THESIS

MAINTAINING LEACHATE FLOW THROUGH A LEACH BED REACTOR DURING ANAEROBIC DIGESTION OF HIGH-SOLIDS CATTLE MANURE

Submitted by

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ABSTRACT

MAINTAINING LEACHATE FLOW THROUGH A LEACH BED REACTOR DURING ANAEROBIC DIGESTION OF HIGH-SOLIDS CATTLE MANURE

To address the accumulation of high-solids cattle manure (HSCM) found at many of the state's Animal Feeding Operations (AFOs), researchers at CSU have developed a Multi-Stage Anaerobic Digester (MSAD). The MSAD system consists of a leach bed reactor (LBR), a compositing tank, and a fixed-film methanogenic reactor. The LBR is a critical part of the MSAD system since hydrolysis can be a rate-limiting step in the anaerobic digestion of HSCM (Hinds 2015; Veeken and Hamelers 1999). To ensure that hydrolysis is occurring properly within the reactor, leachate injection and reactor operation must proceed in a manner that facilitates uniform distribution of leachate through the manure waste bed. Since the leachate must be recirculated through the LBR for the entirety of the batch digestion time, any phenomena that disrupt the duration or uniformity of leachate distribution must be addressed. The overarching goal of this thesis project was to improve the hydraulic performance of the LBR stage of the MSAD. This research included a multi-criterion decision analysis (MCDA) to assess unique design aspects of the MSAD relative to other technologies, construction and operation of a prototype LBR, and the development of an experimentation strategy to assess mechanism of hydraulic failure in the LBR.

The MSAD system was compared to four other high-solids anaerobic digester technologies using a MCDA. The purpose of this comparison was to identify unique design features of the MSAD

technology compared to other high-solids anaerobic digestion technologies to inform the focus of future design and research activities. The technologies were rated and evaluated for the following criteria: operational requirements, impact of hydraulic failure, capital requirements, operational control, feedstock technology fit, and process efficiency. The scores ranged from 2.9 to 3.7 out of 5 possible points. Under equal criteria weighting, the MSAD system received the highest rating with a score of 3.7. The MSAD system received high ratings due to its strong hydraulic performance, operational control, and process efficiency.

Knowledge gained through laboratory and prototype-scale LBR experimentation was used to establish possible improvements to LBR design. The primary improvement to the LBR was the modification from a downflow to an upflow configuration. A prototype LBR was operated in the upflow configuration to facilitate longer durations of undisrupted leachate permeation. In addition, it was determined that leachate injection spacing should be studied further as results from operation of the prototype LBR suggested that higher volatile solids reduction occurred closer to the leachate influent manifold.

Column experiments and prototype operation showed some successful operation of LBRs for treating HSCM. However, hydraulic failures due to clogging and preferential pathway formation were observed. Due to the continued risk of hydraulic failure, further research was needed to understand mechanisms for hydraulic failure and to determine approaches to overcome these issues. At commercial scale, hydraulic failure of LBRs would result in decreased energy and agricultural product output and increased operating costs. Since commercial processes rely on reproducible results, a high degree of LBR reliability is required to achieve technical and economic feasibility. Therefore, control over the hydraulic performance of LBRs is critical for commercialization of the MSAD system. To this end, an experimentation strategy was developed, with the goal to elucidate the mechanisms behind hydraulic failures occurring in the LBR. To evaluate these mechanisms, the experimentation strategy recommends the use of electrical resistivity tomography (ERT) to render visualizations of leachate distribution throughout the waste bed. Further characterization of the pore space network geometry at the microscale using either Magnetic Resonance Imaging (MRI) or X-ray Computed Tomography (X-ray CT) is recommended.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1 Use of Anaerobic Digestion to Harness Resources from Manure

Implementation of anaerobic digestion (AD) can provide an effective method for the management of organic wastes. The proper treatment of such wastes can reduce greenhouse gases, create renewable energy, reduce odor, reduce water pollution, and facilitate agricultural nutrient recycling (Sharvelle et al. 2011a). AD is a means of treating organic waste materials in a sealed reactor where microbial communities degrade the waste in an environment free from oxygen. The gaseous product of AD is called biogas. Biogas is a mixture of approximately 60-70% methane, 30-40% carbon dioxide, hydrogen sulfide, ammonia, water vapor, and other trace gases (Sharvelle et al. 2011a). The liquid effluent of AD is called digestate. Digestate is composed of water, inorganic nutrients, and residual carbon remaining from the digester feedstock (Sharvelle et al. 2011a). As illustrated below in Figure 1, AD systems typically "include manure collection, pre-treatment processing, biogas generation, biogas purification, biogas utilization, and byproduct disposal" (Sharvelle et al. 2011a). (Lewis 2017b)

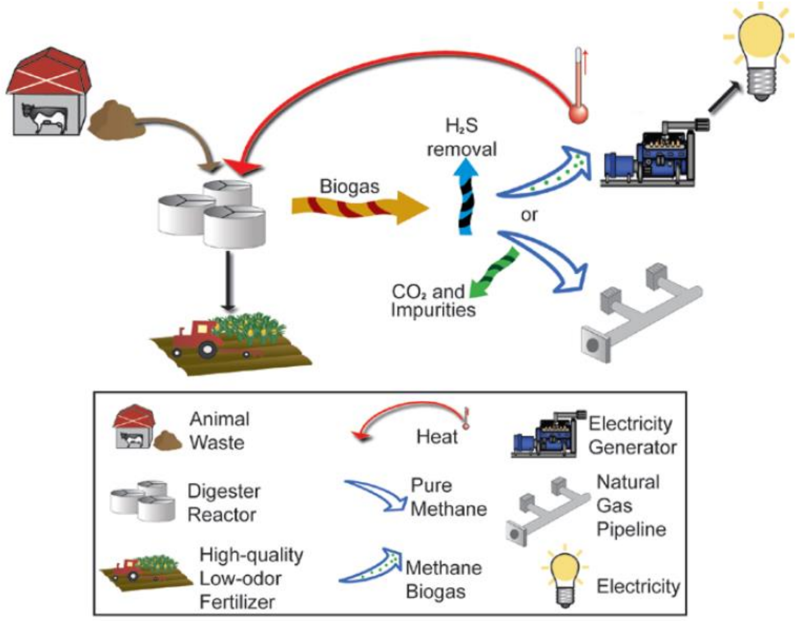


Figure 1 - Anaerobic Digestion System Configuration (Sharvelle et al. 2011a)

The four major steps in AD are hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Figure 2; Rapport 2008). In hydrolysis, complex organic molecules such as proteins, polysaccharides, and lipids are converted into simple molecules such as amino acids, monosaccharides, fatty acids, alcohols, and other small organic molecules. In high-solids anaerobic digestion (HSAD), hydrolysis can often be considered the rate-limiting step (Hinds 2015; Veeken and Hamelers 1999). In acidogenesis, the products of hydrolysis are converted into short-chain volatile organic fatty acids, including butyric, propionic, and acetic acid (Hinds 2015). In acetogenesis, the products of acidogenesis are converted to acetate or hydrogen and carbon dioxide. In methanogenesis, the products of acidogenesis are converted into methane and carbon dioxide.

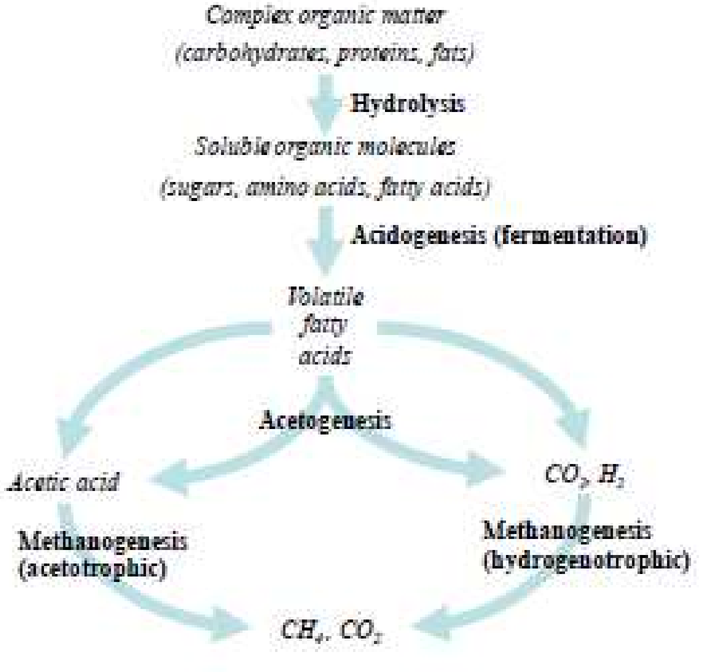


Figure 2 - Biological Steps in Anaerobic Digestion

Additionally, in anaerobic digestion, sulfate is reduced to hydrogen sulfide and ferric iron is reduced to ferrous iron (Hinds 2015). The syntrophic (mutual dependence) relationship between acetogens and methanogens is crucial for the anaerobic digestion process to proceed in a continuous, steady-state manner (Hinds 2015)

1.2 Challenges for AD of Animal Feeding Operation Waste

There are a variety of physicochemical properties of manure that can affect anaerobic digestion process operations at Animal Feeding Operations (AFOs). Conventional anaerobic digestion technologies usually necessitate a feedstock that is less than 15% solids (Sharvelle et al. 2011a). However, manure collected in dry lot agriculture operations can have significantly greater solids content. Cattle manure is generally around 12% solids (as excreted), while manure collected on dry lots in Colorado can be between 65-90% solids because of water loss to evaporation (Sharvelle et al. 2011a; Lewis 2017b).

