedicated hydrolysis reactors, or leachate bed reactors (LBRs), to extract organic matter and nutrients. Solid waste substrates are placed in the LBRs which are operated in a sequential batch timing schedule, which new batches replacing old batches in a semicontiguous manner. Within the LBR where hydrolytic microbes convert complex organic polymers into more simple organic molecules (

Figure 5). Because simple organic compounds are much more soluble and mobile than their parent molecules, water passes through the column and collects high concentrations of these soluble organic compounds. The water that has passed through the LBR is referred to as leachate. After leachate is enriched with soluble organic molecules and passes through the LBR, it is stored in the leachate feed tank (LFT). The LFT serves as an important reaction vessel for the biological and chemical reactions that transform the soluble organic constituents from the LBR into the chemical precursors of bio-methane. The LFT also functions as a mixing tank for

the recycled leachate that returns from the LBR and the fixed film reactor (FFR). Leachate from the LFT is then pumped in a continuous loop through the LBRs and This cyclic process serves to circulate leachate from the LBR, where it is enriched with hydrolysis biproducts, to the FFR, where it serves to degrade the components into bio methane. Within the FFR, methanogenic microbes colonize the surface area of packing material to form an attached film of microorganisms. These microorganisms act as a biological filter for the leachate and serve to convert the organic molecules within the leachate into methane biogas. The newly digested leachate is then passed back into the LFT to be cycled through the process again.

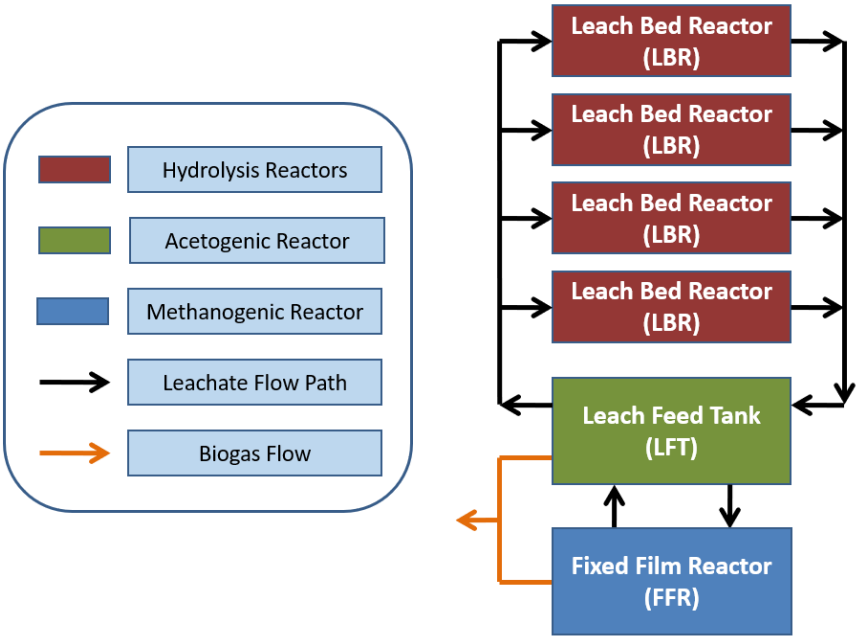

Figure 5: The CSU Multistage Anaerobic Digestion Process Flow Diagram

The design of the CSU MSAD system leverages multiple aspects of existing technologies. Batch digesters are well suited to complex variable wastes with high levels of contaminants, but the key issue with these digesters is the low digestion rates encountered in the system. In the MSAD system, the limitations of the batch digester are addressed by increasing solution transport via leachate recirculation. When the generated low solids leachate from this

process is then passed through a high rate fixed film methanogenic reactor, the process is further optimized by utilizing the positive aspects of both technologies in a synergistic way.

A key aspect of this design is the use of the LBR as a mobile waste collection, transportation, and processing module. Within the same module, all aspects of the solid waste handling are carried out, which reduces concerns with waste handling such as spills and odor releases.

The process utilizes a sequential batch configuration of the substrate batches. In a commercial scale system, there may be more than 100 LBR batches operating at a site (Figure 6). With such a high number of LBR modules, the solids retention time (SRT) for specific LBRs is configurable. Rapidly degradable substrates can be operated with a very low SRT, while the SRT of slowly degradable substrates can be increased accordingly. This configuration enables the process operator to manage variable substrate loadings by prioritizing which substrate batches are to remain in the system. Suitably degraded wastes can be slated for removal from the system to make room for new substrate batches.

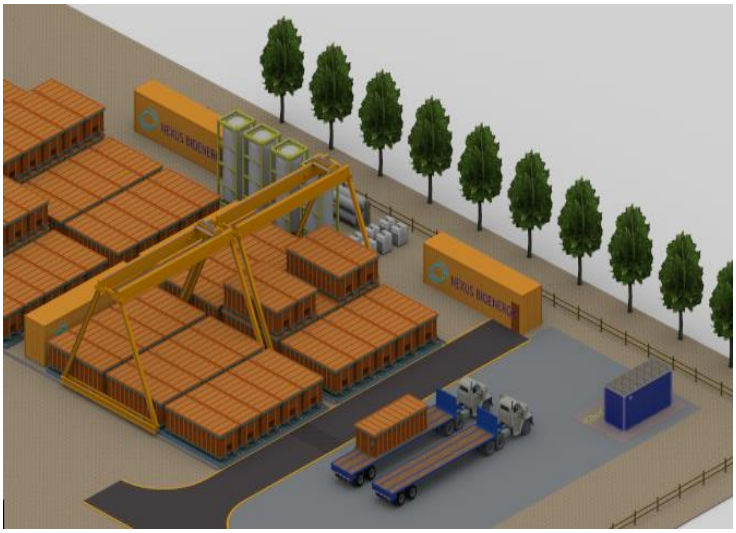

Figure 6: Rendering of possible layout for commercial scale MSAD system using LBR modules

Central to this multi-stage approach is the exclusion of solid substrates from the methanogenic digester. Solid wastes are digested within LBR modules. This approach can facilitate the digestion of low solids waste substrates by passing the substrates first through an LBR module to retain solids within the LBR module.

Variable substrate feed conditions will ultimately result in variable organic loading rates for the methanogenic reactor. Furthermore, in many conventional AD systems, the addition of substrate displaces methanogen enriched sludge which must be removed from the system. Thus, the addition of substrate results in the temporary reduction of methanogenic biomass. In the MSAD system, the addition of substrate does not change the retained methanogenic biomass within the system. This is due to the use of the FFR, which addresses this feed rate limitation through the selective retention of microbial biomass. Through the use of high surface area packing, methanogenic microbes are provided a support surface that is retained within the reactor. Furthermore, the exclusion of solid substrates from the FFR prevents the

fouling/clogging of the packing material and ultimately allows the use of media with extremely high relative surface areas.

The use of the LFT and FFR reactors further protects the system from process upsets common to digestion systems. Methanogenic microbes are typically the most sensitive to process upsets due to pH and organic acid accumulation, and as these microbes are present in the FFR in high concentrations, the LFT acts as a mixing tank and serves to store leachate as needed. Should the FFR begin to accumulate organic acids, the feed rate from the LFT may be reduced to enable the FFR to recover through the degradation of these organic acids. This configuration enables continued hydrolysis within the LBR reactors (although at a lower rate) during any period of methanogenic rate reductions. Organics that accumulate in the LFT during this period can be added into the FFR at a controlled feed rate.

Several important design criteria used to guide the MSAD system design are highlighted in Table 2. As such, the CSU MSAD system scores very well in comparison with the listed existing technologies. This is at the expense of the system being more operationally complex system.

4.3 The CSU MSAD System for the Digestion of High Solids Foods Wastes

Although the CSU MSAD system was originally designed for use on high-solids wastes from dry-lot feedlots and dairies, the technology can be applied to a variety of digestion substrates. The technical design considerations applied to dry-lot manure substrates have created technology that has the capacity to manage other challenging high-solids substrates. A key aspect of the CSU MSAD technology is the way it enhances solution transport within the high-solids digestion system. This approach leads to the technology's extensibility to other high-solids substrates, such as high-solids food wastes. Several attributes of dry lot manures have analogous counterparts in high-solids food wastes. High-solids food wastes:

- Contain inert materials (such as plastic bags and utensils),
- Have wide variations in solids content over time,
- Have variable substrate methane yields
- And, their digestion wastewaters are highly odorous.

The CSU MSAD technology addresses contaminats, variations in substrate solids contents, and methane yields through the use of separate leachate bed reactors. Retained microbial biomass in the FFR enables the digestion of high methane potential food wastes in a more reliable way. Additionally, the digestion of high-solids wastes is facilitated through the re-use of process water which is recycled within the system many times.

The CSU MSAD digester could offer additional advantages for use in the digestion of high-solids food wastes. One of the central tenants of the CSU MSAD system was to address methanogenic instability due to the overproduction of organic acids. This is addressed through the systems' use of a separated hydrolysis and methanogenic reactor. Due to the low methane potential of dry-lot manure, this design aspect is unlikely to be fully appreciated. However, in the case of food waste substrates with much higher methane potential, this is a valuable design criterion.

Chapter 5: Experiment Description and Results

5.1 CSU MSAD System for the Digestion of High-Solids Food Waste

The CSU MSAD system was originally developed for the digestion of dry-lot manure wastes, but this system draws upon many features of existing high-solids food waste digestion systems. Unlike many existing leach bed systems utilized for high-solids food wastes, the CSU MSAD system is a multi-stage process with a dedicated leachate feed tank that serves to buffer chemical gradients between the hydrolysis methanogenic dominated reactors. This configuration lends itself to the digestion of energy dense high-solids food waste.

Food wastes are classified as a high-solids waste for AD. These high-solids wastes can be either pre- or post-consumer food wastes collected from the food service industry or directly from consumers. These wastes differ from the low solid's wastewaters generated by food processing plants, which are easily digested by conventional low solids digestion systems. High-solids food wastes are generally high in degradable organics and can have methane potentials above 500 liters of methane per kilogram volatile solids (Cho 1995). The multi-stage leach bed CSU MSAD system is well equipped to handle variable organic loading conditions, conditions that are likely to occur in the digestion of energy dense and rapidly degradable high solids food wastes (Xu 2018).

Mono-substrate digestion of food wastes can be more easily inhibited than the digestion manure wastes. Notably mono-substrate digestion of food waste can at a greater risk of instability due to ammonia inhibition (Xu 2018). Food wastes, when digested directly as a sole substrate, are prone to the buildup of toxic compounds, the development of nutrient imbalances, and the lack of influxes of synergistic organisms (Zhang 2007).

While not central to the core technology, the CSU MSAD system was designed under the assumption (design parameter) that fresh water supplies should not be mixed with waste products simply to facilitate waste treatment. This design parameter is particularly relevant within the context of a semi-arid environment where water is considered a valuable resource that should not be purposefully mixed with waste products. This design is partially in conflict with the economical digestion of high-solids food waste substrates where ammonia and soluble salts may accumulate to inhibitory levels. Although dilution water could simply be added to dilute the ammonia and salts in the reactor and allow continual digestion of these substrates without inhibition, the design principles of the CSU MSAD system are to reduce water requirements. If additional dilution water is to be utilized, then the trade-off of additional water requirements must be weighed by an understanding of the benefit to digestion rates. Under this design scenario, it is important to understand what levels of ammonia and salt are appropriate to maintain within the digestion system as to not overuse dilution water.

Previous studies at CSU have indicated that anaerobic microbes can be conditioned to operate at higher ammonia and salinity levels if they are gradually acclimated (Griffin 2012). This inoculum, once acclimated, can be much more resistant to ammonia and salt inhibition than the original inoculum (Griffin 2012). Although this work has only been demonstrated at a laboratory scale, this approach may be promising as a strategy for reducing dilution water in pilot or commercial scale digesters.

A challenge to scaling these laboratory findings, though, is that acclimated inoculum must be able to be transferred into and conserved within a complex and varied environment very different from the controlled environment in a laboratory. Within the CSU MSAD system, methanogenic inoculum (largely on the surface of the media within the FFR) are conserved

between various batches of waste. Any enhancements of methanogenic microbial inoculum are likely to stay within the system. This is in contrast to the hydrolytic bacteria within the LBR, where at the termination of each LBR batch, acclimated hydrolytic microbes will be disposed of with the spent digestate. It was unknown what methodology would be the most appropriate way to transfer and maintain acclimated hydrolytic inoculum to the LBR at the onset of the experiments outlined below.

5.2 Experimental Objectives

A major aspect of this study was to investigate the impact of substrate inoculation on the digestion rates of high-solids food wastes in a MSAD system. The bacterial communities present in freshly collected food wastes are significantly different than those present in manure wastes (Xu 2018), and studies of high-solids food waste systems have indicated that inoculation can improve hydrolysis rates (Liu 2009) (Zhou 2011). Previous studies have investigated the impact of adding previously digested substrate to fresh batches of substrate, and the impact of this methodology on the subsequent digestion of these substrates. In this study, substrate optimal substrate to inoculum ratios as well as alternative methods of inoculation. This work was sponsored as the second part of a two-part grant. The first part of the grant was column scale experiments conducted by Paige Wilson and outlined in her doctoral dissertation (Wilson, 2016).

5.3 Column Scale Experiments

This column scale work was largely conducted before the demonstration scale experiment started, and influenced the experiments included in this work. Results of the column experiments indicated that a small amount of digestate could provide a large number of additional microbes (e.g., 10 percent digestate by mass added doubled the number of hydrolyzers available for waste conversion) (Wilson, 2016); thus, new field applicable inoculum delivery

methods needed to be determined. Thus, the focus of the demonstration scale experiments was modified to test various inoculum delivery methods.

Column experiments conducted by Paige Wilson (L. Wilson 2016), were set up in 20cm diameter columns that were 91cm high. These columns were fitted with specially modified leachate delivery and recovery caps. Leachate was pumped from the LFT to the top of the LBR, where it was returned to the LFT. For long term experiments a FFR was also added to the system, with a pump passing liquid from the LFT to the FFR where it again returned to the LFT. To simulate the inhibitory conditions likely to present themselves in a commercial scale system, the leachate within the columns scale experiments was adjusted artificially to 3.5 g TAN/L and a conductivity of 45mS/cm. In the column scale experiments 10-25 liters of waste mix substrate (depending on the inoculation ratio in the experiment) was added to the LBR for each run. Waste substrates were loaded into the LBR in 900g lifts, with inoculum layers added after each lift (either 0%, 10%, or 60% by mass). Following filling, the columns were put into device for the duration of the experiment. The column scale experiments enabled experiments to be conducted under controlled circumstances.

Column scale experiments conducted by Paige Wilson (L. Wilson 2016) yielded useful results for implementation at the demonstration scale. It was determined that challenges associated with ammonia and salinity inhibition in AD may be reduced by utilizing hydrolysis inoculation of the LBR. In the columns scale studies, high substrate inoculation ratios (40-60% by mass) were found to be useful during start-up conditions, or when ammonia and salinity levels were being increased. After the startup period, when the process had stabilized, significant concentrations of hydrolyzers were found to have accumulated in the recirculating leachate. The

recommendation for substrate inoculation in mature digestion systems was determined to be (~10% by mass) of inoculum added to freshly prepared LBRs.

5.4 Objectives of Demonstration Scale Operations

The objective of the experimentation outlined in this work, was to conduct a long-term demonstration of the MSAD technology using layering of digested waste (digestate) and fresh waste as the inoculum method. This work was sponsored as the second part of a two-part grant.