The high-solids cattle manure (HSCM) that accumulates at dry lots in Colorado can have a considerable amount of inert materials such as rocks, sand, and soil material. Inert materials can lead to difficulty in the operation of anaerobic digesters and typically must be removed before the waste can be treated in a reactor. If not removed, the reactor may experience buildup of inert materials as well as damage to pumps and other equipment. "Removal of rocks, soil, and sand is possible, but typically involves addition of water to the waste and subsequent settling of the particles (Sharvelle et al. 2011a). Since the addition of an inerts removal step can add capital and maintenance costs, developing an anaerobic digester that can effectively treat inert-laden material has been a priority for the Sharvelle Research Group (Sharvelle et al. 2011a; Lewis 2017b).

1.3 Background on High-Solids Anaerobic Digestion

As pointed out in Hinds 2015, it is important for anyone reviewing literature on anaerobic digestion to be aware that there are "numerous interchangeable terms" for high-solids anaerobic digestion; these terms may include any combination of the following terms: "solid-stage", "dry", "solid-substrate", "fermentation", and "anaerobic composting" (Hinds 2015). It may be advisable to become familiar with the HSAD literature review methodology presented in Appendix C of Hinds 2015.

The criteria for distinguishing between types of HSAD systems are loading conditions, number of stages, and operating temperature (Hinds 2015; Rapport et al. 2008) as illustrated in Figure 3.

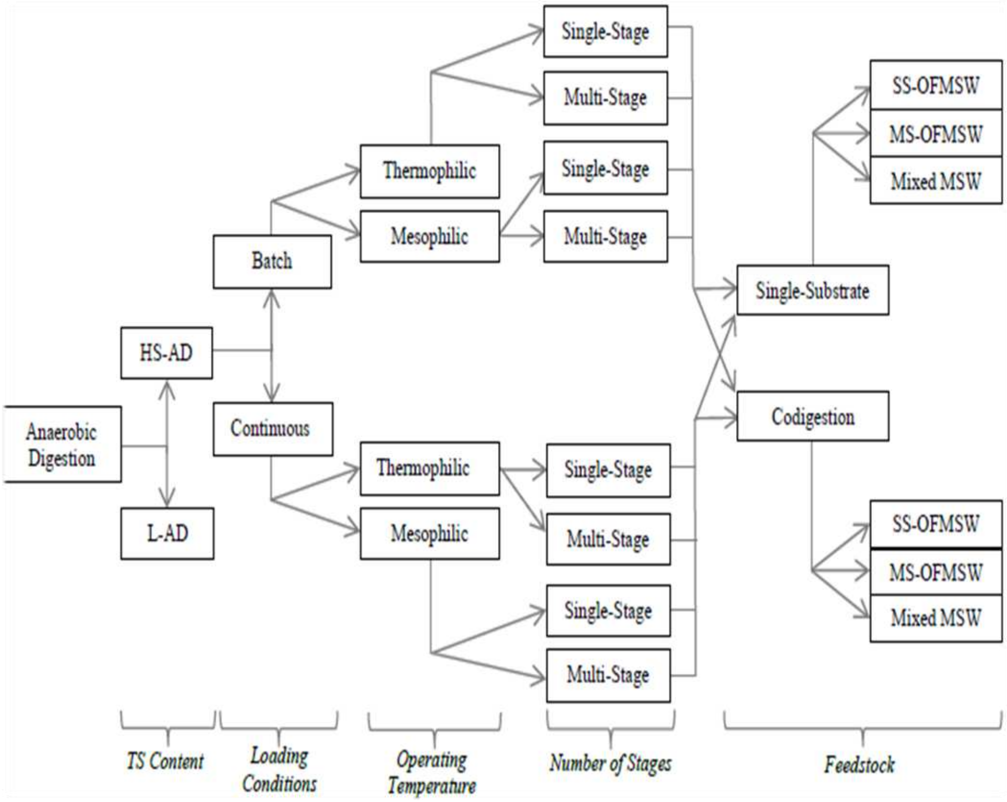
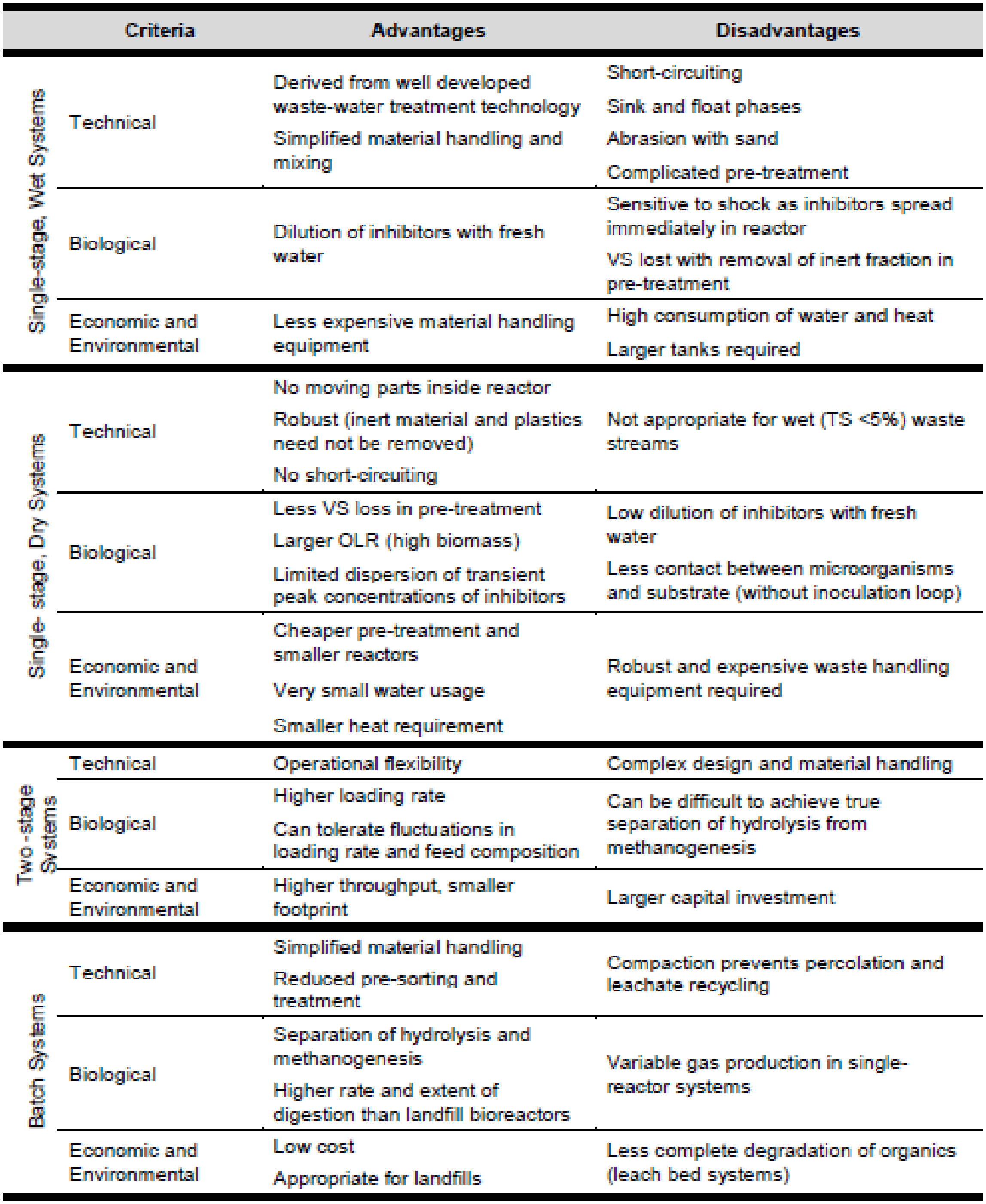