This experiment focused on comparing three main methodologies of inoculation: fully mixed digestate inoculation, leachate inoculation, and enhanced leachate inoculation. Due to the relative performance of the 10 percent and 0 percent digestate controls in this and previous studies, it was determined that there could be opportunities in using leachate as a primary inoculum transport mechanism. In the enhanced leachate inoculation method, the post digestate solid inoculum was introduced to the leachate in an attempt to increase the concentration of inoculum organisms in the leachate. This mechanism was explored to reduce costs associated with inoculation.

5.5 Experiment Setup

Five experimental batches were conducted in the demonstration scale MSAD. Three different inoculation procedures were evaluated in these experiments including mixed, injected, and top inoculated (Table 3). The most commonly used method was the mixed inoculum method. In this configuration, the inoculum was fully mixed into each LBR batch. The inoculation method was the same regardless of the specific inoculation ratio (60 percent or 10 percent). Two methods of enhanced leachate inoculation were investigated (injection and top inoculation). The first method (injection; evaluated exclusively in experimental batch 4) utilized a leachate/digestate contact vessel to transfer microbes to the leachate before being delivered to the LBR. The resulting leachate was then sprayed onto the un-inoculated substrate. The second

method (top; Table 3) was developed with a goal to simplify the enhanced leachate methodology. In this method, digestate was added as a discrete layer on top of a simple filter placed on top of the non-inoculated substrate within the LBR. This method used the action of leachate percolation through the digestate layer to carry the inoculum throughout the LBR. More details on the inoculation methods are included in the Inoculation Addition Section.

Table 3: Outline of Experiments Conducted

Experiment	**Dates of Operation**	**Inoculation Ratios (percent by wet mass)**	**Inoculation Method**
Batch 1	08/24/2015 – 09/14/2015	60%	Mixed
		10%	Mixed
		0%	-
Batch 2	09/15/2015 – 10/5/2015	60%	Mixed
		10%	Mixed
		0%	-
Batch 3	10/5/2015 – 11/05/2015	60%	Mixed
		10%	Mixed
		0%	-
Batch 4	11/09/2015 – 12/07/2015	10%	Injection
		10%	Mixed
		0%	-
Batch 5	01/15/2016 – 02/22/2015	10%	Top
		10%	Mixed
		0%	-

5.6 Demonstration-Scale Multi-Stage Anaerobic Digestion System

The MSAD constructed at CSU was designed as a mobile demonstration of the technology. The mobile system can be dispatched to different locations, as it is mounted onto an 8-foot wide and 48-foot long refrigerated transport trailer (Figure 7).

The facility is equipped with:

- Six mobile LBRs, 60-gallon capacity in each LBR
- Three LBR docking stations, each capable of delivering and draining two gpm from the LBRs
- Loading dock and hoists for maneuvering the LBRs
- One 200-gallon LFT
- One 200-gallon FFR$ with 30 ft^3 of BioPortz media (Entex Technologies)
- Two 275-gallon gas storage tanks
- Gas flare and generator to dispose of the gas produced
- Dedicated control room to house the system electrical panels and controls
- A programmable logic controller (PLC) to monitor and control the process
- Separate control room and column lab to facilitate column experiments

Figure 7: View of the Front of the CSU Demonstration Scale MSAD

The control room is located at the front of the trailer (Figure 8-far left). The control room houses many important functional components of the system, including heating and ventilation, electrical panels, and the system's PLC. The reactor room is the area where the LFT tanks, FFR tanks, and the gas storage tanks are housed (Figure 8-right of control room). Beside these tanks are the LBR docking stations (Figure 8). Lastly, a column scale laboratory is in the back of the trailer (Figure 8). The column scale laboratory did not support experiments for this project.

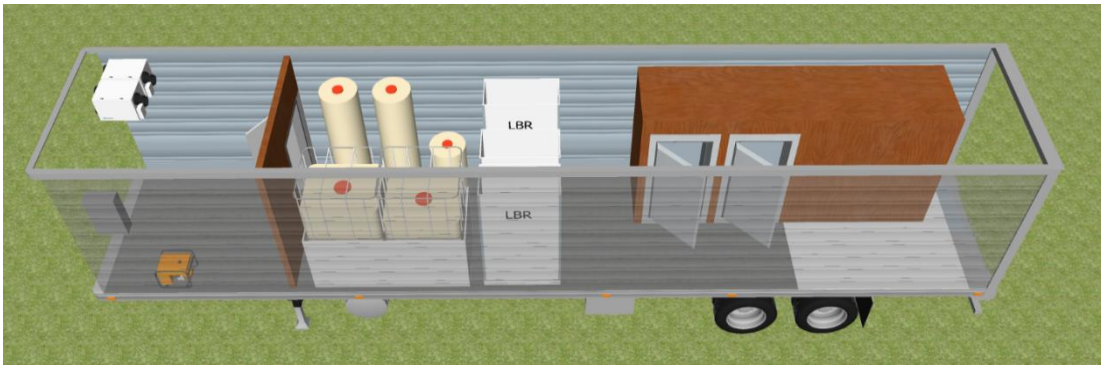

Figure 8: Depiction of the CSU Demonstration Scale MSAD

This system is configured to operate with six, 60-gallon portable LBR modules. However, within the demonstration scale system, only 3 LBR docking stations were in use during operations. These stations are used so that three LBRs can be docked while the other three are being cleaned and pressure tested before the next experimental batch.

The demonstration-scale system used three different pumping stations to circulate leachate in the system: one for pumping leachate from the LFT to the LBRs, one for pumping leachate from the LFT to the FFR, and one for returning the leachate from the sump pit back to the LFT (Figure 9). Leachate was drawn from the LFT (200-gallon tank) by a series of pumps. Leachate is pumped from the LFT to the top of the LBR where it trickles down through the substrate inside. The resulting liquid that drains from the LBRs is collected into a sump pit (1800 gph) where a submersible sump pump returns the leachate to the LFT (Figure 9).

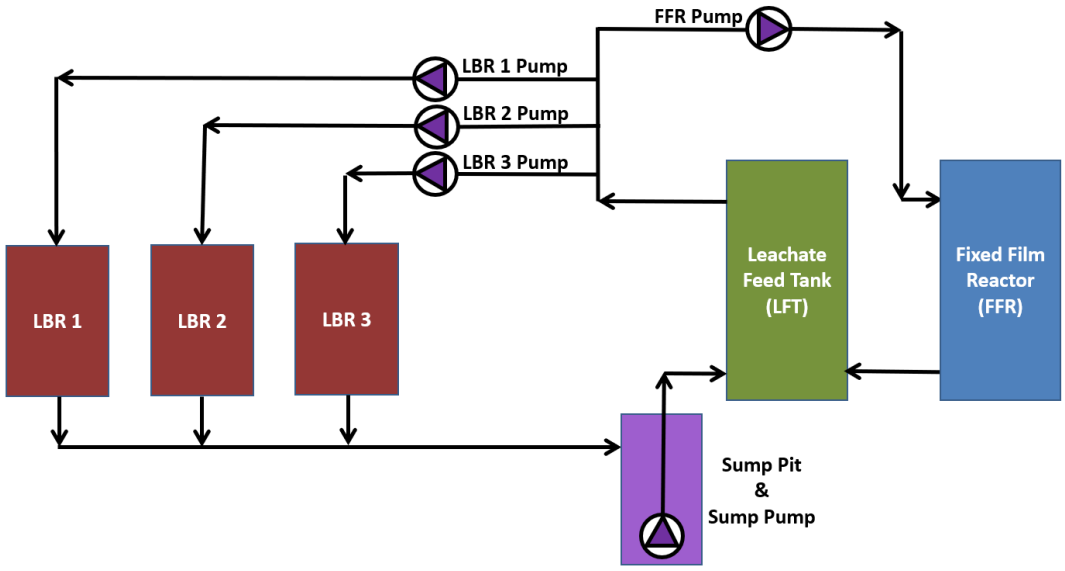

Figure 9: Process Diagram of MSAD Demonstration-Scale System

The LFT also served as a source of leachate for the FFR (Figure 9). The FFR (200-gallon tank) was equipped with a dedicated leachate supply pump (2 gpm) that pumps leachate from the LFT to the top of the FFR. Liquid from the LFT was recycled through the FFR about 4.5 times per

day, for a typical retention time near 9 hours. The FFR and LFT were hydraulically connected near their bases. This allowed liquid to return under gravity to the LFT, thus completing the recycle loop. Within the system, this recycle process was repeated continuously (approximately 45 times) over the course of a 21-day digestion cycle.

5.7 Detailed Demonstration-Scale System Description

There are several subsystems operating in tandem in the demonstration-scale system. The following components will be covered in detail: control systems, LBR leachate system, FFR leachate system, gas handling system, process heating system, environmental and safety systems, and process support systems.

5.7.1 Demonstration Scale Electrical System

As part of this project a fully functioning electrical and control system was designed and installed. This system utilized a 240V split phase power connection which was rectified to supply 12 and 24-volt power for associated control system. The entire system was controlled by a PLC control system used for electrical as well as process-based control.

5.7.1.1 Alternating Current System

The electrical system in the trailer was powered off a 50Amp 240V service line. A 150ft outdoor rated cable was provided to supply power to the trailer. A Nema 14-50 plug was provided on the cable. At the front of the trailer a Nema 3r meter box was provided as an external power shut off. At the meter the power was split into three circuits. The main circuit is a 30A circuit which provides the bulk power to all circuits inside the trailer. There were also two 20A breakers which provide power to various outlets mounted externally around the trailer.

The 30 Amp service is wired to a 50A automatic transfer switch also located on the front of the trailer. The automatic transfer switch is provided to automatically switch the power from the system to a supporting generator or power supply. This system can be used with the biogas

burning generator located inside the trailer, or to an external generator which is used for backup purposes. The automatic transfer switch will switch power supplies when the appropriate voltage is sensed on the auxiliary power feed. Contacts on the PLC have been provided to allow the generator to operate as a backup power supply in the case of power failure.

In the automatic transfer switch, power from either source is sent to a set of terminals which are connected through a flexible conduit to a contactor inside panel 1 at the front of the trailer. This contactor is a three-pole contactor which functions as a PLC controlled electronic disconnect for the two 120V circuits as well as the common neutral line. The PLC provides a signal to an auxiliary relay which supplies 12V power to the contactor which switches the 120V lines on. The power then runs through a current transmitter on its way to a 30A two pole circuit breaker. This is the upstream circuit breaker for the inverter/charger which is required by the manufacturer of this inverter/charger.

Inverter/chargers are commonly used in the recreational vehicle (RV) industry to charge large battery banks and later invert that power for use with common 120V DC devices. This is similar to the application this device is used for in the AD trailer unit. The charging portion of this device uses the 240V- 30A AC power feed to charge a set of 12V batteries. These 12V batteries are kept in a fully charged state at all times, and they supply power to operate most DC operated equipment in the trailer. In the event of a power outage upstream of the inverter, the inverter will instantaneously pull from the 12V DC batteries and begin inverting that power to generate 120V AC which is supplied to the system. In effect the combined system acts as an uninterruptible power supply which also supplies 12V power. The inverter charger has a series of circuit protection features which are outside the scope of this document but can be found in detail in the product manual.

Circuit protection is provided downstream of the inverter as well. A two pole 30A circuit breaker is provided in panel two. Following this circuit protection there is a distribution block with is used to distribute power for the two power circuits as well as the neutral. Line 1 (L1) and Line 2 (L2) from the inverter supply power to 12 circuit breakers each. These circuit breakers are all 15A circuit breakers which are all tied to dedicated electromechanical relays. These relays receive a 24V DC signal from the PLC which ultimately switch the 120V power on and off. The normally open contact of the relay is double tapped with two wires. One wire is reserved for a 120V feedback relay (120V coil, 24 v contact) which provides feedback about the status of the circuit to the PLC. The other wire in all cases service a single duplex outlet. All outlets serviced by this panel are Nema 5-15R ground fault circuit interrupt (GFCI) outlets. In summary, two 30A circuits service a total of 24 PLC addressable outlets which are each rated for 15 amps.

5.7.1.2 Direct Current Circuits

Low voltage direct current was utilized for many operations in the trailer. The PLC, control equipment, sensors, most pumps and lighting all used low voltage direct current (DC) at either 12V or 24V DC. The decision was made early on to select DC operated equipment when available to help simplify wiring and increase the overall safety for the system. Other benefits include reduced costs in key areas like pump controls and the utilization of backup power provided in the DC backup batteries.

The PLC system and all control signals operate at 24V DC. The PLC has a dedicated power supply which is externally located at the front of the trailer. This compartment has a 12V-20A power supply which charges two 7AH batteries. Each battery supplies power to a 12V to 24V DC to DC converter which supply the power the 24V devices. One power supply is a dedicated supply to the two PLC's and the associated touch screen panel. The other 24V power

supply supports the removable PLC modules and all sensors needing additional 24V DC power supplies.

The 12V circuits are supplied primarily from the main 12V battery bank that is associated with the inverter/charger. The negative terminal of this battery bank is physically grounded to the extruded aluminum floor of the trailer, so that in effect the metal trailer body operates as the negative terminal. Using massive metal frames as a return path for direct currents is often used in the automotive and RV industries. In this case it is primarily used for a return path for a few circuits on the exterior of the trailer as most the circuits inside the trailer are hard wired directly.

Panel 4 in the trailer is the panel responsible for distributing the 12V power coming from the batteries. A single aught (1/0) welding cable is connected to each terminal on the battery. These cables are passed through a conduit which is passed into panel four. In panel 4 these cables are connected to a large distribution block which distributes the power to various 12V circuits. The largest of the circuits connected to this distribution block is a 1/0 cable which travels to a panel under the trailer. This panel primarily services the DC sump pump. It includes a contactor and its interposing relay. There are also multiple control terminations in this panel.

The distribution block in panel 4 supplies power to another pump panel. This panel is located above the leachate pumps in the control room of the trailer. This panel supplies power to four diaphragm pumps used for supplying leachate to the LBRs and the FFR. The power comes into this panel in a 10gauge wire which terminates into a distribution block. The distribution block distributes power to four 5A circuit breakers. The circuit breakers supply power to dedicated relays controlled by the PLC. The relays supply power to four motor controllers which receive a 4-20ma control signal from the PLC. The motor controllers then supply a variable voltage output directly to the brushed type motors of the pumps.

The distribution block in panel 4 also supplies power to a 20A circuit breaker located in panel 6. This 20A is a main circuit breaker for the 12v circuits located in panel 6. This breaker supplies 12 sub-breakers of various sizes located in panel 6. These breakers supply power to dedicated relays which supply power to various pieces of equipment in the trailer. Feedback to these relays feed directly into the discrete input modules of the PLC as they are capable of handling the 12V DC voltage directly without the use of a dedicated feedback relay.

5.7.1.3 Control System

The demonstration-scale system is equipped with a control system capable of monitoring and controlling many points within the trailer. The control system is composed of four main parts: field devices, the in/out (I/O) modules, the PLC, and the human machine interface (HMI). Together, these components operate to enable process automation as well as remote monitoring and control. The PLC, HMI, and I/O modules used for this project were all manufactured by EZ Automation while the field devices (e.g. sensors, switches, and control devices) were selected from a multitude of manufacturers.