Figure 3 - "Possible AD system 'types' based on predominant system classification" (Hinds 2015)

Loading conditions can consist of batch or continuous reactor operation. Number of stages can consist of single-stage or multi-stage systems. Operating temperature can consist of mesophilic (35 degrees Celsius) or thermophilic (55 degrees Celsius). In addition, digester systems can be classified by whether they treat feedstock composed of a single substrate or multiple substrates. (Hinds 2015; Rapport et al. 2008)

Table 1 - "Summary of digester technology advantages and disadvantages" (Rapport et al. 2008)



	Criteria	Advantages	Disadvantages
Single-stage, Wet Systems	Technical	Derived from well developed waste-water treatment technology Simplified material handling and mixing	Short-circuiting Sink and float phases Abrasion with sand Complicated pre-treatment
	Biological	Dilution of inhibitors with fresh water	Sensitive to shock as inhibitors spread immediately in reactor VS lost with removal of inert fraction in pre-treatment
	Economic and Environmental	Less expensive material handling equipment	High consumption of water and heat Larger tanks required
Single- stage, Dry Systems	Technical	No moving parts inside reactor Robust (inert material and plastics need not be removed) No short-circuiting	Not appropriate for wet (TS <5%) waste streams
	Biological	Less VS loss in pre-treatment Larger OLR (high biomass) Limited dispersion of transient peak concentrations of inhibitors	Low dilution of inhibitors with fresh water Less contact between microorganisms and substrate (without inoculation loop)
	Economic and Environmental	Cheaper pre-treatment and smaller reactors Very small water usage Smaller heat requirement	Robust and expensive waste handling equipment required
Two-stage Systems	Technical	Operational flexibility	Complex design and material handling
	Biological	Higher loading rate Can tolerate fluctuations in loading rate and feed composition	Can be difficult to achieve true separation of hydrolysis from methanogenesis
	Economic and Environmental	Higher throughput, smaller footprint	Larger capital investment
Batch Systems	Technical	Simplified material handling Reduced pre-sorting and treatment	Compaction prevents percolation and leachate recycling
	Biological	Separation of hydrolysis and methanogenesis Higher rate and extent of digestion than landfill bioreactors	Variable gas production in single-reactor systems
	Economic and Environmental	Low cost Appropriate for landfills	Less complete degradation of organics (leach bed systems)

(Rapport et al. 2008)

1.4 MSAD Technology

Dr. Sharvelle's research group at CSU has been steadily investigating the feasibility of anaerobic digestion in Colorado for a number of years. As a result of limited technical and economic potential for LSAD implementation at dry lot AFOs in Colorado (Sharvelle et al. 2011a) , Luke Loetscher and Dr. Sharvelle applied the Theory for Inventive Problem Solving (known as "TRIZ") to develop a Multi-Stage Anaerobic Digester (MSAD) that was capable of handling the high-solids cattle manure (HSCM) found to be accumulating at many of the state's AFOs (Figure 4). (Sharvelle et al. 2011a)(Sharvelle et al. 2011b)

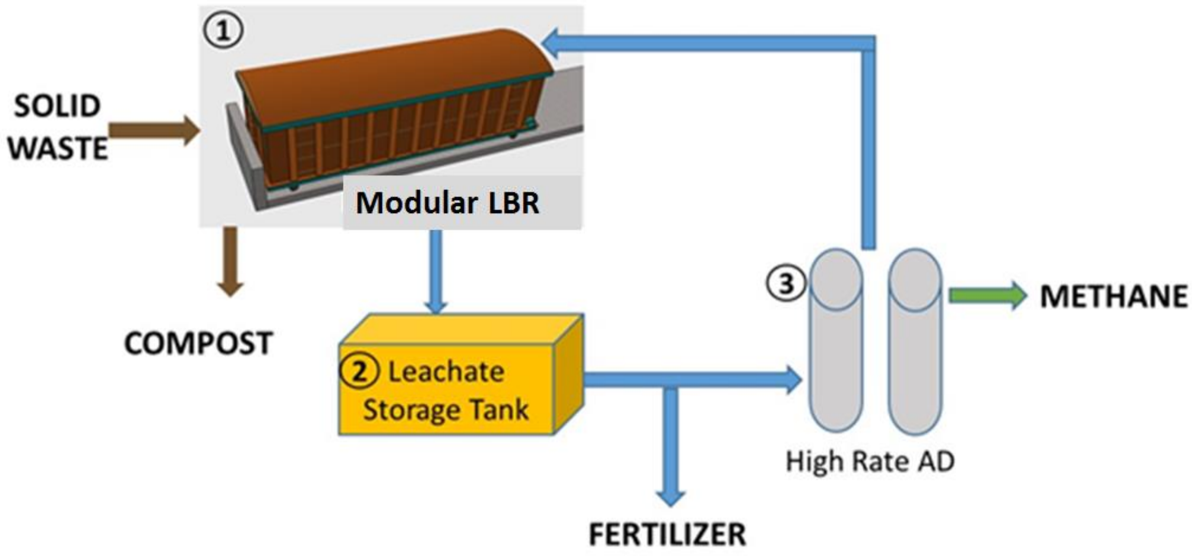


Figure 4 - MSAD Process (Sandefur 2017; Syed Reza)

The MSAD system is a HSAD technology that uses modular leach bed reactors (LBRs) (Figure 4). The modular LBRs can be constructed largely with commercial off-the-shelf (COTS) components and materials. The feedstock being treated is above 15% solids content and is generally handled as a solid material rather than a pumpable slurry. An important facet of the

MSAD system is the LBR, which introduces a small quantity of liquid through high solids waste (Figure 4 and Figure 5). The liquid is recirculated through the LBR where hydrolysis occurs until sufficient organic content has leached into the liquid. The concentrated organic content liquid is stored in a leachate storage tank (LST) and fed at a specified rate to a high rate anaerobic digester (fixed-film anaerobic reactor). Methane is generated in the fixed film reactor and can be subsequently used to fuel combined heat and power, methane vehicles, or purified and compressed for injection into natural gas pipelines. (Hanif 2013; Lewis 2017b)

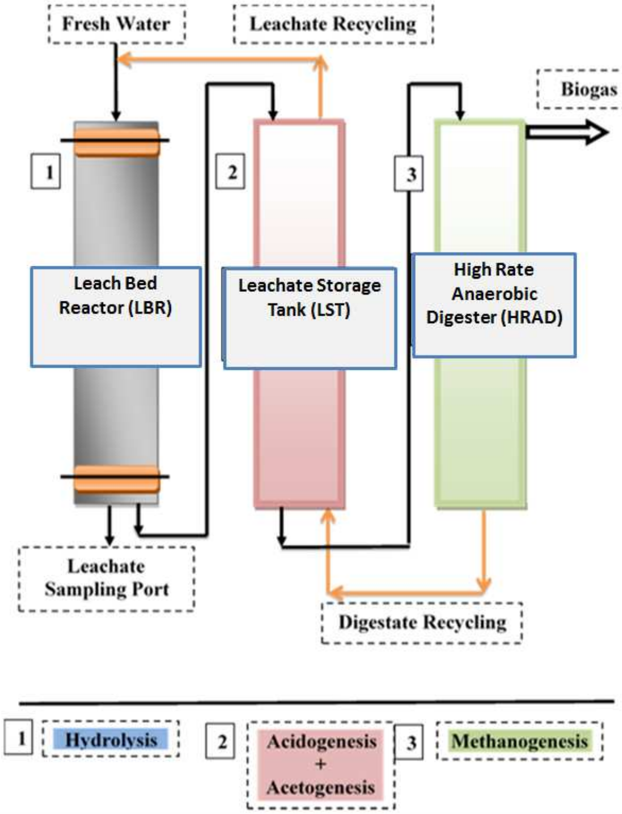


Figure 5 - MSAD Process Schematic (Hanif 2013)

The introduction and rate of continuous flow of liquid through the HSCM is dictated by hydraulic conductivity. Hydraulic conductivity is a function of the coupled physical, chemical, and biological phenomena occurring within the system. It is a crucial parameter for maintaining liquid recirculation during the entirety of the specified solids retention time. For the MSAD to function properly, flow must be sustained for the complete duration of the batch digestion with no clogging of the system. In addition to leachate flowing through an LBR, there are a number of analogous processes that can provide insight regarding reactor operation; these include flow through porous media in: leachate circulation in landfills, septic drain fields, static pile composting, hydraulic fracturing, soil irrigation, bioremediation, and trickle flow biofilters.

The Sharvelle Research Group has previously compared LSAD technologies (Sharvelle et al. 2011b; O*n Farm Anaerobic Digestion Feasibility Tool* (https://erams.com/AD_feasibility_general_info/) that are often used in the US for AD of manure. However, a gap in knowledge exists with respect to how the MSAD and other HSAD technologies compare to each other. Therefore, further advancement of the MSAD system may benefit from a comparison of HSAD technologies. There are a variety of HSAD technologies that have been applied in Europe (Rapport et al. 2008). These HSAD technologies have thus far been primarily used at commercial scale for AD of the organic fraction of municipal solid waste, and have not been applied for AD of manure. Since these technologies have been applied commercially in a successful manner, a comparison of their strengths and weaknesses can be instructive in further development of the MSAD system. The comparison, however, must be performed with a focus on how each digester’s relative advantages would manifest during the digestion of HSCM. The relevant subcriteria for this type of analysis include the systems’: number of individual reactors, material handling requirements, resilience to clogging, achievable flow regime, preprocessing requirements, and achievable volatile solids (VS) reduction.

Sustaining Liquid Flow through the MSAD

The Sharvelle Research Group has conducted previous research to assess clogging issues in LBRs (Hanif 2013; Wu 2017). Hanif (2013) evaluated the use of sand as a dispersion layer on top of the LBR manure bed. The dispersion layer was reported to promote improved hydraulic flow and reduce clogging problems. Hanif (2013) also performed a comparison of performance between nutrient dosed and non-nutrient dosed single-pass LBRs. Wu (2017) evaluated additional natural and geosynthetic materials for effectiveness as dispersion layers in LBRs. Wu (2017) found that using an upward flow configuration enabled leachate flow in the LBR to be sustained for longer average durations during batch digestion. However, Wu (2017) did not find the addition of a sand layer to be effective in all columns, so additional work is needed with the goal to elucidate potential mechanisms of hydraulic failure.

1.5 Use of Systems Analysis for Agricultural Waste Management

The precepts of Systems Engineering and Industrial Ecology can guide technical development efforts towards solutions which are conceived in a more holistic and sustainable manner than efforts undergirded by outmoded metanarratives. To realize global sustainability efforts, the needs of the human population must be met in a manner that maximizes the utility derived from renewable natural resources. The principles of Industrial Ecology can be applied to create coupled food, energy, and water systems that minimize waste and pollution. These systems—in addition to being complex per se—must be developed within an increasingly complex socio-technical milieu that must consider the consequences of both their current and long-term interactions with the natural world. Systems Engineering provides an esemplastic framework that facilitates instantiation of the complex engineered systems that will be needed to achieve a sustainable human ecology. (Lewis 2017d)

A growing population, along with rising incomes and accelerating urbanization, are driving an increased demand for the production of livestock (Herrero and Thornton 2013). “Recent global assessments have considered particular elements of livestock and livestock systems, but none addresses such systems and their considerable variations in a comprehensive, integrated way (Herrero and Thornton 2013).” “The lack of a systems perspective has also curtailed explorations of more sustainable options for the sector’s development (Herrero and Thornton 2013).” Implementing anaerobic digestion at AFOs can potentially address a variety of the economic, social, and environmental challenges faced in agriculture.

1.6 Research Motivation and Objectives

This thesis project was undertaken with the goal of improving the hydraulic performance of the LBR stage of the MSAD. Based on previous research, there remain some gaps in knowledge that would be useful in furthering the design of the MSAD system. There is a need to investigate how the MSAD compares to other HSAD technologies. Another gap includes the lack of knowledge regarding how LBRs will operate at a larger scale. Additionally, Wu (2017) points out that the reasons behind clogging issues and non-uniform hydrolysis in the LBR remain unknown. Therefore, there are gaps in our understanding of how the microscale structure of the HSCM affects hydraulic conductivity.

The objectives of this research were: 1) to assess the MSAD system in comparison to industrially relevant HSAD technologies to provide a frame of reference for informing design decisions during system development, 2) to assess the methods of maintaining hydraulic flow through the LBR that were deemed successful at the column scale and evaluate them at the prototype scale, and 3) to analyze the information obtained thus far on hydraulic failure and propose a line of research that may provide additional insights regarding possible mechanisms of hydraulic failure.

This thesis presents a Systems Engineering perspective on the research and development work undertaken to further the optimization of the MSAD technology, as well as presenting a detailed exploration of the avenues of inquiry and experimentation required to improve hydraulic performance in the LBR. Chapter 2 provides an explanation of the operational requirements and unique design features of the MSAD system. It presents the context within which initial design decisions were made and then compares the unique features of the MSAD to other industrially-relevant anaerobic digestion technologies. Chapter 3 presents information on the design and operation of the prototype-scale LBR. It explains the lessons learned during prototype operation and provides recommendation for future LBR design improvements. Chapter 4 gives an overview of an experimentation strategy aimed at understanding mechanisms of hydraulic failure and outlines a means of developing hydraulic control strategies to improve LBR performance.

CHAPTER 2: MSAD OPERATIONAL REQUIREMENTS AND UNIQUE DESIGN FEATURES

An understanding of the system design process in conjunction with the environment in which the system will operate can facilitate a properly designed system. System design "is an essential activity ensuring the orderly realization of the final configuration and composition of a system" (Blanchard and Fabrycky 2011). System design uses the following elements: an understanding of what the system is intended to do, operational requirements that describe "the functions that the system must perform to accomplish its intended purpose", exploratory studies that contribute to the definition of technical approaches, identification and prioritization of design criteria, performance of trade-off studies (equivalent to an MCDA), and selection of a system alternative (Blanchard and Fabrycky 2011).

This chapter is not intended to present an entire system design process. This chapter presents operational requirements and a trade-off study (MCDA) to provide a contextual exploration of the technical design space in which the MSAD system was conceived, with the objective of identifying unique design features of the MSAD and informing the focus of future design and research activities.

2.1 MSAD System Environment: Dry Lot Animal Feeding Operations

Figure 6 provides an illustration of a beef feedlot and its associated agricultural waste management system. This figure provides an overview of the possible elements in a beef feedlot, however this project assumes that the feedlot would not be paved, which means that the presence of inert material in the manure would likely be higher compared to waste from a paved feedlot.