Process data is collected through the use of various field devices, namely sensors and switches, and there is great diversity in the devices. The control system uses these devices to either gather process data (input devices) or to support environmental and safety related systems (output devices). Examples of devices for process data monitoring include temperature sensors, liquid level switches, and pH sensors. These devices are configured to be monitored on a continuous basis. However, the primary impetus for using a control system is to control field devices, not just to monitor them. As such, the input signals are received by the control system and the programmed response is carried out by sending control signals to output devices. Common output devices in this process are pumps, lights, fans, and alarms.

The various field devices are located in various locations throughout the process, but they are all wired into the I/O modules. The I/O modules are removable devices that plug into the PLC during use. I/O modules act as an intermediary between the PLC and field devices. The I/O modules electrically isolate the PLC and field devices from one another, while still relaying signals between them (Figure 10).

Figure 10. Eight I/O modules plugged into a PLC base

The PLC is a configurable control system which enables logic-based control of the process. Custom control programs specifically generated for the demonstration-scale unit were uploaded to the PLC system. The PLC uses this program to interpret input signals from field devices as well as provide output signals to control devices. In this installation, two separate PLCs are provided. These PLCs are connected and operate as a single control unit through the use of a protocol known as Modbus. The Modbus protocol requires the designation of master and slave units, which enables the devices to share information and commands between the units.

The HMI enables operators to interface with the process both locally and remotely. Locally, operators may utilize the touch panel HMI (EZ Automation EZ Dura-panel 6”) to access a custom graphical interface (Figure 11Figure 11). The graphical user interface developed for this process is composed of over 30 separate slides which display various variables from the

process. Using this local HMI, the status of the system can be monitored and controlled based on operator input. This same graphical interface may also be controlled remotely from a computer located on the same network. Remote monitoring and control software, provided by the manufacturer, enables access of the HMI from a computer connected to the network via Ethernet. This access point serves the same basic functions of the local interface. Utilizing commercially available remote desktop software, this computer and subsequently the HMI, may be accessed from off-site locations. With this functionality, the demonstration-scale system may be accessed for monitoring and control purposes from anywhere a suitable web connection is available.

Figure 11. Human machine interface- EZ automation EZ Dura-panel 6."

5.7.2 The Leach Bed Reactor System

The three LBRs within the CSU demonstration-scale MSAD serve as the primary location for substrate hydrolysis. The digestion of solids within the LBR is facilitated though the delivery of leachate into the LBR. Soluble hydrolysis products from this reactor are then collected in the LFT. Leachate in the LFT is filtered, pH adjusted if needed, and pumped to the LBR. The leachate picks up organic products again and flows under gravity to a collection sump where it is pumped to the LFT once again. The detailed process is outlined below.

5.7.2.1 LBR Leachate Pretreatment and Distribution

Under normal operations, stored leachate passes out of the LFT through a ball valve located on the side of the tank. The water passes through a 0.75” flexible vinyl hose into the pretreatment area of the front control room (Figure 12).

Figure 12. Leachate-pretreatment area of the trailer

Leachate chemical and physical pretreatment equipment is installed in this system. Chemical pretreatment is used to allow monitoring and control of leachate pH. A pH transmitter is equipped to monitor and report pH values to the PLC. Based on the pH value reported, the PLC can be programmed to initiate dosing of an aqueous 1 M NaOH solution. In operation pH remained stable and pH dosing was not utilized for the duration of the testing. Physical pretreatment is provided through a two-step filtration system to remove particulates in order to protect downstream components from unnecessary wear and failure.

Leachate then passes through a canister filter (Pur Flo 10-micron pleated filter; Figure 13). This canister filter is connected with isolation valves and union disconnects on both sides.

The lid of the canister is equipped with a gas removal port. This is a custom modification to allow removal of the gasses that tend to come out of solution inside the filter. As the liquid passes out of the canister filter, it enters an inline pH sensor where the pH is measured. In this configuration, the effects of the pH adjustment dosage are delayed considerably from the actual time of dose at this post filter location due to the dissolution and buffering within the filter.

Figure 13. LBR pre-filter- PurFlo 10 micron pleated filter.

After the pH detector, leachate passes into the LBR pump leachate manifold (Figure 13Figure 14). Here, leachate is distributed to three identical branches that distribute liquid to each LBR. Each branch has a PVC gate valve (Figure 14), a stainless steel inline pre-filter (1/2" NPT 80 mesh; Figure 16), and connection to leachate feed pumps (detailed in the following section).

Figure 14. LBR pump manifold.

Figure 15. Detail of LBR pump manifold valve and inline filter.

Figure 16. In-line fliter1/2" NPT 80 mesh inline Y strainer of generic manufacture.

5.7.2.2 Leachate Pumps

Following pre-filtration, the leachate enters the LBR leachate delivery pump. The selected pumps are low-voltage DC pressure-demand equipped diaphragm pumps (NorthStar model # 2682271) which deliver 2 gallons per minute at up to 70 psi (Figure 17). Diaphragm pumps are commonly used for chemical dosing and high-pressure water delivery applications, but they are usually poorly suited for conventional digestion effluents due to clogging from suspended particulates. However, the leachate drawn from the LFT is very low in suspended solids and requires only minor pre-filtration to bring the water to a quality suitable to be reliably pumped with the diaphragm pumps (LBR Leachate Pretreatment and Distribution).

Figure 17. Low voltage diaphragm pump- NorthStar Model #2682271.

The diaphragm pumps are oversized for this particular application, but smaller diaphragm pumps were discontinued from use after reliability issues were encountered related to small particles. Without motor speed control, the flow rate of 2 gpm equates to a leachate hydraulic loading rate of 26 $Lm^{-2}min^{-1}$ across the surface of the waste. This is roughly 25 times the design HLR of 1 $Lm^{-2}min^{-1}$ used for related projects. As such, motor speed control was provided to reduce the flow rate of the pump down to a leachate flow of approximately 0.5 gpm. This hydraulic loading rate (1 $Lm^{-2}min^{-1}$) is higher than the design HLR, but a safety factor is provided to ensure continuous flow. The selected low-voltage pumps are equipped with

preinstalled dc brushed motors that may be controlled with voltage-based speed controllers (Control Resources, SmartFan Aurora DC Motor Speed Controller). The selected motor controllers receive an analog signal from the PLC control panel which allows remote monitoring and control of the pump speeds.

The selected pumps come from the manufacturer with a preinstalled pressure switch which will automatically disconnect power to the pump when the pressure at the outlet of the pump reaches 70 PSI. In the demonstration-scale system, this configuration protects the plumbing fixtures and piping from overpressure conditions in the event of a plugged fitting. The outlets of all three LBR pumps are connected to .5" rubber hoses which carry the leachate to the top of the LBRs where it is sprayed onto the substrate within the LBR.

5.7.3 The Leach Bed Reactor

The portable LBR modules (Figure 18) are constructed from 60-gallon open head polypropylene drums which have threaded tank adapters installed into the lids and bases. The clearance required by the port in each base is provided by a metal drum carriage (or drum dolly) which raises the LBR off the ground. During operation, the LBR is connected into docking stations located within the body of the trailer unit.

Figure 18. 60-gallon LBR.

Leachate is pumped to the LBR and passes through a misting head (Dramm 10-12344 610F) which disperses the stream of water into a fine mist. This mist of liquid sprays out onto the surface of the substrate inside the LBR where it is further diffused as it begins to trickle through the unsaturated column. As the liquid passes through the bottom of the column, it passes through a non-woven monofilament geo-net composite material (Figure 19). This material is of an unknown manufacturer as it was recovered from the surplus of another CSU project. This material serves to provide structural support for the waste substrate as well as to serve as a coarse filter for retaining solids entrained in the leachate stream.

Figure 19. Detail of non-woven monofilament geo-net composite material.

The liquid which collects at the bottom of the LBR passes through a spiral mesh filter which serves to prevent particle sizes greater than 3 mm from passing into the LBR drainage line. This filter is constructed with a 3 mm plastic mesh wrapped in a spiral around a porous PVC pipe (Figure 20). This filter is affixed to the drain bulkhead at the bottom of the LBR. A flexible hose carries the leachate through a series of valves and union disconnects before it drains into a common collection manifold.

Figure 20. LBR filtration apparatus with drain port shown at the bottom.

5.7.3.1 Leachate Collection and Leachate Return to LFT

The provided manifold is located underneath the trailer and has three drain ports to service three LBRs. The collection manifold is located underneath the floor of the trailer. Due to numerous layers of pipe insulation and heat trace cables, the manifold is obscured from view. The manifold serves to collect the leachate from the LBRs as well as direct the flow of the leachate to the sump pit. Embedded in ports in the manifold are temperature transmitters which are used to measure the temperature of the leachate exiting each LBR. These values were recorded to provide information surrounding process stability.

This manifold drains into a modular sump pit. The elevation of liquid in the sump varies between 1.5ft and 4ft above the ground surface. A pump must be provided to return the liquid to the elevation of liquid inside the trailer, which is approximately 12’ above the ground surface.

The sump pit is equipped with a sump pump, external level switches, and a drain port for use in system maintenance. The sump pump (Wayne Pump model #ESP25) is a submersible pump operated on 12 V DC from an external circuit controlled by the PLC. The PLC uses feedback signals provided by two level switches (Grainger Item #5DYC2) to determine when the sump pump should be operated. As liquid is pumped out of the pit, pressure is equalized in the pit with new leachate flows or gasses from the system. After the sump pump empties leachate from the sump pit, a check valve prevents liquid from draining back to the pit when the pump is not operating. As the leachate returns to the LFT, it completes the first leg of the leachate recycle loop.

5.7.4 Leachate Storage and Treatment System

The leachate storage tank (200-gallon polyethylene tank) serves as a buffering tank for the leachate. In particular, this tank improves the operational characteristics of the FFR. The methanogens within the FFR are sensitive to small changes in the surrounding liquid's solution chemistry. Thus, the LFT acts as a buffering tank to allow concentrations of soluble compounds as well as the pH of the leachate to equalize before it is pumped to the FFR. The decoupling of the hydrolysis stage from the methanogenic stage is essentially enabled by the ability to store leachate while still operating the LBR leachate pumps.

To remove the hydrolysis products produced by the LBR, the FFR needs to be reliably supplied with leachate. The FFR is equipped with a nearly identical leachate delivery process to the one the LBRs used. This leachate is pumped to the FFR (200-gallon polyethylene tank; see details in section below) and then completes the cycle when it is returned to the LFT.

5.7.5 Leachate Pretreatment and Distribution

The leachate pretreatment and associated leachate pump hardware for the FFR is very similar to the hardware used for the LBR's filters and pumps (Figure 21) (See LBR Leachate

Pretreatment and Distribution and Leachate Pumps). The FFR leachate supply equipment is physically located below the LBR equipment and follows a parallel and identical arrangement as described LBR Pretreatment section. These systems are distinct and completely separate but are linkable by a single valve placed at the common leachate manifold these two systems share (shown at bottom left of Figure 22Figure 14). The linked configuration allows leachate to be pretreated by either system and is utilized during filter maintenance as a provision to allow continued operation of the leachate supply pumps.

Figure 21. FFR leachate pre-filter and inline pH transmitter

5.7.5.1 Leachate Pump

The fixed film reactor is equipped with a single pump identical to the pumps for the LBR system (Figure 22). This pump, however, is not configured with a motor speed controller. Instead, it operates at its full capacity (2 gpm) whenever it is turned on. This pump delivers leachate to the top of the FFR.

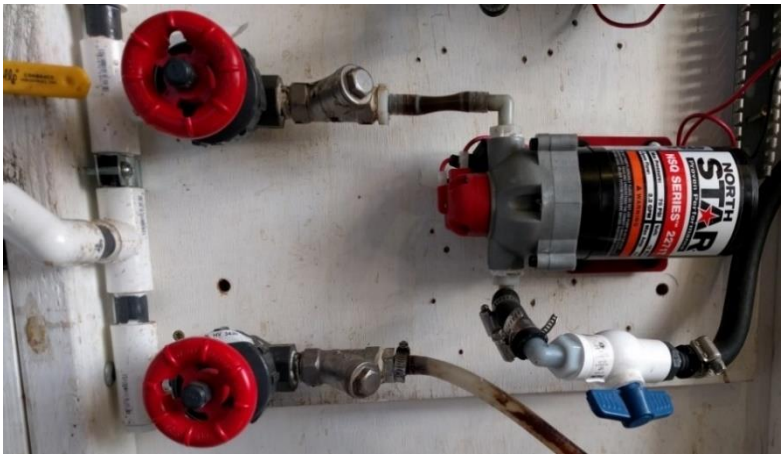

Figure 22. FFR leachate delivery pump (top valve) and leachate sample port (bottom valve)

5.7.6 Fixed Film Reactor

The fixed film reactor uses suspended media to grow an attached film of anaerobic microbes, most notably methanogenic microbes. Typical FFR reactor installations used in industrial wastewater treatment consist of a FFR in a single pass configuration. In such an installation the process liquid has a hydraulic retention time (HRT) within the reactor of no less than 24 hours. But unlike FFs used in single pass systems where HRT typically ranges from 30-72 hrs (Najafpour 2006), the FFR in this system is configured in a recirculating loop where the effluent from the FFR returns to the LFT to be recycled again. This recycle loop enables the use of lower retention times than strict single pass systems. In a 24-hour period, the leachate will be recycled through the FFR on average 4.5 times, to spend on average 9 hours in the system. The higher flow rate of the FFR pump (120 gph) allows for higher velocities in the tank without the use of a dedicated FFR recirculation pump as is often provided with FFs. While the HRT in the FFR is low compared to typical anaerobic systems, of note is that the organic matter in the LFT has already undergone hydrolysis in the LBRs, and some acidogenesis/acetogenesis has also likely occurred in the LFT. Results confirmed that the 9-hour retention time was sufficient for conversion of organic matter in the LFT to methane (see Experiment 5 Results). Once inside the

FFR, the pumped leachate partially fluidizes the media near the injection port at the top of the FFR. The provided plastic media, BioPortz from Entex Technologies (Figure 23), is neutrally buoyant when suspended in water and readily fluidizes at low water velocities. This mechanism, although not fully utilized in this design, helps to free excess biological growth from the media, which helps the media maintain highly active biological films over its surface. The FFR contains 30 ft^3 of BioPortz media, as the leachate migrates down through the FFR, it comes in contact with the colonized surfaces of the media. Through this process, methanogens growing on the media convert soluble compounds within the leachate into methane and CO_2. Within the reactor, a concentration gradient is created from the top of the reactor towards the bottom. The concentration of organic molecules within the leachate progressively decreases as the liquid progresses through the media.

Figure 23. Entex Technologies BioPortz Media.

At the base of the FFR, there is a large 2-inch threaded tank adapter that serves as a leachate exit port for the reactor. The leachate flows out through the port under gravity through a 2-inch diameter rubber hose which conveys the leachate under a very low-pressure loss back to the LFT. Due to the hose size, the liquid level in the FFR is only a fraction of an inch above the

liquid in the LFT when the FFR leachate pump is operating. This transfer is a passive gravity flow transfer that serves as a simple liquid return.

5.7.7 Gas Handling System

The gas handling system serves as a conduit to extract biogas out of the reactors where it is generated so that it can be disposed of in a safe and effective manner. Low volumes of gas are produced from all parts of the system, and their removal from high points is essential. The gas handling system also serves an important function in that it helps equalize gas pressures between tanks within the system.

5.7.7.1 Gas Collection

Every vessel where liquid levels change has a gas equalization line. Example vessels with this equalization line include the: LBRs, LFT, FFR, and sump pit (Figure 9). In particular, these lines ensure a constant pressure in the head space for all tanks in the system. These gas lines also serve as a conduit for gas to be collected as it is produced in the system. The key gas production areas are the LFT and FFR reactors. Key gas equalization areas are the sump pit, LBRs, and gas storage tanks.