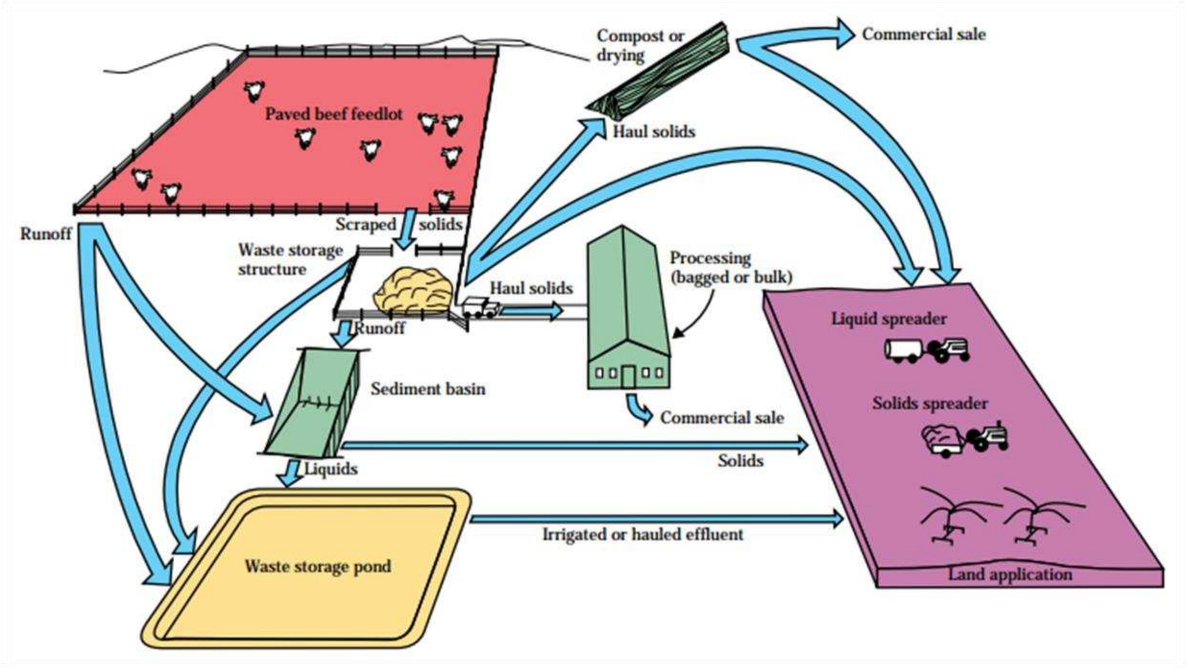
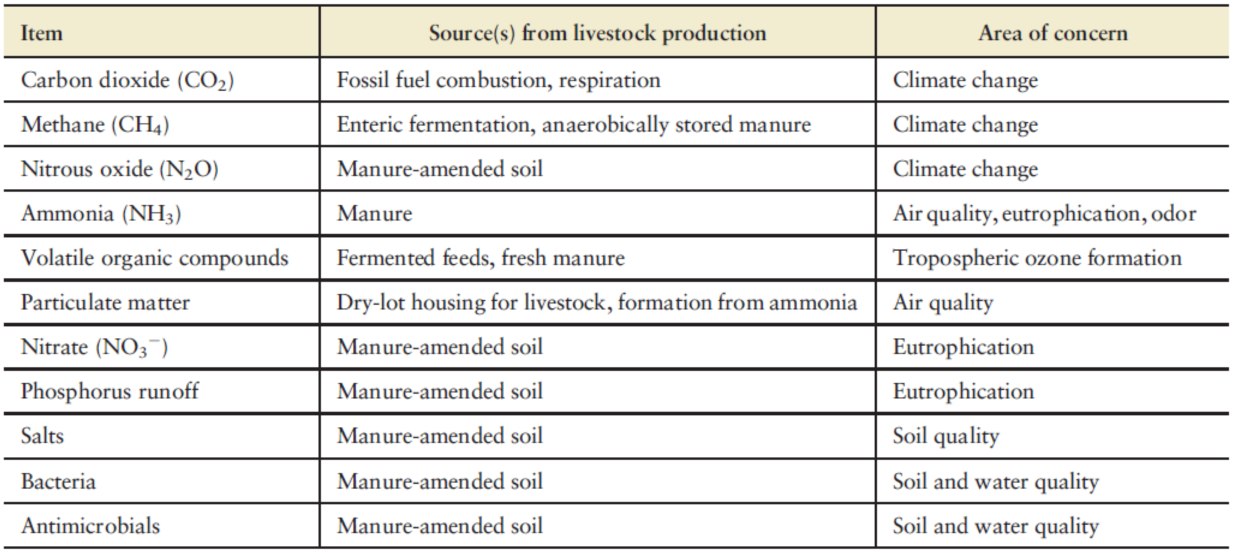


Figure 6 - Beef Feedlot Agricultural Waste Management System (USDA 2011)

2.2 Environmental Impacts Associated with Livestock Agriculture

The environmental impacts associated with livestock agriculture can generally be separated into problems stemming from air emissions and those stemming from water and soil quality (Table 2; Place and Mitloehner 2014).

Table 2 - Livestock Associated Environmental Impacts (Place and Mitloehner 2014)



Item	Source(s) from livestock production	Area of concern
Carbon dioxide (CO_2)	Fossil fuel combustion, respiration	Climate change
Methane (CH_4)	Enteric fermentation, anaerobically stored manure	Climate change
Nitrous oxide (N_2O)	Manure-amended soil	Climate change
Ammonia (NH_3)	Manure	Air quality, eutrophication, odor
Volatile organic compounds	Fermented feeds, fresh manure	Tropospheric ozone formation
Particulate matter	Dry-lot housing for livestock, formation from ammonia	Air quality
Nitrate (NO_3^-)	Manure-amended soil	Eutrophication
Phosphorus runoff	Manure-amended soil	Eutrophication
Salts	Manure-amended soil	Soil quality
Bacteria	Manure-amended soil	Soil and water quality
Antimicrobials	Manure-amended soil	Soil and water quality

2.2.1 Air Emissions

Greenhouse Gas (GHG) Emissions

The first type of air emissions produced due to livestock production are GHG emissions, primarily methane and nitrous oxide. Methane and nitrous oxide have 100-year CO_2 equivalent global warming potentials of 25 and 298, respectively. In the United States, emissions from enteric fermentation in ruminants results in 23% of emitted methane, while manure from all types of animals left in anaerobic conditions produces 9% of emitted methane. With regard to enteric fermentation in ruminant animals, "Total CH_4 emissions per animal per day will depend largely on the forage-to-concentrate ratio of the diet, the level of feed intake, the degree of fat inclusion in the diet, the digestibility of the carbohydrates in the diet, and the presence of any feed additives that may alter the microbial populations of the rumen (e.g., monensin)". (Place and Mitloehner 2014). Nitrous Oxide emissions from livestock result mainly from fields that have had manure applied to them. The primary mechanism for nitrous oxide emission is during the reduction of nitrate to dinitrogen during microbially-mediated denitrification. (Place and Mitloehner 2014)

Ammonia

Ammonia (NH_3) from manure is the chief pollutant, which impacts air quality due to livestock production. NH_3 is created when urea from animal urine mixes with the enzyme urease from animal feces and the urea is hydrolyzed. NH_3 emissions from livestock facilities can vary considerably due to the extent of mixing of urine and feces, pH, temperature, wind speed, manure management, and amount of protein in the livestock feed. (Place and Mitloehner 2014)

Particulate Matter

Particulate matter can be released into the air as a result of animals churning up the ground on dry lots, from animal-housing ventilation, or from dust stirred up from farm machinery. Particulate matter can be released indirectly via the creation of "secondary aerosol particles" that can form as a result of NH_3 emissions (Place and Mitloehner 2014). NH_3 emissions can also affect water quality as gaseous NH_3 can be redeposited onto land and surface water. (Place and Mitloehner 2014)

Volatile Organic Compounds

Volatile organic compounds are created mainly from fermented animal feed, with some minimal emissions coming off of manure. Some volatile organic compounds can also promote the oxidation of NO to NO_2, which along with direct sunlight can increase the production of photochemical ozone (O_3). (Place and Mitloehner 2014)

2.2.2 Water and Soil Quality

Runoff from animal feeding operations and manure-treated farm land are the primary means by which livestock production affects water and soil quality. Phosphorus and nitrogen are the most common elements that impact water quality. When manure is applied to farmland, NH_4^+ can be oxidized to NO_3^-, which is the form of nitrogen most able to leach out of soil and into groundwater (Place and Mitloehner 2014). NO_3^- in groundwater used for human drinking presents a risk of methemoglobinemia, a serious condition where hemoglobin has a reduced ability to transfer oxygen throughout the body (Self and Waskom 1992). Nitrogen and phosphorus are a major cause of eutrophication present in many bodies of water around the world. (Place and Mitloehner 2014) Appropriate use of anaerobic digestion enables increased control and mitigation of nutrients such as nitrogen and phosphorus.

Salts, Bacteria, and Antibiotics

Additional concerns related to water and soil quality are the release of salts, bacteria, and antibiotics into the environment. Salts can have a negative effect on plant growth as well as water quality. Bacteria and antibiotics are a concern for human and environmental health and safety, including food, water, and recreational contact. (Place and Mitloehner 2014)

2.3 System Operational Requirements

Livestock agriculture can have a variety of environmental impacts. These impacts include emissions that affect air, water, and soil quality. The MSAD system is designed to address the environmental impacts associated with livestock agriculture.

Defining the operational requirements of the MSAD provides a frame of reference for establishing system design and operation objectives. When the system's operational priorities are established, criteria can be selected and used to provide a relative assessment of how well each system alternative meets overall operational objectives. This section outlines the operational requirements of the MSAD and sets the stage for the MCDA presented in section 2.4 (Lewis 2017b; Blanchard and Fabrycky 2011).

Water requirement is a major consideration in the MSAD system design process. Due to limited water availability, many AFOs in arid regions do not use water to flush manure as part of their waste management system (Sharvelle et al. 2011a). In these situations, manure is generally scraped up, which can lead to manure with up to 90% solids (Sharvelle et al. 2011a). Since Colorado is located in the semi-arid Western United States, this system has been created with attention to digester water addition requirements.

In Figure 7 below, a decision tree for implementation of conventional anaerobic digester technology is presented (On Farm Anaerobic Digestion Feasibility Tool (https://erams.com/AD_feasibility_general_info/; Sharvelle et al. 2011b). The decision tree was created to be used by agricultural operators in semi-arid regions to evaluate the feasibility of successfully operating a conventional anaerobic digester based on their sites water availability (Sharvelle et al. 2011b). Figure 7 shows that AFOs which presently flush or scrape manure and have adequate water resources may be able to install a conventional anaerobic digester. Agricultural operations that use dry lot or concrete scrape manure collection which do not have sufficient water resources available face a significant technical impediment to successful operation of conventional anaerobic digesters. (Lewis 2017b)

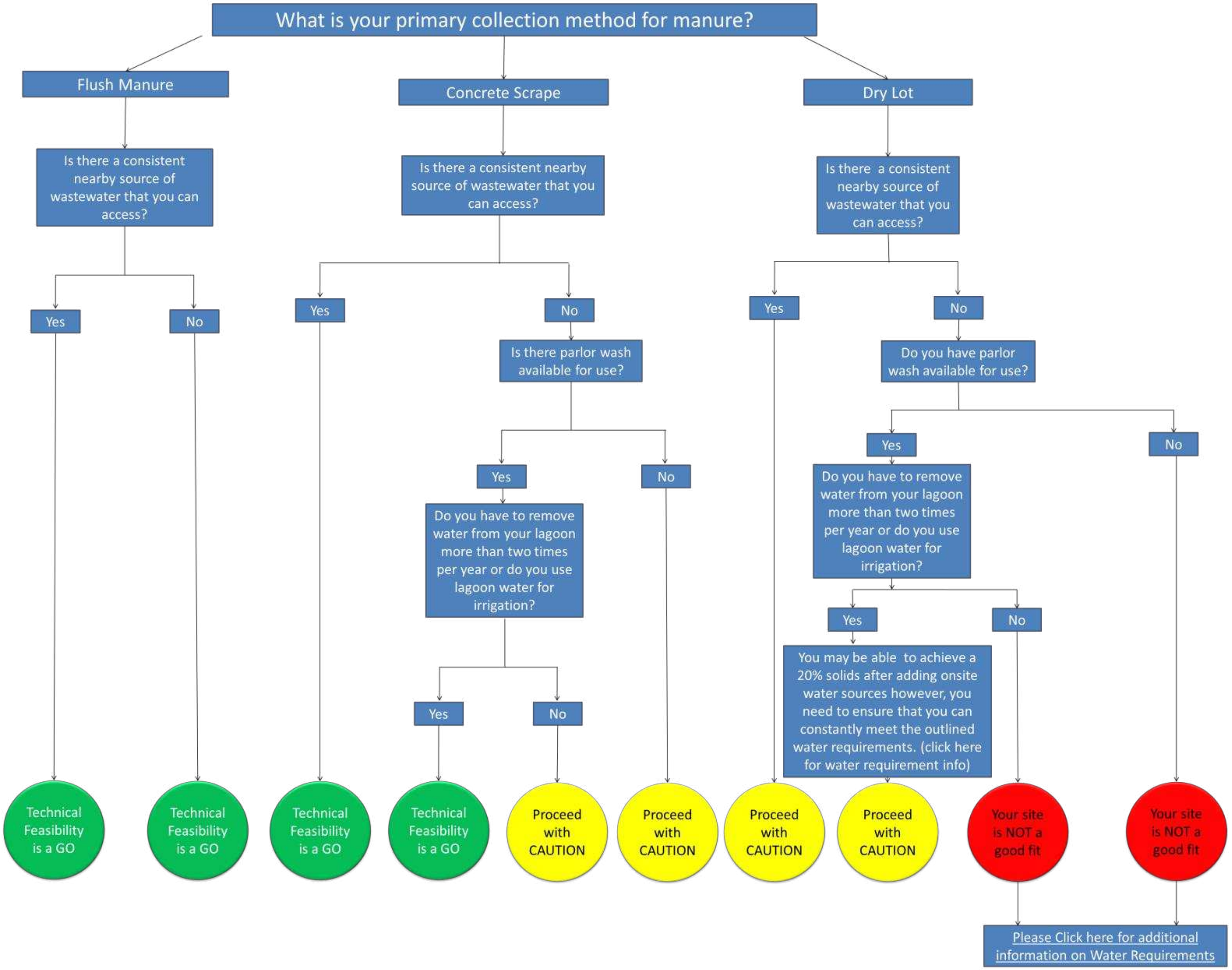


Figure 7 - Decision Tree for Implementation of Conventional Anaerobic Digester Technology (Sharvelle et al. 2011b)

This technical impediment provided the impetus to develop an anaerobic digester system that does not require large amounts of additional water for dilution of digester feedstock. Therefore, the capability to function with minimal supplemental water, while maximizing water recycling within the system has been recognized as a system operational requirement. (Lasker 2013; Lewis 2017b)

Description of Additional Operational Requirements

The system is a multi-stage, high-solids anaerobic digester, which is used for solids reduction and stabilization of cattle manure (Figure 5). The system will create a methane energy product, a liquid digestate fraction, a solid fiber fraction, and possibly additional high value organic products. The reactor will be operated at either a mesophilic (35 degrees Celsius) or thermophilic (55 degrees Celsius) temperature. To meet operational requirements, the system must operate above a minimum degree of waste degradation. The digester must be able to reach at least 40% volatile solids destruction. The system will operate in Colorado's semi-arid climate, on agricultural land. It will be repeatedly loaded with substantial amounts of waste material. The system must be resilient to the ongoing presence of organic acids created inside the reactor vessel. (Lewis 2017 b; Blanchard and Fabrycky 2011)

2.4 Assessing Performance of MSAD Technology via a Multi-Criterion Decision Analysis (MCDA)

A variety of HSAD technologies have been applied in Europe (Rapport et al. 2008). These HSAD technologies have been used at commercial scale largely for AD of the organic fraction of municipal solid waste, and have not been widely applied for AD of manure. Since these technologies have been applied commercially in a successful manner, a comparison of their advantages and disadvantages can be instructive in further development of the MSAD system. The comparison, however, must be conducted with an emphasis on how each digester's relative advantages would manifest during the digestion of HSCM.

This thesis has reviewed the important facets of the system environment (dry lot AFOs in Colorado) along with background information on the needs of AFOs for more advanced waste management practices. From this foundation, the project now presents a MCDA (trade-off analysis in Systems Engineering parlance). The objective of the MCDA is to identify unique design features of the MSAD system relative to other HSAD technologies, which helps inform the focus of future design and research activities. Conducting a MCDA elucidates the technical design space in which MSAD design decisions were made so that the information and recommendations in subsequent chapters can be better understood.

Technology Alternatives Assessed

The MCDA is used to evaluate CSU's MSAD system against four alternative technologies for HSAD of high-solids cattle manure. The alternatives include anaerobic digesters based on the following technologies (Table 3):

- **horizontal mixed plug flow**; this technology is a continuous, multi-stage, mechanically-mixed, plug flow reactor (Figure 8).
- **vertical pumped plug flow**; this technology is a batch, multi-stage, pump-mixed, plug flow reactor (Figure 9).
- **garage-type LBR**; this technology is a batch, single-stage, unmixed static pile, downflow LBR (Figure 10).

- **landfill-cell LBR**; this technology is a batch, single-stage, unmixed static pile, mesophilic/psychrophilic downflow LBR with waste bed integrated gas and leachate injection and collection (Figure 11).

- **modular LBR** (MSAD system), this technology is a batch, multi-stage, unmixed static pile, upflow LBR (Figure 4).