Gas collected from the system enters a common PVC pipe manifold physically located near the insulated ceiling of the trailer. This manifold is hidden from view for most of the extent of its length but serves an important role in conveying gasses and equalizing pressures throughout the system. This manifold has multiple PVC fittings into which the gas passes. These locations are equipped with isolation valves, sample valves, and/or union disconnects based on the requirements of each tank location. The mobile LBRs, for instance, have an isolation valve and a union disconnect to facilitate LBR isolation and removal at the end of the digestion process. Other locations, such as the FFR and LFT, are not equipped with a union disconnect.

Instead, they utilize valves at sample ports to provide access to sample gasses produced at those locations.

At the front of the reactor room, biogas collects in the gas manifold and flows toward the front of the trailer. The manifold ends at a “T” plumbing fitting that directs the flow either upwards or downwards. If gas pressure is above 0.5 psi, the biogas travels through a gas exit on the trailer’s roof.

In typical operations (< 0.5 psi gas pressure), the gasses travel downward and pass through a removable clear polycarbonate pipe that allows visual inspection of the gas stream. Leachate or condensed gasses entrained in the biogas can be viewed in this pipe. After this junction, the gas then is then directed towards the biogas storage tanks.

5.7.7.2 Biogas Storage

The biogas storage equipment used in this system is a collection of over water gas storage tanks (Figure 24). This type of system uses gas pressure to lift a submerged tank out of a contained volume of water. The pressure inside the vessel can be modified by placing weights on top of the vessel and modifying the downward force. Under normal operations, gas pressure from the gas manifold causes the gas vessel to rise out of the water tank it is in, thus creating a variable volume constant pressure gas collection system. The water tank used for this application is a custom fabricated steel framed plywood tank coated with marine grade epoxy. The gas tanks used for this application are 1000 L blow molded polyethylene IBC tanks which have been inverted in the water tank.

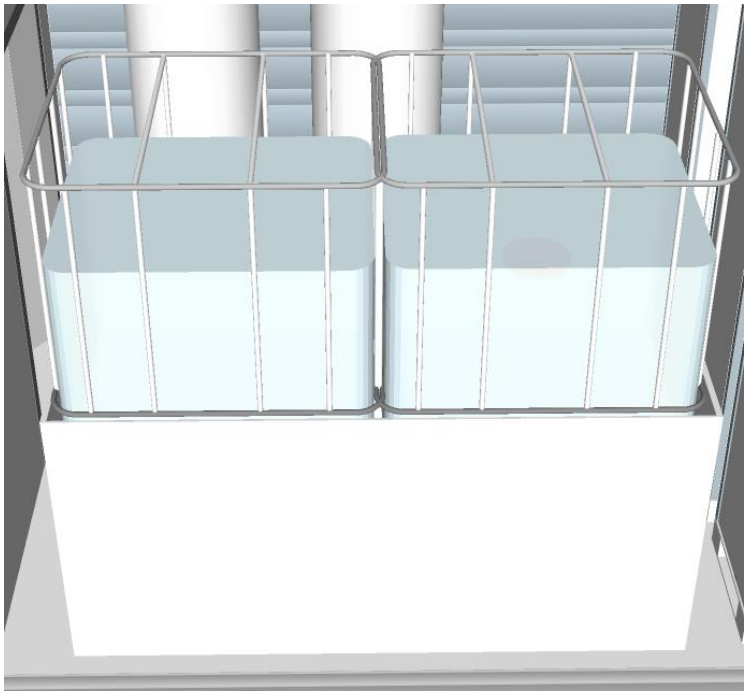

Figure 24. Gas storage tanks**.**

5.7.7.3 Gas Disposal

Due to the combustible nature of the collected gas, it is important to ensure it is collected and removed from the interior space of the trailer. Under normal operations, the PLC initiates gas release to a provided stack. A level transmitter (Flowline EchoPod DL14) measures the height of the floating gas tanks at all times. When the measured level indicates that the tanks have reached 50% capacity (volume of stored gas approximately 1,000 L), a biogas solenoid valve (Asco 8200 series) located on the roof of the trailer is opened to enable the gas to escape through the biogas exit line out to the top of the flare stack (Figure 25 Figure 25low-pressure gas storage in this system (< 0.5 psi) the flare stack simply was a location for the gas to be released to atmosphere, an ignited flare would cause undue safety concerns at this pressure range.

Figure 25. Biogas vent stack and location of future flare.

5.8 Research Methods

5.8.1 Substrate Pre-Processing

The substrate used to fill the LBRs for this project were of two types: pre-consumer food waste and yard waste (e.g. small limbs, leaves, etc). In addition, the anaerobic inoculum was also added to LBRs in ratios based on the experiment plan outlined below (Anaerobic Inoculum Preparation). In a full-scale implementation of this technology, nearly the entire volume of the waste generated from a particular location would be processed in the system. At that scale, the substrate used in the process would inherently be representative of the available waste stream. In the scale of this experiment, however, only a small portion of the generated waste could be digested. As such, a careful approach was taken to select representative substrate samples for use in this study.

Because this study was conducted with such diverse substrates, it was imperative to use systematic methods to homogenize these substrates before loading into LBRs. This posed

challenging in the demonstration-scale operations due to the larger volumes of substrate required. The detailed procedure for the collection and preparation of these three categories of waste substrates is explained in detail below.

5.8.2 Food Waste Collection

Pre-consumer food waste was collected from a variety of locations. During school months, food waste was collected from CSU's housing and dining services as part of their established food waste diversion program. CSU dining facilities placed food waste products into 65-gallon dumpsters (Figure 26). When food waste was not available from the University, pre-consumer wastes were collected from off-campus sources such as grocery stores and coffee shops. Various food waste products were used in this study (Table 4). Of note, experimental batch 1 used a homogeneous waste of little variety, but efforts were taken to ensure representative samples in experimental batches 2-5.

Figure 26: Food waste in 65-gallon waste container

Table 4: Detail of the food waste substrates utilized in this experiment

Experiment	Waste Description
Batch 1	Lettuce/ Kale/chopped greens
Batch 2	Chopped Raw Fruit Rinds, Salad Ingredients
Batch 3	Fruit, Pasta, Tomato Sauce
Batch 4	Fruit, Pasta, Tomato Sauce, Bread, Vegetables
Batch 5	Potato Wastes, Fruit, Coffee Grounds

5.8.2.1 Qualitative Food Waste Selection Criteria

A suitable amount of waste, typically three 65-gallon dumpsters, were manually selected from the loading docks outside CSU dining facilities. The waste dumpsters were roughly categorized there and selected for use according to the criteria below:

1. Food waste was in an unprocessed state (i.e. pulped food waste would not be used).
2. $\geq$ 90 % of the waste could be categorized into definable basic categories (i.e. vegetables, pasta, meat).
3. Food type could be classified into no less than 3 basic categories.
4. Food waste was more or less made up of common food ingredients and was not disproportionally skewed by rare foods.
5. Wastes with standing liquid were excluded due to difficulties posed by the excess liquid to the collection of representative samples for analysis and use in the experiment.

There was often a wide variety of wastes to select from during these months. Thus, it was important to collect samples that would provide a good representation of the mix. For example, a 65-gallon dumpster with 45% kiwi fruit and 55% oranges would fail by criteria 2 and 4. Thus, a dumpster with these wastes in it would be passed over in favor of other containers. Based on this

criteria, we selected only about 1 out of every 5 dumpsters that we inspected at the CSU dining facilities.

5.8.2.2 Food Waste Preparation

Once the food waste dumpsters were selected, they were loaded onto a hydraulic lift gate enabled truck and then transported to the digester site. The delivered food waste dumpsters needed to be composited so that each set of three reactors could be provided with the same representative substrate. This was accomplished by mixing the entire allocation of food waste used for the three 60-gallon LBRs in a shallow trough. An 110-gallon plastic stock tank (2'H x 3'W x 5'L) was used. Wastes from various sources were layered into the stock tank in such a way as to provide a partially homogeneous condition within the tank. This allotment of wastes was then manually inverted using shovels for several minutes. Once sufficiently mixed, this large batch of relatively homogenous food wastes served as a stockpile of waste to pull from during the final substrate preparation prior to loading of materials. A detailed outline of this is documented in below section (Substrate Blending).

5.8.3 Yard Waste Material Collection

A common source of yard wastes was collected in a single event from a local organics recycling company located in Fort Collins, CO. Wastes received at this facility were collected from around the city and spanned from grass clippings to woody biomass. Based on the criteria below, yard waste was selected from multiple piles of composting materials around the facility. A total of 12 cubic yards of yard waste was loaded into two truckloads and transported to the CSU laboratory.

5.8.3.1 Yard Waste Material Selection Criteria

Due to the considerable seasonal variation of yard wastes collected in our temperate climate, great care was taken to select and preserve a sample that was consistent and stable over time. Basic selection criteria for this material are listed below:

1) Roughly equal volumetric ratio of shredded wood chips, grass clippings, and tree leaves.
2) "Single grind" wood chips were selected and often contained small un-chunked branches and leaves.
3) A rough mix of both deciduous and coniferous wood chips and leaves were chosen.
4) Only very fresh lawn clippings were selected as to limit unnecessary decomposition prior to collection.

A representative sample of the collected yard waste was manually sorted into four distinct groups. The represented sample was first sieved with a 5 mm mesh to separate the larger particles from the smaller particles. The particles which passed through the sieve were categorized as the mixed particles fraction due to pragmatic considerations associated with separating and categorizing that material. The particles retained on the sieve (> 5 mm diameter) were manually separated with tweezers into three categories: wood chips, tree leaves and pine needles, and grass. These samples were oven dried at 110° C, and the resulting dry mass fractions of the ingredients in the yard waste were recorded Table 5).

Table 5**.** Composition of the yard waste used throughout this study

Categories of Substrates in Yard Waste Materials	**Fraction by Dry Mass**
Wood Chips >5 mm	56.6 %
Tree Leaves and Pine Needles >5 mm	10.2 %
Grass Clippings >5 mm	12.2 %
Mixed Particles <5 mm	20.8 %

5.8.3.2 Yard Waste Material Preparation

After delivery to our site, the truckloads were dumped out, mixed, and then carefully layered in a shallow pile approximately 15” deep on a large cement slab. The hot and dry weather allowed the surface of the pile to dry out considerably. After the surface of the pile had reached a dry consistency, the pile was then manually mixed in a bi-directional pattern. This mixing and drying process was repeated until excess moisture had been removed from the yard waste material. Afterward, the yard waste material was stacked into a 48” deep pile and covered with a tarp to protect it from moisture and extreme temperatures. It was stored for the duration of the experiment (five months). Total and volatile solids analysis of the yard waste samples were analyzed periodically to account for any degradation while in storage (See sections Solids Sampling Methods Total and Volatile *Solids*). Representative samples of yard waste were used as an additive to all LBR batches at 25% of the total mass (mass of solids and water) of each batch.

5.8.4 Anaerobic Inoculum Preparation

The initial digestate inoculum was collected from the acclimated inoculum utilized in the long-term laboratory-scale experiments conducted at 60% inoculum (see Laboratory-Scale Study Methods, Reactor Operation). Inoculum was delivered to the demonstration-scale system in a 5-gal bucket, purged with nitrogen and sealed. Due to the difference in scale between the laboratory-scale experiments and the demonstration-scale experiments, the 15 kg initial sample of inoculum was cultured in progressively larger batches within the demonstration-scale LBRs. As each batch completed its digestion cycle, the resulting substrate was used as anaerobic inoculum for subsequent tests (Table 6). This inoculum production method mirrored the operation of the full system as it provided the inoculum fresh food waste and bulking materials at the beginning of the test, as well as continuous leachate delivery. All aspects of the inoculum

grow-out procedure were operated in an analogous method to normal operations (see Substrate Blending, Inoculation Addition , and LBR Loading and Transport sections below for more details on these procedures).

Table 6. Outline of inoculum grow-out procedure

Inoculation Batch	# of LBRs Operated Simultaneously	Inoculum Wet Mass at Start (kg)	Food Waste to Inoculum Mass Ratio	Inoculum Wet Mass at End (kg)	Inoculation Duration (days)
A	1	15	2:3	30	21
B	1	30	2:3	50	21
C.1	2	40	2:3	75	21 (concurrent with experiment 3.2)
C.2	2	5	10:1	50	21 (concurrent with experiment 3.1)

The starter batch of inoculum at the beginning of the test was 15 kg and at the end of inoculation batches C.1 and C.2, this inoculum had been grown into a total of 125 kg of digestate ready for inoculation. This quantity of inoculum was enough to be used as inoculum for experimental batch 1. Similarly, the anaerobic digestate from previous experimental batches would be used as inoculum for all further experimental batches.

5.8.5 Substrate Blending

Once the food waste substrate, yard wastes substrate, and inoculum were properly processed as outlined above, these representative groupings were mixed together and added to the LBR. A primary goal in each experimental batch was to operate the LBRs with the same quantity of fresh food waste in each of the three replicates, and the maximum mass that could be added to an experimental batch was 60 kg. When a 60% inoculum LBR was tested (e.g.,

experimental batches 1-3), this meant adding 18 kg of food waste and varying amounts of inoculum and yard waste to achieve the desired percentage by mass of each material (Table 5). When the highest inoculation percentage tested was the 10 % inoculum, a larger amount of food mass could be added to experimental batches (40.5 kg; Table 7). Yard waste was added so that it would make up 25 % of the total mass of the prepared mass. For the most common total mass of 60kg, this equates to 15kg of yard waste. All masses for the substrate blending process were measured as wet mass. The following outline specifies the systematic methodology used in the substrate blending process (Figure 27 and Figure 28).

1. An 110-gallon stock tank was placed on a low-profile floor scale, 5,000 lb, (U-line brand)
2. The scale was tared to the weight of the empty 110-gallon tank.
3. The required mass (25 % of total mass) of yard waste was added to the bin (Table 12).
4. The specified amount of food waste was added to the bin (Table 12).
5. The material was mixed thoroughly until the food waste and yard wastes were fully incorporated. Particular attention was paid to the bottom and corners of the tank.

Figure 27. 110 Gallon mixing tank. Note blue pallet scale which is used to measure the substrates mass.

Figure 28. 110 Gallon mixing tank with food waste added on top of wood chips

Table 7. Substrate ratios used in this experiment

Experiment	Replicate Number	Inoculation (%)	Food Waste Wet Mass (kg)	Yard Waste Wet Mass (kg)	Inoculum Wet Mass (kg)	Total Wet Mass (kg)
Batch 1	R1.1	60%	18	15.0	27.0	60.0
	R1.2	10%	18	6.7	2.0	26.7
	R1.3	-	18	6.0	-	24.0
Batch 2	R2.1	60%	18	15.0	27.0	60.0
	R2.2	10%	18	6.7	2.0	26.7
	R2.3	-	18	6.0	-	24.0
Batch 3	R3.1	60%	18	15.0	27.0	60.0
	R3.2	10%	18	6.7	2.0	26.7
	R3.3	-	18	6.0	-	24.0
Batch 4	R4.1	10%	40.5	15.0	4.5	60.0
	R4.2	10%	40.5	13.5	4.5*	54.0*
	R4.3	-	40.5	13.5	-	54.0
Batch 5	R5.1	10%	40.5	15.0	4.5	60.0
	R5.2	10%	40.5	15.0	4.5	60.0
	R5.3	-	40.5	13.5	-	54.0

*(R4.2 was inoculated with the injected inoculation method so it's prepared mass is 4.5 kg less than R4.1)

5.8.6 Inoculation Addition Methods

The three inoculation methods (mixed, injected and top; Table1) were evaluated in the six experimental batches of the demonstration scale MSAD. The solid digestate collected from the anaerobic inoculum growth batches C.1 and C.2 were used as inoculum for LBR experimental batch 1. Inoculum from all subsequent experimental batches was derived from the previous experimental batches inoculum. In experimental batches, 1-3 Inoculum was added to new LBR batches at 0 %, 10 %, and 60 % ratios by wet mass (Table 7) In subsequent experimental batches (4-5), enhanced leachate delivery methods were evaluated (injected and top inoculation).