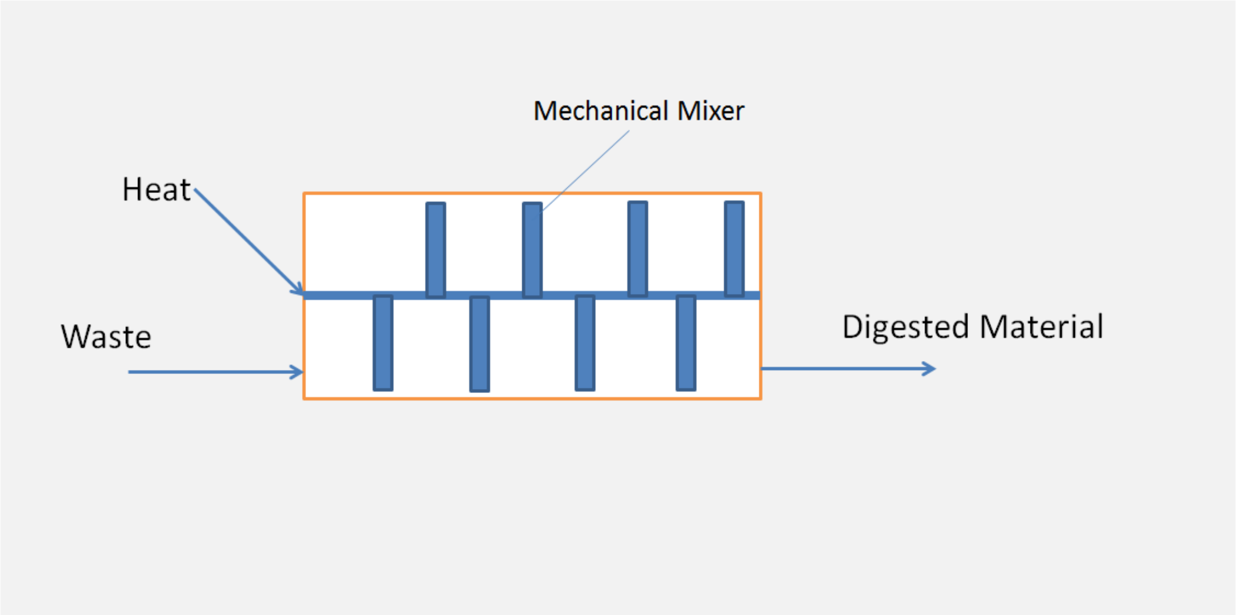


Figure 8 - Horizontal Mixed Plug Flow Process Schematic

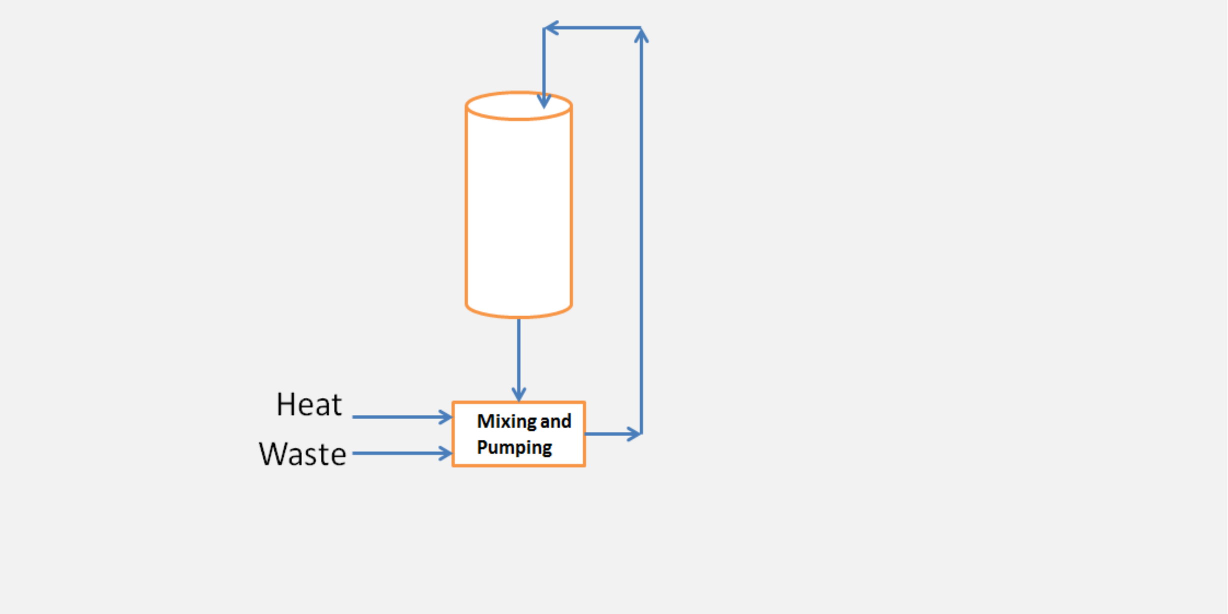


Figure 9 - Vertical Pumped Plug Flow Process Schematic

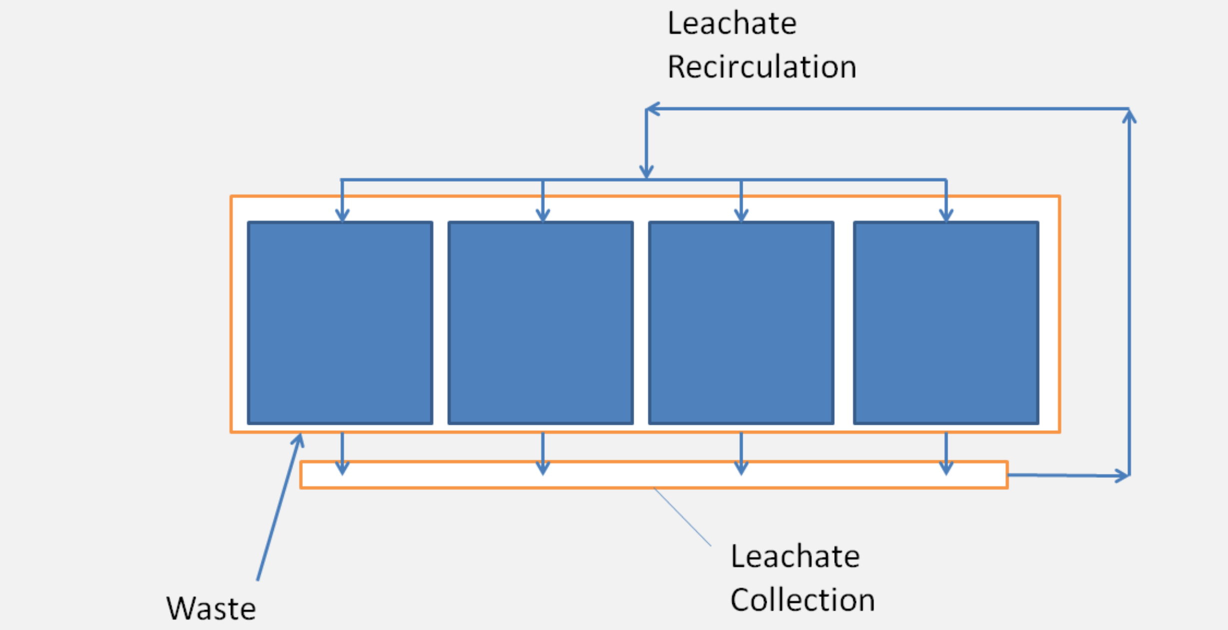


Figure 10 - Garage-Type LBR Process Schematic

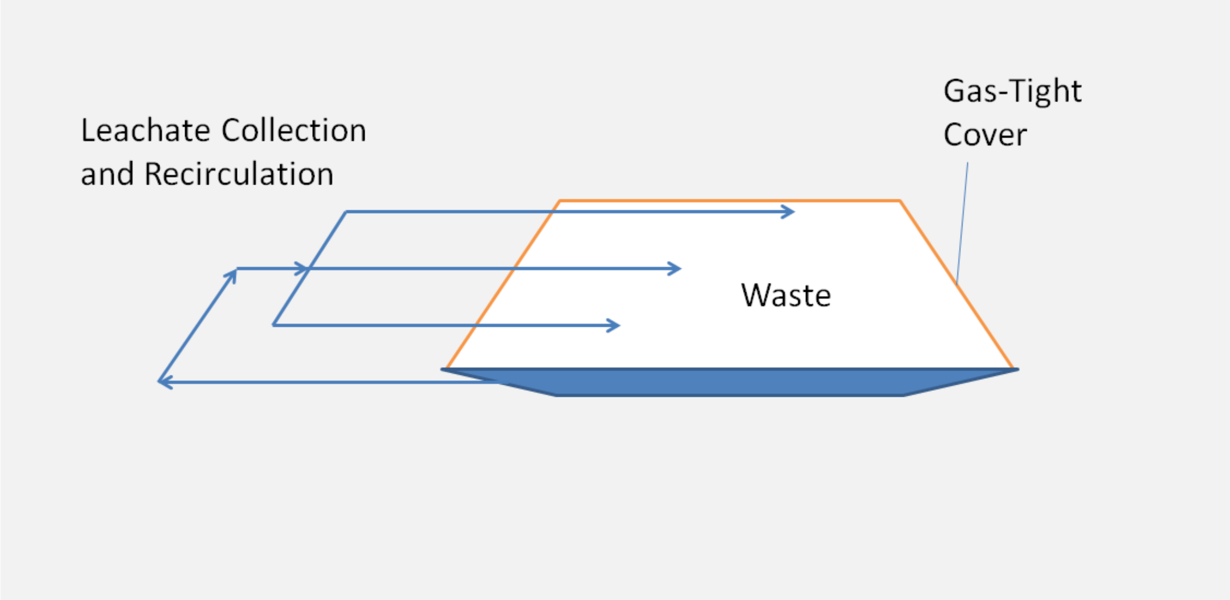


Figure 11 - Landfill-Cell LBR Process Schematic

MCDA Methodology

The MCDA provides an understanding of the MSAD's strengths and weaknesses relative to established industrially relevant systems. The basic data used in the MCDA analysis consists of a variety of digester operating parameters (Table 3). Where possible, the basic data is connected to the MCDA subcriteria and the respective rating for each alternative technology. The criteria (defined below) include: operational requirements, hydraulic failure, capital requirements, operational control, feedstock composition fit, and treatment efficiency.