5.8.6.1 Mixed Inoculum Methodology

Steps 1-4 were followed as describe in Substrate Blending. For LBR batches that required a mixed anaerobic inoculum, the appropriate amount of inoculum was then added to the top of the mix inside the 110-gallon tank. Then the entire batch was then mixed until the inoculum was fully incorporated. After being fully mixed, the material was ready for reactor loading (see LBR Loading and Transport). All three LBRs were delivered leachate from the same source, and thus the impact of leachate inoculation should have been similar for all LBRs. These three inoculum ratios were tested in parallel using the same substrates.

5.8.6.2 Injected Inoculum Methodology

In the inoculation injection method, the inoculum was placed in a 20 liter sealed vessel where leachate was passed prior to being pumped into LBR 1 (Figure 29).Within this vessel, leachate flowed around submerged particles of solid digestate that were contained within a coarse mesh bag composed of a French drain mesh tube which had been closed at both ends (Advanced Drainage Systems 0420HA). This method was used only for LBR 1 of experimental batch 4 (R4.1) (Table 7).

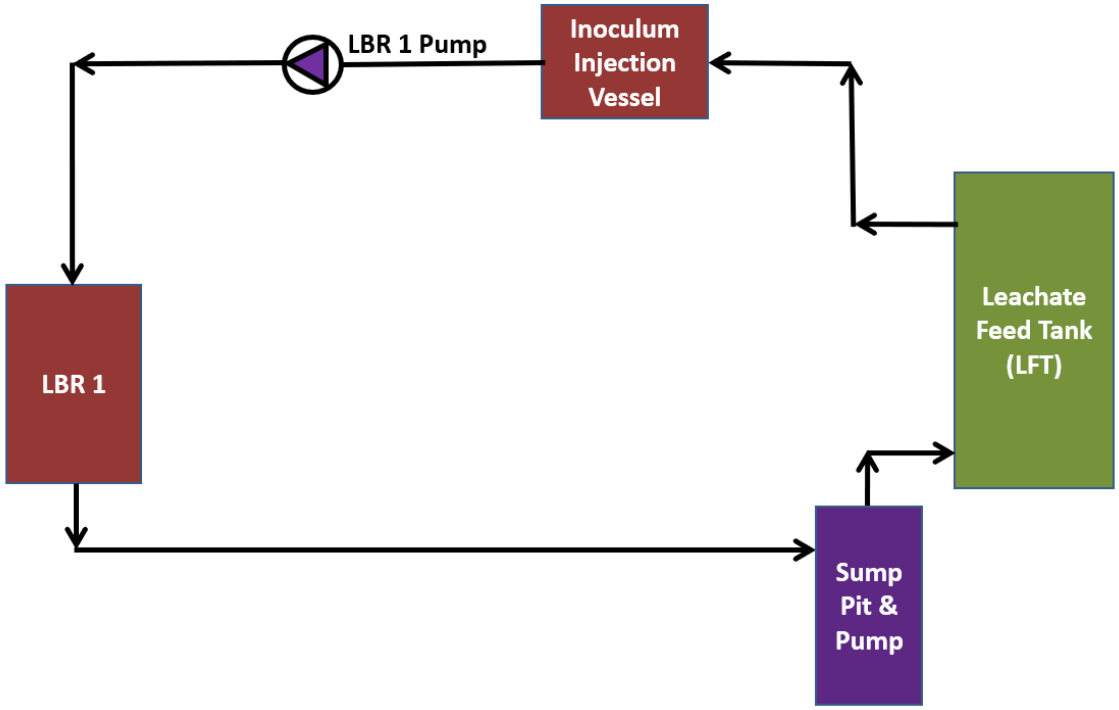

Figure 29. Inoculum injection process diagram

5.8.6.3 Top Inoculated- Inoculum Methodology

Steps 1-4 were followed as above. In experimental batch 5 (Table 12), the top inoculation approach was utilized for LBR 1. In this method, the LBR was filled in the same fashion as a non-inoculated column. However, before the lid was sealed on the LBR, the entire mass of the inoculum (in this case 4.5 kg, Table 7) was added to the top of the LBR. At the start of the batch, liquid leachate was trickled through the top inoculum with the hope that liquid leachate would transport the inoculum throughout the LBR.

5.8.7 LBR Loading and Transport

LBRs were filled on the ground level and then lifted onto the dock with the barrel elevator. The LBRs were then transferred into the interior of the trailer where they were connected into the leachate and gas plumbing of the trailer.

1. The entire volume of the mix was added into the LBRs with efforts taken to limit the time the mix was exposed to air.
2. An excess sample of approximately 20 L was removed for solids analysis (Solids Sampling Methods).
3. The lid was then placed on the LBR and was sealed with the factory provided drum seal.
4. The LBR was sealed and transported to the loading dock where it was loaded on the drum elevator (Figure 30).
5. The barrel elevator was used to transfer the drum from the loading dock to ground level without the use of heavy equipment.
6. Once the LBR was placed on the loading dock, it was rolled inside and connected to one of the three loading docks.

Figure 30. Drum elevator next to loading dock

5.8.8 Analytical Methods

The multiple objectives of this experiment required the ability to measure the results of the various experimental batches conducted. These results were primarily measured through

analysis of solid samples taken from the different substrates and inoculums, as well as liquid samples of the leachate from various points in the system.

5.8.8.1 Solids Sampling Methods

As outlined above, the substrates utilized in this study were highly variable in size, shape, and composition. In this experiment, total and volatile solids analysis were the two primary methods for characterizing the solid substrates and inoculums. All solid substrates, inoculums, and the resulting digestate were analyzed independently. After these materials were blended together and before they were added to the LBRs, another sample was collected. Both analyses were based on a 10-15 g sample weight. With the above highly variable substrates, it was very challenging to collect a representative sample of only 10-15 g. As such, a rigorous and systematic sample collection methodology was developed. This methodology was a multi-step process that used a 212 cc wood chipper (Earthquake brand; Figure 31) to pulverize batches of 20 L of materials at a time. Before the start-up of the three LBRs, 20 L representative samples (collected from more than 4 locations of each material) were taken from the unblended food waste, composited yard waste, and the post-digestate anaerobic inoculum. In addition to the individual samples, the blended mix (see section Substrate Blending) was also sampled for each LBR that was prepared.

Each of these 20 L samples was then passed through the chipper and the resulting pulverized samples collected for solids analysis. Each batch was pulverized with the waste shredder (Fig. 45) to produce a pulped material. The pulped material was collected in a 5-gallon bucket and manually mixed. Three to five samples of 10-15 g each were collected for solids analysis from each 5-gallon bucket.

Figure 31: Waste shredder with 4" PVC nozzle installed on the outlet

5.8.8.2 Total and Volatile Solids

EPA Method 1684 was used to analyze the total solids (TS), fixed solids (FS) and volatile solids (VS) of the substrates and inoculums employed in this test. All solid waste products processed as described above (Solids Sampling Methods) were analyzed for solids content. This provided information about the pre- and post-digestion TS and VS percentages. Experimental batches 1-4 were compared as the difference between the initial and final VS. The final % VS value was subtracted from the initial % VS value to yield the decrease in % VS. This method of comparing LBR performance was found to be limited in its application due to leaching of fixed and volatile solids from the solids mass into the leachate.

Due to limitations in data collected for experimental batches 1-4, the analysis utilized for experimental batch 5 used the initial and final TS and VS percentages by multiplying them by the total mass of the substrate (i.e. wet mass; mws) in the reactor at the respective sampling points (Eqn. 1 and 2). This yielded the quantity of the entire mass of the TS and VS at the beginning and the end of the experiment. The mass of volatile solids m_{vs} within the reactor was

determined at the beginning and end of experimental batch 5 ($m_{vs(initial)}$ and $m_{vs(final)}$). These values were used to calculate the removal efficiency for VS ($\%VS_{reduction}$) over the duration of the experiment (Eqn. 3).

$\%TS * m_{ws} = m_{ts}$ (Equation 1)

$\%VS * m_{ts} = m_{vs}$ (Equation 2)

$\%VS_{reduciton} = (m_{vs(initial)} - m_{vs(final)})/m_{vsinitial}$ (Equation 3)

It is important to note that the decrease in % VS reported for Experiments 1-4 is different from the $\%VS_{reduction}$ reported for Experiment 5. Further, reported $\%VS_{reduction}$ is the same metric reported for the laboratory-scale studies.

5.8.8.3 Leachate Sampling Methods

It had become clear after analysis of the previous four experimental batches that additional information was needed to augment the solids analysis from these experiments. The use of TS and VS analysis methods was complicated by the utilization of the relatively recalcitrant yard waste. In addition to the solids analysis employed in the first four experiments (experimental batches 1-4), leachate samples were also collected and analyzed from the fifth experiment (experimental batch 5). These leachate samples enabled a complete characterization of the process. In particular, leachate analysis was conducted over the duration of the study, which helped to augment the TS and VS data which was only collected at the beginning and the end.

In this process, leachate serves as a primary transport mechanism in the flow of organic compounds through the system. This created an opportunity for collecting detailed data on the production, destruction, and accumulation of organic compounds within the leachate.

In the 5th experimental batch, leachate was collected between two and three times per week (greater frequency at the beginning of the test) from multiple points in the interconnected system. The primary points for leachate collection were at the leachate pump manifold (Figure 22) and at the leachate drain port located at the base of each individual LBR (Figure 20). The samples collected from these points effectively resulted in leachate being collected before it entered and after it exited the LBR. This sampling configuration enables analysis of the flow of organic compounds in and out of the LBR.

Multiple tests were conducted on the leachate including chemical oxygen demand (COD), biochemical methane potential (BMP), conductivity, and total nitrogen. The COD test was performed as a method of quickly estimating the overall concentration of oxidizable compounds within the leachate. BMP tests were carried out to understand the anaerobic degradability of these leachates. The ratio of BMP to COD was used to estimate the relative production of methane producing compounds from the LBR using the entire set of COD data and a correlation between COD and BMP that was established via multiple sampling events (see BMP Estimation Section below). Conductivity and total nitrogen were collected to compare the conducted experiments to previous work funded by this grant. Due to the recirculating nature of this process (and the conservative nature of ionic solutes and ammonia), these tests were only conducted on a limited number of LFT samples.

5.8.8.4 Chemical Oxygen Demand Samples

Leachate COD samples were analyzed by using Hach high range (20-1,500 mg/L) Test 'N Tube COD test kits. These tests were conducted weekly on samples which were immediately frozen after collection.

5.8.8.5 Biochemical Methane Potential

BMP tests were utilized in this experiment as a way of determining the methane producing fraction of the COD at different periods of the cycle. An anaerobic inoculum and a nutrient solution were used in conjunction with a suitable organic substrate to enable the formation of biogas. The biogas is collected and analyzed for methane content. In the CSU MSAD system, these tests help determine the gas production potential of the leachate as it exits the LBR.

The BMP tests we conducted in 150 ml Luer lock syringes by a previously developed method (Quinn 2014). To each syringe, 50 ml of a liquid nutrient solution and 25 ml digester inoculum were added. Then 100 mg of COD worth of leachate was added (typically between 5-20 ml leachate). Gas volumes were recorded daily, and the methane content of the gas was analyzed using a Hewlett Packard Series 2180 gas chromatograph (Hewlett-Packard, Palo Alto, CA) equipped with an Alltech column (Alltech, Deerfield, IL) packed with HayeSep Q 80/100 mesh (HayeSeparation, Inc., Bandera, TX). The gas chromatograph was operated at injection and detector temperatures of 100°C.

5.8.9 Data Analysis Methods

5.8.9.1 Substrate Normalization

Yard waste substrates composed 25% of the total wet mass of the digestion substrate. The lignocellulosic compounds in the woody biomass within the yard waste is poorly biodegradable under the anaerobic conditions within this process. Thus, the lower degradability of these samples suppressed the apparent degradation of the food waste within the process as measured by volatile solids. However, there was no clear way to specify the difference between the yard waste and the food waste at the end of the process. For example, if a significant amount of volatile solids reduction was achieved in the food waste substrate a simple measurement of

volatile solids in the post-digestate may not reveal volatile solids reduction due to the remaining fraction of woody biomass that still contains volatile solids. The interpretation of the volatile solids destruction in the process was normalized based on literature values for the % biodegradability of the various fractions of the yard waste. These literature values were based on a large set of data which sought to determine the biodegradability of various substrates under anaerobic conditions (Triol 2012).

The method used in this analysis used a literature provided value for the fraction of each substrates VS which was composed of cellulose ($\%VS_{Cellulose}$). This value was then multiplied by that fractions biodegradable cellulose fraction ($\%BD_{Cellulose}$), provided by the same force, to yield the biodegradable fraction of VS ($\%BD_{vs}$) (Eqn. 3). The biodegradable vs fraction value is then multiplied by the mass of volatile solids for the experiment to yields the mass of biodegradable solids ($\%BD_{vs}$) for each of various fractions of the yard waste (Triol 2012). The fraction of non-degradable solids within the yard waste represented the mass of yard waste which would be left unchanged in the process. This mass of the non-degradable yard waste was subtracted from the mass VS value in Eqn. 2. Using this approach, the removal percentages for the food waste values were more easily separated from the more recalcitrant lignocellulosic wastes. Future studies may include an in-house study of biodegradability, specific to the substrates included in experiments, instead of literature provided value.

Table 8. Comparison of biodegradability of various yard waste substrates (Triol 2012)

Substrate Type	Cellulose Fraction of VS in Substrate ($\%VS_{Cellulose}$)	Biodegradable Cellulose Fraction ($\%BD_{Cellulose}$)	Biodegradable VS Fraction ($\%BD_{vs}$)
Lawn Cuttings	47.5%	66.6%	31.6%
Hedge Cuttings (with leaves)	42.0%	39.9%	16.8%
Wood Cuttings	45.0%	32.7%	14.7%

The non-degradable portions of this material were regarded as inert and removed from the solids calculations noted above (Total and Volatile *Solids*).

$$\%VS_{Cellulose} * \%BD_{Cellulose} = \%BD_{vs}$$ (Equation 4)

$$\%BD_{vs} * m_{vs} = m_{bdvs}$$ (Equation 5)

5.8.9.2 BMP Estimation

BMP serves as an important analysis to understand the methane potential of the leachate generated from this multi-staged technology. Yet the analysis is costly and time-consuming. We sought to use the lower cost and quick results from COD analysis as an analog for the BMP value. By analyzing both COD and BMP for many samples, a ratio of BMP to COD was found. This ratio was then applied to the larger set of COD data to estimate the BMP of the leachate at all points COD was collected (Table 9).

Table 9. Summary of BMP:COD ratios for the BMP estimation procedure (LFT samples)

Day of Test	Measured BMP:COD Ratio	Applied BMP:COD Ratio
6	0.140	0.140
10		0.140
12	0.018	0.018
14		0.018
16		0.018
23		0.018
33	0.007	0.007
37		0.007

5.9 Experimental Results

5.9.1 Experiments 1-4

For experimental batches 1-4, solids data was the primary analysis for performance. For these experiments, it was important to determine how the various inoculum additions (i.e. 10 percent versus 60 percent) and approaches impacted the TS and VS destruction of the food waste. The percent VS at the beginning and end of each batch was measured, and the difference in the VS values was calculated. As each experimental batch included a non-inoculated control, the VS percent decrease over the non-inoculated was calculated for each batch (

Figure 32). Of note is the relative similarity between the values observed. The maximum improvement over the control was near 5 percent, while the maximum decrease in VS destruction was near 5 percent. The results for the decrease in percent VS were lower than expected, but there was no evidence that inoculated batches performed substantially better than non-inoculated controls. Under stressed conditions, one could expect that inoculums would show a benefit in comparison to non-inoculated controls.

Of note is that the decrease in percent VS ranged from 1 percent to 15 percent decrease in VS over the process. Pre-digestion VS values for these experimental batches started at an

average value of 88.8 + 5.2 percent VS. The post-digestion VS value averaged 82.0 + 13.3 percent. This resulted in an average decrease of 6.9 + 4.7 percent VS. The decrease in percent VS was lower than expected and the final VS content of the processed material was higher than expected. Pre-digestion VS values for this work averaged 91.3 + 1.7 percent VS while the post-digestion VS value averaged 73.1 + 4.7 percent. The percent VS decrease observed in previous work at a column scale was higher than the values noted in experimental batches 1-4 (Wilson 2016). These column experiments in resulted in an average decrease of 19.8 + 6.1 percent VS (Wilson 2016). The disparity between the column scale experiments performed by Laura Wilson, and demonstration scale experiments in batches 1-4 were due to the system operating under largely suboptimal conditions. During these tests, multiple supporting systems within the demonstration scale system MSAD were experiencing technical issues. Experimental batches 1-3 were conducted while the pump controllers were not operating in a reliable way. As such, leachate would stop being delivered to the LBRs for as many as 16-48 hours during the test. As leachate delivery was the primary method that heat was transferred to the LBR, the temperatures would fluctuate and occasionally drop to as low as 15° C. The weather conditions during experimental batch 4 (and the first weeks of experimental batch 5) overwhelmed the heating system in the demonstration unit and the temperatures at the outlet of the LBR fell as low as 25° C and only rose to 32° C as a high temperature. These variable and overall low-temperature conditions during the bulk of experimental batches 1-4 undoubtedly impacted digestion rates in the process, resulting in the lower than typical biodegradation in the process. Despite these operational issues, the process clearly resulted in substrate degradation (as observed by decrease in percent VS) and comparisons amongst inoculum amounts and approaches could still be made.

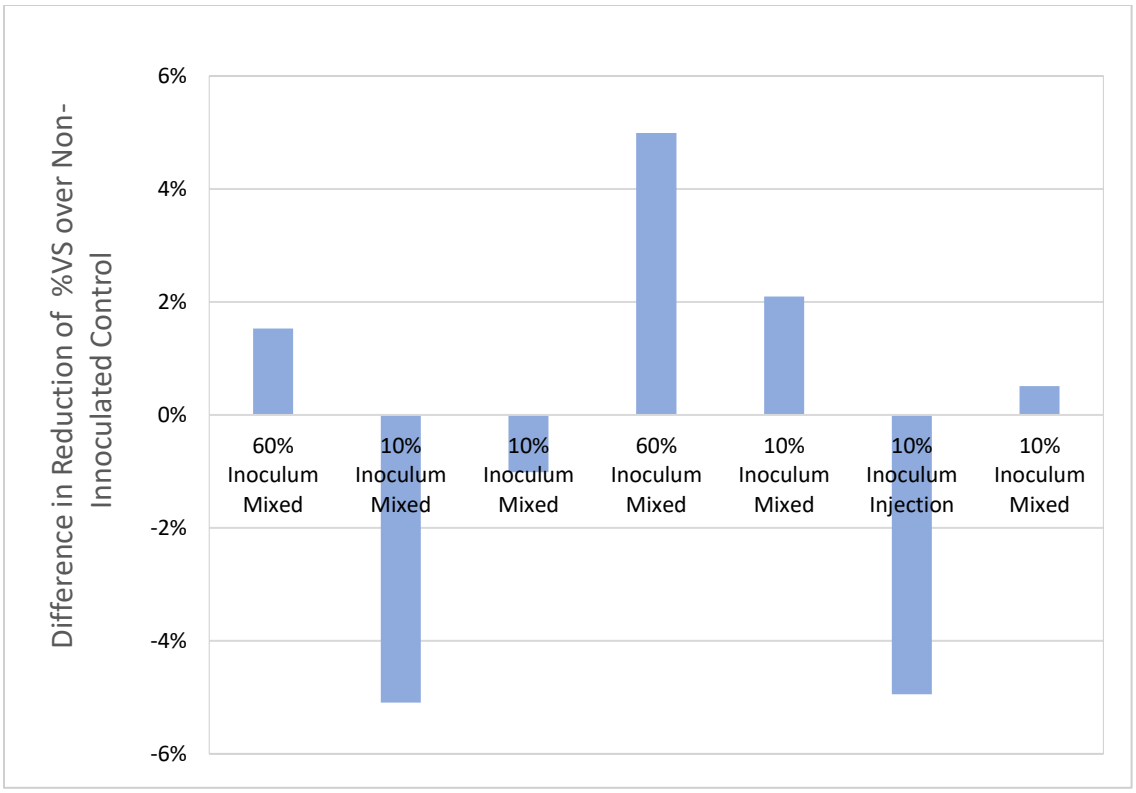

Figure 32: Experimental batches 1-4 with the Percent Improvement for VS Destruction of the Inoculated Batches versus Non-Inoculated Control for that Batch of Experiments

5.9.2 Experiment 5 Results

Due to technical issues in the first four experimental batches, detailed analysis was suspended in favor of focusing resources into developing technical solutions to the problems. This was largely successful, and although it took around 6 days to heat the mass of each LBR to a minimum temperature of 32° C, the process was maintained between 32° C and 35° C for the duration of experimental batch 5.

Experiment 5 was the first experimental batch where leachate samples were collected in addition to solid samples. In experiment 5, the solid samples were characterized this time with starting and ending masses which enabled calculation of the total mass of TS and VS for the LBR (Total and Volatile Solids). This was used to calculate the difference between the pre- and post-digestion TS and VS masses. These masses were compared for the three LBRs where

different inoculum approaches were evaluated (Figure 33). VS reduction was within the range expected for this type of system and more successful than experiments 1-4. VS reduction values from the 10 percent top inoculation method (62 percent reduction) and the 10 percent mixed inoculation method (47 percent reduction) in this experiment compared favorably with VS reduction of the 10 percent inoculation method in the column experiments conducted by Laura Wilson (50 percent reduction) (Wilson 2016). The higher values noted in this experiment could be attributed to the readily degradable nature of the waste selected for this experimental batch (see Food Waste Collection section). The zero percent inoculated batch in this experiment had a VS reduction of 49 percent while the column-scale experiment zero percent inoculated columns averaged 37 percent reduction (Wilson 2016). This could also be due to the readily degradable nature of the food waste processed in this experimental batch, additional leachate inoculation in the demonstration scale system, or possible unintentional inoculation from the use of the same equipment for handling the various batches which was difficult to clean at the demonstration scale.

Compared with the operating conditions of experiments 1-4, the operating conditions of experiment 5 was far more stable due to the replacement of faulty equipment within the system. Although there exist little substantial differences between the various batches of experiment 5, substantial VS reduction was observed for the 10 percent mixed inoculation, the 10 percent top inoculated and the zero percent inoculum.

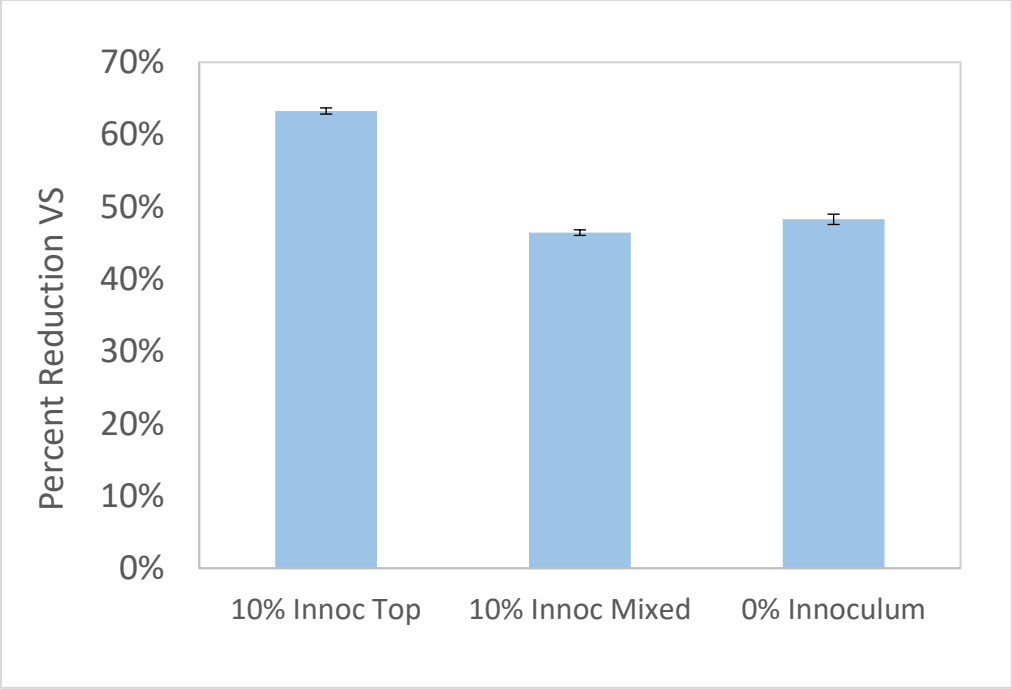

Figure 33: Percent Reduction VS during Digestion Process (error bars represent replicates of analytical samples of VS taken from the same sample)

The three inoculation approaches tested in experiment 5 appear remarkably similar (Figure 33). However, in this experiment, there appears to be little difference between the mixed and the zero percent inoculum, while there seems to be a slight increase in the degradation in the top inoculated LBR. This is an unexpected result, as it is reasonable to assume that the hydrolyzing microbes would inoculate the substrate more completely when the inoculum is fully mixed within the LBR. Overall, it appears from these non-replicated findings, that the top inoculated inoculation method did not adversely affect the performance of the process when compared to its mixed inoculated counterpart. This serves to support the findings from the column-scale experiments conducted by Paige Wilson, which indicates that leachate is acting as a substantial transport mechanism for the hydrolyzing microbes within the LBR (Wilson 2016). Further experimentation could seek to explore this finding in greater detail.

As leachate is the primary transport mechanism for organic compounds within the system, understanding the chemical quality of the leachate is an important way to interpret the extent of digestion process. In these experiments, ionic salts and ammonia were not artificially adjusted, and remained low throughout the experiment. Conductivity values were typically below 1.0-1.1 $mScm^{-1}$. Also, ammonia values were similarly low. The values ranged between 120-250 mg/L as ammonal nitrogen in the leachate samples. These values were far below the 2,500 or 5,000 mg/L as ammonia nitrogen maintained in the column experiments conducted by Paige Wilson (Wilson 2016).

High COD values were observed near the beginning of the test with these values tapering off as the substrate degraded (Figure 34). This trend is due to the action of the methanogenic microbes within the system (predominantly the FFR) which continually degrade many organic compounds within the leachate. The clear downward trend of the LFT COD value indicated that although the single pass retention time of the FFR was much lower than conventional systems, the constant recirculation of the leachate through the FFR resulted in notable methanogenic activity.

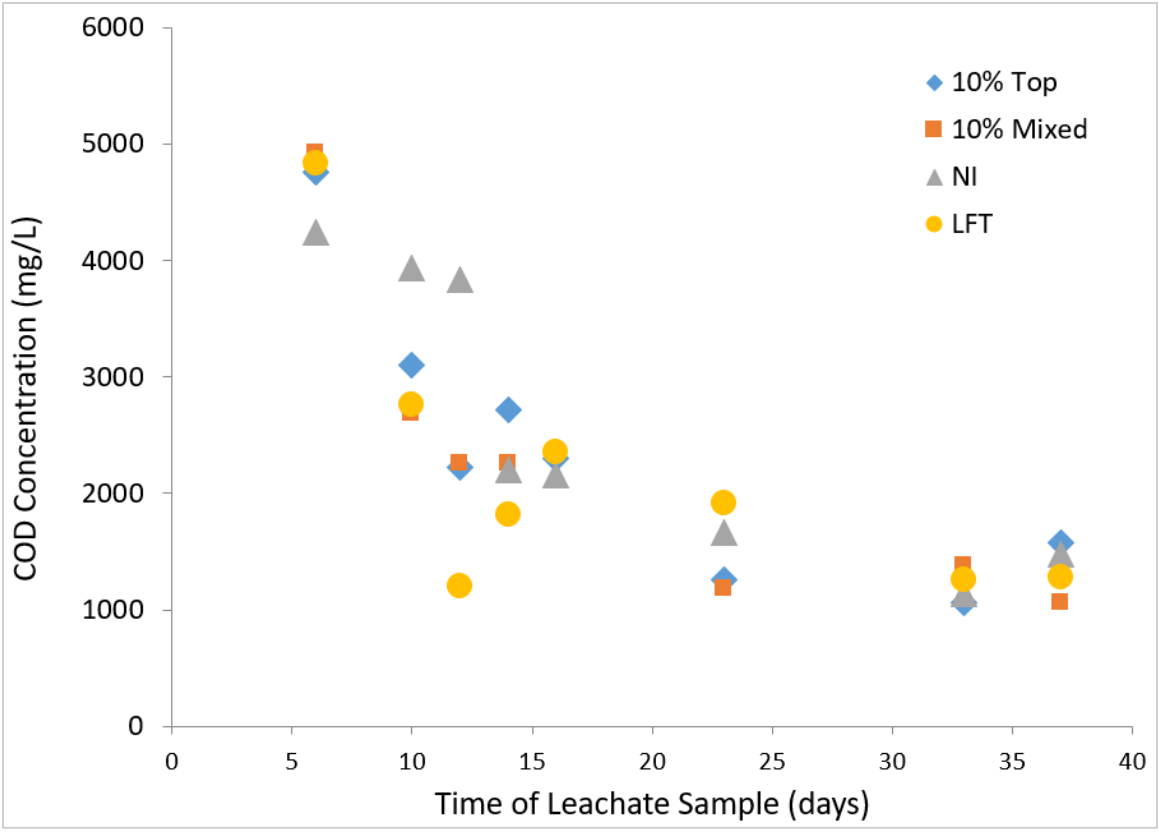

Figure 34: COD of the Leachate at the Exit of the 3 LBRs and the LFT Tank.

It is important to note that not all hydrolysis byproducts are bioavailable to the methanogens. This resulted in the leachate accumulating organic molecules which were recalcitrant to further breakdown. This is observed after day 30 in the process when the leachate has reached a minimum concentration of organic compounds (Figure 34). At that point, it appears that it had reached an equilibrium where solid material in the LBRS did not substantially contribute to LFT COD and COD is the LFT does not substantially decrease from methanogenesis in the FFR. Also, of note is the high COD within the leachate from the LFT during the first ten days. This was likely due to leaching of the substrate in the preheating stage in the first six days of the process. Although it took nearly a week for the process to reach 32°C, there was likely low temperature mesophilic degradation occurring during this period, as well as leaching of material solubilized from aerobic degradation prior to process startup. Digestion at

these low temperatures (< 30° C) is generally regarded for most substrates to be much slower than experienced in the 35°C range. In the case of this set of experimental batches, it is likely that the partially degraded potato waste, which made up a component of the food waste portion of the waste, contributed to the initial increase in leachate COD.

The BMP tests conducted in this experiment serve to provide information on the relative bioavailability of the various organic compounds in the leachate. The resulting values were used to generate a BMP:COD ratio ultimately representing the liters of methane produced per gram of COD. This is a useful measure to understand how biodegradable COD is. An aqueous glucose solution, which is highly biodegradable organic compound, has a theoretical BMP:COD ratio of 0.35 L methane per gram COD(4). This value of 0.35 L methane per g COD represents a typical value for bioavailable hydrocarbons. The BMP:COD ratios of the various leachate samples in this experiment (0.005 - 0.15 L methane per g COD; Figure 30) were substantially lower than the theoretical value (Figure 30). Of note is that the BMP:COD ratio observes in samples collected from the LFT may not be representative of the BMP:COD of leachate directly exiting the LBRs. The LFT is a combination of effluent from LBRs and the FFR, where organic matter in the LFT is converted to methane (Figure 8). Thus, some of the methane potential of liquid in the leachate is constantly removed via the recirculation between the LFT and FFR. Through each pass to the FFR, readily biodegradable compounds are removed, and non-degradable compounds accumulate. Early on In this experiment the leachate demonstrated a higher BMP:COD ratio than at the end, indicating the COD remaining at the end of the experiment was composed of a greater fraction of non-bioavailable organic compounds (Figure 35). As these non-biodegradable compounds accumulate the BMP:COD falls even further below the theoretical maximum value of 0.35 L methane per g COD. While BMP:COD measured in the LFT was relatively low likely

due to the recirculating nature of the system, the trend of BMP:COD indicates that organic matter in the LFT was ultimately converted to methane (Figure 30).

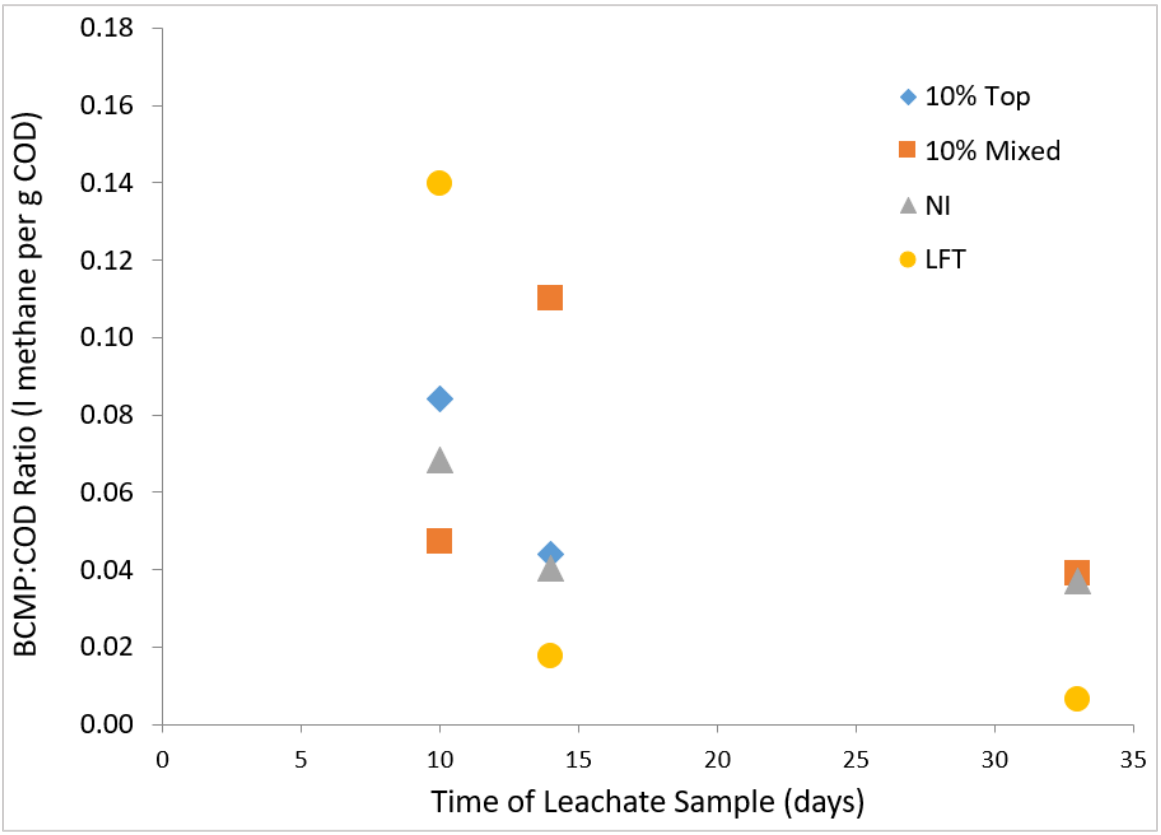

Figure 35: BMP:COD Ratios for the Various LBRs and the LFT

The BMP:COD ratios noted above (Figure 35) were used to estimate the BMP values from the entire test, using the collected COD values (Figure 36).This data was used to generate a relationship of COD to methane potential at various time points in an experimental batch In this interpolated data set, the LFT BMP values start out very high, but then quickly drop much lower than the LBR values after day 10. This indicated that the FFR was not fully degrading the LFT leachate COD values until after 10 days into the experiment. Methanogenic microbes (largely within the FFR) served to reduce the COD of the leachate. During a period in the first few days of the process, the FFR was unable to respond immediately to the influx of organic compounds within the leachate. This is to be expected in a process where all LBRs were started at the same

point in time. A full-scale system will have LBRs which are operating at all stages of decomposition, and LBRs will be replaced gradually. Also, of note is that the microorganisms in the FFR were not acclimated to high loads of organic matter prior to experiment 5.

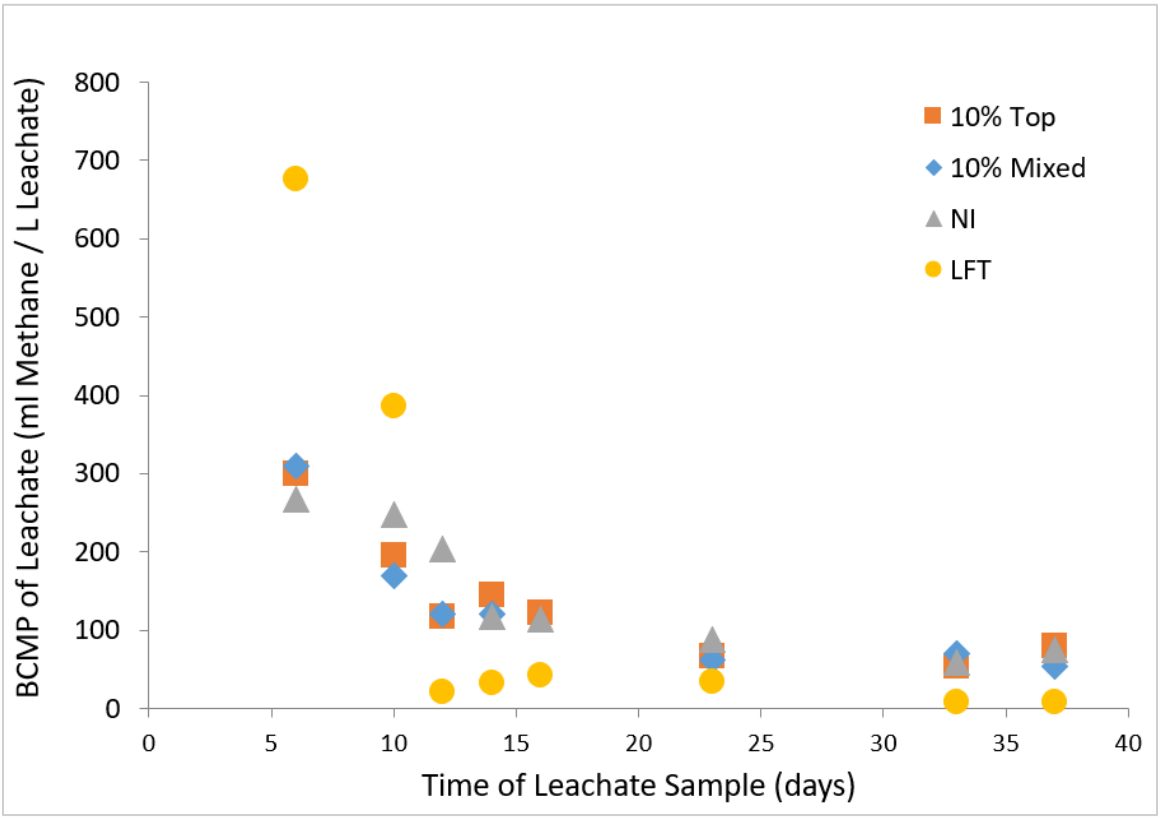

Figure 36: Estimated BMP of the Leachate at Each COD Collection Point

5.10 Summary

In the first phase of experimentation, conducted at the column scale by Paige Wilson (L. Wilson 2016) it was determined that challenges associated with ammonia and salinity inhibition in AD may be reduced by utilizing hydrolysis inoculation of the LBR. In the columns scale studies, high substrate inoculation ratios (40-60% by mass) were found to be useful during start-up conditions, or when ammonia and salinity levels were being increased. After the startup period, when the process had stabilized, significant concentrations of hydrolyzers were found to have accumulated in the recirculating leachate. The recommendation for substrate inoculation in

mature digestion systems was determined to be (~10% by mass) of inoculum added to freshly prepared LBRs.

Within this study, inoculation was not found to have a substantial impact on the solubilization of wastes within the LBR. This is likely related to the low salinity and ammonia concentrations that were observed in the demonstration scale tests. Unlike the column scale experiments conducted by Paige Wilson (L. Wilson 2016), the salinity and ammonia concentrations in the demonstration scale system were not actively managed. This experimental strategy was originally intended as a more realistic alternative to an artificially adjusted solution, but it resulted in much lower ammonia and salinity concentrations within the system. As a result, the leachate in this experiment had lower concentrations of ammonia and ionic salts. Additionally, these demonstration scale experiments utilized a variable mix of substrates, that added variation in the results. Further experimentation, employing triplicate replication, better temperature regulation, and higher ammonia and salinity levels could provide more complete data to help understand the details surrounding the disparity observed between the column scale experiments and demonstration scale experiments. As it stood, these two experiments should not be considered as parallel experiments conducted under similar conditions. However, like the column scale experiments, there was no strong indication from these experiments that inoculation provided a notable benefit after the startup phase.

There are important findings from the demonstration scale experiments which complement previous results from the column-scale experiments. After startup conditions, the 0 percent inoculum (no substrate inoculum) control performed as well as the 10 percent mixed control, which indicates that leachate serves as a transport mechanism for the inoculum. This finding has important implications for large-scale digestion projects. The imperative that initiated

this study was to determine how to speed the rate of hydrolysis within the process in a cost-effective way. The use of post-digestate within new batches is a conventional method for inoculating new substrate, but this approach increases the total reactor volume for the system. Thus, the increased costs associated with this increased volume may end up negating any monetary benefits that inoculation may have. As such, the use of leachate as an inoculum conveyance method could have the potential to cut reactor volume costs while still gaining some of the benefits that inoculation may have.

Chapter 6: MSAD Technology Gap Analysis

6.1 Overview

The current state of technical development for the CSU MSAD technology has been shaped by multiple state and federal research grants. The nature of these grants has facilitated isolated development efforts focused at specific aspects of the technology development process. This process has left the technology well developed in some respects while lacking sufficient development in others. The purpose of this chapter is to assess the current state of the technology for the digestion of dry-lot manure wastes and to identify next steps in the development and eventual commercialization of this technology.

6.2 Technical Risks

Through roughly a decade-long technical development process, the MSAD system has undergone an informal risk reduction process. In each new grant cycle, the focus of the new funding was prioritized based on the greatest level of perceived risks. At the outset of the development process, there were general questions about the suitability of the technology. As experimentation continued, a better picture of the technology and its potential limitations and capabilities grew. The broad categories of technical risks are outlined below:

- Mechanics and operations of the LBR
- Process-related kinetics
- Ammonia/salinity inhibition
- Digestate processing

Maintaining flow through the LBR module has been a major topic of research in the development of this technology. Solution transport within the LBR is a critical design parameter for this process. Through the majority of the technical development process, this aspect

constituted the majority of the perceived technical risks in the process. Digestion kinetics, particularly under conditions of ammonia and salinity inhibition, were also important technical risk factors for the technology. A major value proposition of the technology was the low water requirements of the system. However low water requirements result in the concentration of potentially inhibitory compounds within the process liquid. Experiments were designed to quantify the impacts of the accumulation of ammonia and salinity. Additional risks were noted in the treatment of the solid digestate generated from the process. Unlike the digestate generated from low solids digesters, there were unique challenges to the handling of the high-solids digestate. It became a priority to determine suitable methods of post-processing the solids generated from the process. A summary of the experimental methods and conclusions utilized to access these technical risks is outlined in the following three sections.

6.2.1 LBR Mechanics and Operations

Initial comparisons between different manure types in the LBR led to the finding that dry-lot manures yielded a more consistent and generally higher hydraulic conductivity than low solids manure wastes. This finding was not studied in detail but it leads to a more rigorous study of the hydraulic characteristics of dry-lot manures within the LBR. This project utilized intrinsic permeability tests as well as tracer studies to determine the hydraulic conductivity and mean residence times within the column. A key finding from this work indicated that trickle flow dry-lot manure LBRs can function at significantly higher hydraulic conductivities than literature values indicate (Wasserbach 2013). Further work on the enhancement of leachate flow through the LBR lead to the development of a new approach that utilized an up-flow liquid flow instead of the previously studied downward flow (Wu 2017). This work leads to findings that indicate that operation of the reactor in an up-flow geometry could increase the performance of the reactor system by permitting additional liquid flow.

The development of the up-flow hydrolysis LBR process was continued through a project that explored the design and operations of a larger demonstration-scale LBR system. This project resulted in the design and construction of an LBR with a 4 cubic yard capacity. This LBR was loaded with high-solids dry-lot manure wastes and operated as an up-flow LBR. This study characterized flow through the LBR in the up-flow process, as well as explored the various mechanisms of hydraulic failure within the LBR. (Lewis 2018)

6.2.2 Digestion Kinetics

A series of experiments were performed that focused on the kinetics and yield of the process under different experimental conditions. Early in experimental work on the CSU MSAD system, it became clear that it is difficult to quantify the kinetics within separate stages of the process while still maintaining the integrity of the connected system. This was partially addressed by an experiment designed to mimic BMP tests within a single pass flow through LBR (Hanif 2013). This experiment fed a nutrient solution through an LBR and measured the resulting concentrations of various chemical constituents as they exited the column. This experiment provided valuable insight into the leaching potential of dry-lot manures, which led to early efforts to commercialize the technology.

A significant concern in the digestion of high-solids wastes within the CSU MSAD system was the accumulation of ammonia and salinity in the leachate. There is a plethora of research in the scientific literature detailing the inhibitory nature of ammonia and salinity on digestion rates. However, there were few examples detailing which microbial group was responsible for this inhibition. A research project was created to study the inhibition of ammonia and salinity on the hydrolysis and methanogenesis steps. This project resulted in the findings that hydrolysis is less inhibited from ammonia and salinity than methanogenesis (Griffin 2012). Additionally, prolonged acclimation periods for microbial inoculum can yield a less inhibited

microbial community (Griffin 2012). Further work indicated that ammonia inhibition reduces a microbial community's ability to adapt to stresses due to substrate changes (Wilson 2016). Additionally, it was determined that mature MSAD systems do not benefit from substrate inoculation to the same degree that reactors in start-up phases might benefit from substrate inoculation (Wilson 2016).

6.2.3 Digestate Post Processing and Application

The resulting solid digestate from the CSU MSAD system is a challenging substrate to properly manage. These materials often have residual odors and are not completely stabilized. A research project was organized to study the impact of in-vessel aeration on the stabilization of dry-lot manure digestate. This project compared the extent of stabilization, nutrient qualities, and a solids content of the manure before and after aeration as well as after a post-aeration passive curing process. Cured manure digestate was found to meet the stability requirements of a Class 1 compost (Sandefur 2017). This project paved the way to study the suitability of the manure digestate as a potting soil additive. This study compared mixes containing cured manure digestate solids to mixes containing conventional materials such as peat moss and coconut coir. Manure digestate solids were found to be less suitable for plant mixes requiring plant germination but maintained significant growth potential in mixes once germination had occurred (Surendran 2018).

6.3 Impact Levels and Technical Readiness Levels

The CSU MSAD technology was designed using first-principle design methodologies, and due to the premanufactured nature of its reactors and the mobile LBR design of its reactors, many of its subsystems and components have never been tested for use in AD systems. This lends a significant risk to the technology, and thus poses challenges to its commercialization. An

understanding of the relative risk levels involved and the current state of technical development is necessary for the prioritization of future development efforts.

Risk can be defined as the possibility that an undesired outcome, or the absence of the desired outcome, disrupting project objectives (Smith and Merrit 2002). Risks are distinguished from issues, by uncertainty. The occurrence of a risk is uncertain, while an issue has already happened or is expected to happen (Smith and Merrit 2002). Therefore, any uncertain factor that threatens to negatively impact project objectives could be classified as a risk. The risk is often computed as a product of two components, the impact, and the probability of the impact occurring. For example, in the case of monetary investment risks, an investment of $100,000 with a 20% chance of failure has a risk cost of $20,000.

The objective of this development effort was the creation and commercialization of an AD technology that addresses the limitations of existing technologies for the digestion of high-solids substrates. In the case of this technical development process, a modified approach for calculating risk was utilized to compare various project risks.

First, a qualitative scale was utilized to classify the impacts of risks into three categories of impact levels:

1. Low Impact- Risk will likely work itself out in the commercialization process.
2. Moderate Impact- Dedicated research efforts should be organized to address risks.
3. High Impact- This is a major barrier to technology commercialization and should be addressed before the technology is further developed

Secondly, an analog for the probability of impact, The Technology Readiness Level (TRL), was borrowed from the field of Systems Engineering. The TRL method is a well-developed process for assessing a technology's state of the technical state of readiness. It was

developed by NASA engineers to both assess a technology's existing development level as well as to develop criteria to evaluate and prioritize spending related to the technical development of these technologies (Blanchard and Fabrycky 2011). For the purposes of this study, the TRL assessment tool served to classify risks and technical development tasks into definable categories.

There are nine levels in the TRL system, ranging from level 1, the most basic technical development state, to level 9, a well understood and proven technology. The definition of the nine TRLs as stated by the European Commission is summarized in Table 10 (European Commission 2018).

Table 10. Technical Readiness Levels

Technology Readiness Level	Description
TRL 1	Basic principles observed
TRL 2	Technology concept formulated
TRL 3	Experimental proof of concept
TRL 4	Technology validated in lab
TRL 5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7	System prototype demonstration in operational environment
TRL 8	System complete and qualified
TRL 9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

A summary of relevant TRLs and Impact levels for the CSU MSAD system is outlined in Figure 37. Past CSU studies have primarily focused on development stages between TRLs three and four. This level of validation is important before the technology may be scaled to a more commercially relevant level. For developing the technology into TRL 6 and 7, different technical and funding approaches should be explored to address the different challenges at this scale.

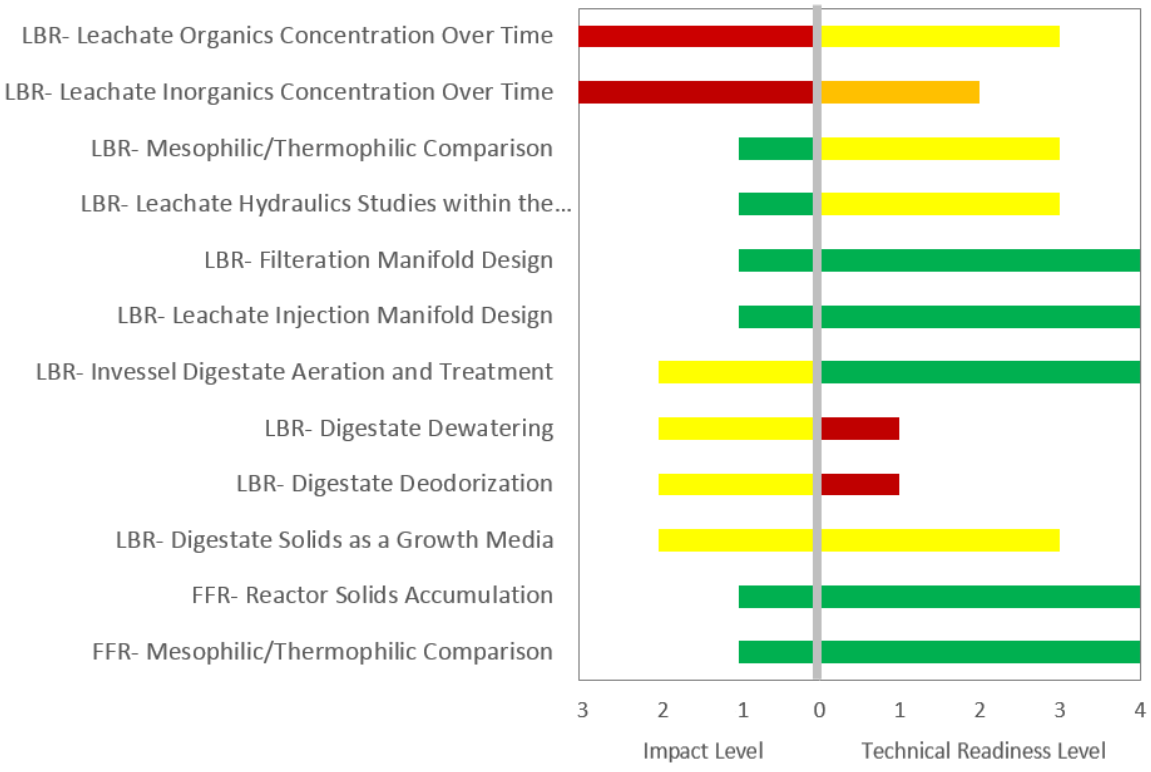

Figure 37: Summary of Impact Levels and TRLs

6.4 Next Steps for MSAD System Development

The successful commercialization of the MSAD system requires a careful prioritization of the technical development process. The recommended development objectives for the process are outlined below:

1. The complete mass balance of organics and inorganics within a connected and linked MSAD system.
2. Study to determine methods and designs for the dewatering, deodorization, and aerobic stabilization of anaerobic digestate produced from the CSU MSAD system.
3. Conduct an economic analysis to determine the economic readiness level of the technology and further guide development efforts.

6.4.1 Mass Balance Study

A major factor in the commercialization of the CSU MSAD system is the required substrate retention time of the process. Capital costs for this process are largely governed by this singular value. Therefore, a careful understanding of the rate of hydrolysis within the connected and linked process is invaluable. From a traditional viewpoint, the production of anaerobically degradable organics is important since they are used to generate biogas, an important process output. Possibly more importantly though is the production of ammonia and potassium salts which could be extracted and sold as commercially valuable organic fertilizers.

6.4.2 Digestate Treatment

Due to the low volume of wastewater generated from the CSU MSAD process, the solid digestate fraction represents the vast majority of material to process on-site. Anaerobic digestate is often odorous and challenging to fully stabilize. Additionally, the design for the existing up-flow LBR does not include an effective method for dewatering the digestate. Once a technical solution is formed for the dewatering of the digestate within the up flow based LBR, a study of the effectivity of aeration for the deodorization and stabilization of the digestate will need to be completed. Although full stabilization within the LBR vessel is likely not feasible, complete deodorization before removal from the LBR should be a goal for this study.

6.4.3 Determination of Economic Readiness Level

The university studies that have been conducted thus far in the development of this technology have focused on perceived technical risks, and as such have largely ignored the economic risks of the technology. This is an area that requires further development due to the challenges with typical business models behind AD projects. The conventional digestion business model has been applied globally, but it is ill-suited to the digestion of high-solids in the semi-arid Great Plains. To be commercially viable, the CSU MSAD technology must also

address the economic constraints of this business model. This is a complex task as there are multiple challenges to the implementation of this technology. An important next step is the determination of specific markets and business strategies that can leverage the strengths of this specific technology. There is renewed interest in the relevancy of a combined technical and economic approach to technical development (Yuniaristanto 2017). A new approach, which is highly analogous to the TRL system is the economic readiness level (ERL) (Yuniaristanto 2017). This approach mirrors the TRL system in presenting a way to identify market and business-based drivers related to technology commercialization. Combined with the TRL system, the ERL approach would help guide further technology development by considering both technical and market-based criteria.

Chapter 7: Summary

On-farm AD can be an excellent tool for agricultural producers. It uses very little energy, stabilizes wastes, and generates biogas. It has, therefore, become an accepted waste management tool for CAFOs in many areas of the country. However, AD is rarely used in the Great Plains region of the United States due to the generally desiccated state of the manure generated on the outdoor feedlots and dry-lots. The manure at these lots have degraded methane potentials, high levels of inert contaminants, and are ill-suited for use in conventional AD technologies. Even so, this manure still has potential to be profitable. Therefore, a first-principle approach was applied to design a new AD system that could address the limitations in the existing technologies.

The CSU MSAD system was designed to process challenging highly variable waste substrates, particularly wastes with a high-solids content and high inert contaminant levels. A central aspect of this technology is the recirculation of a low-solids content leachate through a multi-stage process. This technology has promise to treat dry-lot wastes at the commercial scale. This research work focused on the application of the MSAD technology to process high-solids and the organic fraction of municipal solid wastes.

A mobile demonstration scale MSAD system was constructed. It is mounted onto an 8-foot wide, 48-foot long refrigerated transport trailer. It is equipped with multiple 60-gallon capacity LBR, one 200-gallon LFT, one 200-gallon fixed film reactor FFR, as well as a gas disposal system. In addition to process related equipment, the system has a dedicated control room that houses the system's electrical panels, controls, and a PLC to monitor and control the process.

This system operated for a four-month period treating food waste and yard waste substrates. These substrates were tested with various inoculation procedures over five separate

LBR batches. The experimental outcomes indicated that substrate inoculation was not necessary on mature digestion systems due to the utilization of leachate recirculation.

A gap analysis was conducted on the MSAD system to determine the current development state of the technology, as well as to prioritize future development efforts. This work indicated that further development should be focused on determining an accurate mass balance of the system, ascertaining further options for digestate processing, as well as developing a better understanding of the economic readiness level of the technology.

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Appendix I

Table 11: Summary of Impact Levels and TRLs of Various Process Parameters

	Impact Level	TRL	
LBR and Hydrolysis			
Kinetic Rates for Manure	3	3	(Hanif 2013), (Griffin 2012)
Kinetic Rates for Food Wastes	3	3	(Hanif 2013), (Griffin 2012)
LBR Kinetic Rates for Manure	3	3	(Hanif 2013)
LBR Kinetic Rates for Food Wastes	3	4	(Wilson 2016)
Leachate Organics Concentration Over Time	3	3	(Hanif 2013)
Leachate Inorganics Concentration Over Time	3	2	(Hanif 2013)
Degradable Organics	3	1	(Hanif 2013)
Recalcitrant Organics	1	1	(Hanif 2013)
Nitrogen	2	2	(Hanif 2013)
Phosphorus	2	2	(Hanif 2013)
Potassium	2	2	(Hanif 2013)
Ammonia Inhibition on Hydrolysis	1	3	(Griffin 2012)
Salinity Inhibition on Hydrolysis	1	3	(Griffin 2012)
Pressure Differential in Column	1	4	(Wu 2017)
Mesophilic/Thermophilic Comparison	2	3	(Kim 2003), (Bolzonella 2012)
Effect of Inoculation on Digestion Kinetics	2	4	(Wilson 2016)
Leachate Hydraulics Studies within the Reactor	1	3	(Wasserbach 2013)
Filteration Manifold Design	1	4	(Lewis 2018)
Leachate Injection Manifold Design	1	4	(Lewis 2018)
In-vessel Composting Air Distribution Methods	2	4	(Lewis 2018)
Up Flow Solid Substrate Post Processing			
Digestate Dewatering	2	1	(Lewis 2018)
Digestate Deodorization	2	2	(Sandefur 2017)
In-vessel Digestate Aeration and Treatment	2	4	(Sandefur 2017)
Compost Nutrient Content	1	4	(Sandefur 2017)
VS of Digestate	1	4	(Sandefur 2017)
NH_3 to NO_3 Ratio in Composted Digestate Solids	1	4	(Sandefur 2017)
Stabilized Digestate Solids as a Growth Media	2	3	(Surendran 2018)
Fixed Film Operation			
Optimal Organic Loading Rates	1	3	(Quiroz Arita 2013)
Optimal Surface Loading Rates	1	3	(Quiroz Arita 2013)

Recirculation Velocity	1	3	(Quiroz Arita 2013)
Ammonia Inhibition on Methanogenisis	2	4	(Wilson 2016)
Salinity Inhibition on Methanogenisis	2	4	(Wilson 2016)
Reactor Solids Accumulation	1	4	Unpublished findings from previous experiments
Mesophilic/Thermophilic Comparison	2	4	(Kennedy 1982), (Labatut 2014)

List of Abbreviations

AD	Anaerobic digestion
BMP	Biochemical methane potential
COD	Chemical oxygen demand
CSU	Colorado State University
EC	Electrical conductivity
FFR	Fixed film reactor
ft^3	cubic feet
g	gram
gal	gallon
gpm	gallon per minute
HMI	Human machine interface
hr	hour
HRT	Hydraulic retention time
L	liter
LBR	Leach bed reactor
LFT	Leachate feed tank
MDS	non-metric multidimensional scaling
mg	milligrams
ml	milliliter
MSAD	Multi-stage anaerobic digestion
mS/cm	Millisiemens per cm
OFMSW	Organic fraction of municipal solid waste
OLR	Organic loading rate
PLC	programmable logic controller
TAN	Total ammonia nitrogen
TS	Total solids
VFA	Volatile fatty acid
VS	Volatile solids
yr	Year