The MCDA was conducted using a weighted average method for the main criteria scores via an Excel spreadsheet originally developed by Fontane and Sharvelle (2014). The main criteria were all given equal weighting to calculate the final score. The subcriteria were also given equal weighting to calculate the main criteria. The subcriteria were given ratings from 1 to 5 (using corresponding word scales), with 5 being the best and 1 being the worst (Fontane and Sharvelle

2014). A spreadsheet which shows the ratings entered into the MCDA tool can be found in Appendix A.

Table 3 - HSAD Data Linked to MCDA Basic Data

	Horizontal Mixed Plug Flow[1]	Vertical Pumped Plug Flow[1]	Garage-Type LBR[1]	Landfill-Cell LBR[2]	Portable Container LBR[3]
Total Solids Operating Range	25-35%	Up to 40%	Up to 50%	Up to 60%	Up to 60%
Loading Conditions	Continuous	Continuous	Batch	Batch	Batch
Operating Temperature	Mesophilic	Meso/Thermo	Thermophilic	Psychro/Meso	Mesophilic
Number of Stages	2 Stages	1 Stage	1 Stage	1 Stage	3 Stage
Retention Time	28 days	20 days	21 days	365 days	16 days
Preprocessing Required	No	Grind <40mm	No	No	No
	Criteria: Preprocessing	**Criteria:** Preprocessing	**Criteria:** Preprocessing	**Criteria:** Preprocessing	**Criteria:** Preprocessing
	Rating: Very Good	**Rating:** Poor	**Rating:** Very Good	**Rating:** Very Good	**Rating:** Very Good
Material Handling	Automated	Automated	Loader	Landfill Equip	Loader
	Criteria: Material Handling	**Criteria:** Material Handling	**Criteria:** Material Handling	**Criteria:** Material Handling	**Criteria:** Material Handling
	Rating: Low	**Rating:** Low	**Rating:** High	**Rating:** Very Low	**Rating:** Medium
Parasitic Energy	5-10%	Not Reported	20%	Not Reported	Not Reported
Mixing	Mechanical	Pump Mixed	None	None	None
	Criteria: Flow Regime	**Criteria:** Flow Regime	**Criteria:** Flow Regime	**Criteria:** Flow Regime	**Criteria:** Flow Regime
	Rating: Good	**Rating:** Very Good	**Rating:** Fair	**Rating:** Poor	**Rating:** Good
Leachate Flow Direction	Downflow	None	Downflow	Downflow	Upflow
	Criteria: Flow Regime	**Criteria:** Flow Regime	**Criteria:** Flow Regime	**Criteria:** Flow Regime	**Criteria:** Flow Regime
	Rating: Good	**Rating:** Very Good	**Rating:** Fair	**Rating:** Poor	**Rating:** Good
Leachate Recirculation	Continuous	None	Continuous	Continuous	Continuous
	Criteria: Flow Regime	**Criteria:** Flow Regime	**Criteria:** Flow Regime	**Criteria:** Flow Regime	**Criteria:** Flow Regime
	Rating: Good	**Rating:** Very Good	**Rating:** Fair	**Rating:** Poor	**Rating:** Good
Footprint	Medium	Smaller	Medium	Very Large	Large
Handling Inert Particles	Non-Batch Loading	Non-Batch Loading	Batch Loading	Batch Loading	Batch Loading
	Criteria: Inerts Handling	**Criteria:** Inerts Handling	**Criteria:** Inerts Handling	**Criteria:** Inerts Handling	**Criteria:** Inerts Handling
	Rating: Fair	**Rating:** Poor	**Rating:** Very Good	**Rating:** Very Good	**Rating:** Very Good
Hydrolysis Stage Resilience	Single Vessel	Single Vessel	Multiple Vessels	Single Vessel	Multiple Vessels and Stages
	Criteria: Hydrolysis Stage	**Criteria:** Hydrolysis Stage	**Criteria:** Hydrolysis Stage	**Criteria:** Hydrolysis Stage	**Criteria:** Hydrolysis Stage
	Rating: Poor	**Rating:** Very Poor	**Rating:** Good	**Rating:** Very Poor	**Rating:** Very Good
Composting	Windrow	Windrow	In-Vessel	In-Situ	In-Vessel

1) Hinds 2015; 2) CalRecycle Yolo County 2010; 3) Advanced Industries Final Report

The following explains the assumptions and rationale used in assigning ratings to the criteria. A more detailed explanation of the rating assignment process is available in Appendix B)

Operational Requirements

- *Number of Individual Reactors:* assumes that operational complexity will increase with an AD system that has a higher quantity of reactors. This is due to the need for increased process monitoring and sequencing of LBRs to provide a consistent stream of leachate for conversion to methane. While leachate storage capacity can alleviate some of the concern over steady leachate production, process control (including pumping and valve control) will remain more complex in a system with a higher number of individual reactors. Systems with lower operational complexity receive a higher rating (Table 3).
- *Material Handling Requirements:* evaluates the technologies based on how the systems range from completely manual to fully automatic loading and unloading of feedstock material (Table 3). Technologies with fully automatic loading and unloading of feedstock receive higher ratings due to reduced labor intensity.

Impact of Hydraulic Failure

- *Hydrolysis Stage Resilience:* assumes that the technologies with a larger number of LBR reactors will have a higher degree of resilience to a hydraulic failure occurring because if one LBR fails, it can be taken offline without causing a major disruption. Systems with a higher number of LBR reactors receive higher ratings (Table 3).
- *Flow Regime (hydraulic performance):* evaluates the unique aspects of how feedstock and leachate move through the system give a different level of advantage to each

technology. Systems that can move both the feedstock and the leachate internally receive a higher rating because they have an easier time maintaining the hydraulic performance of the reactor compared to systems that have a static pile waste bed (Table 3).

Capital Requirements

- *Number of Stages:* is quantified using the actual number of stages in the systems. Single stage systems are rated higher due to the lower capital intensity of their designs (Table 3).
- *Retention Time:* is quantified using the actual retention times used by the systems. Systems with lower retention times receive higher ratings due to their ability to process more waste over the course their lifetime (Table 3).
- *Preprocessing Requirements:* is quantified based on the nature of preprocessing required by the systems. A higher rating is given to systems that can operate with minimal preprocessing (Table 3).
- *Reactor Materials Costs:* is based on the resources required to construct the reactors. Systems which have lower materials costs receive higher ratings (Table 3).

Operational Control

- *Customizable Operating Conditions:* assessed the systems' abilities to tailor reactor conditions to a feedstock. Systems that can change process conditions more easily receive a higher rating (Table 3).
- *Customizable Retention Time:* is quantified by evaluating how well each system can tailor the time needed to achieve adequate treatment levels given variation in the

characteristics of each load of feedstock. Systems with a higher number of LBRs receive higher ratings (Table 3).

Feedstock Fit

- *Inerts Handling:* Systems that have static pile waste beds that can be completely emptied have an easier time handling feedstocks with inert materials. Therefore these systems received higher ratings (Table 3).
- *Total Solids (TS) Operating Range:* the LBR systems can handle higher total solids compared to the plug flow systems. Therefore these systems received higher ratings (Table 3).

Treatment Efficiency

- *Volatile Solids (VS) Reduction:* is quantified by the reactors' abilities to destroy volatile solids in the feedstock. Systems that can achieve higher levels of VS reduction receive higher ratings (Table 3).
- *Customizable Retention Time:* is quantified by evaluating how well each system can tailor the time needed to achieve adequate treatment levels given variation in the characteristics of each load of feedstock. Systems with a higher number of LBRs receive higher ratings (Table 3).
- *Biogas Production Stability:* is quantified by the reactors’ ability to produce biogas in a stable manner. Systems that have a high degree of process control, hydrolysis stage redundancy, and leachate storage capacity received the highest ratings (Table 3).

MCDA Results and Implications

The MCDA results provide insight into the advantages and disadvantages of five different high-solids anaerobic digester designs. The modular LBR (MSAD system) received the highest rating of all the technologies with a score of 3.7 out of 5 (Figure 12).

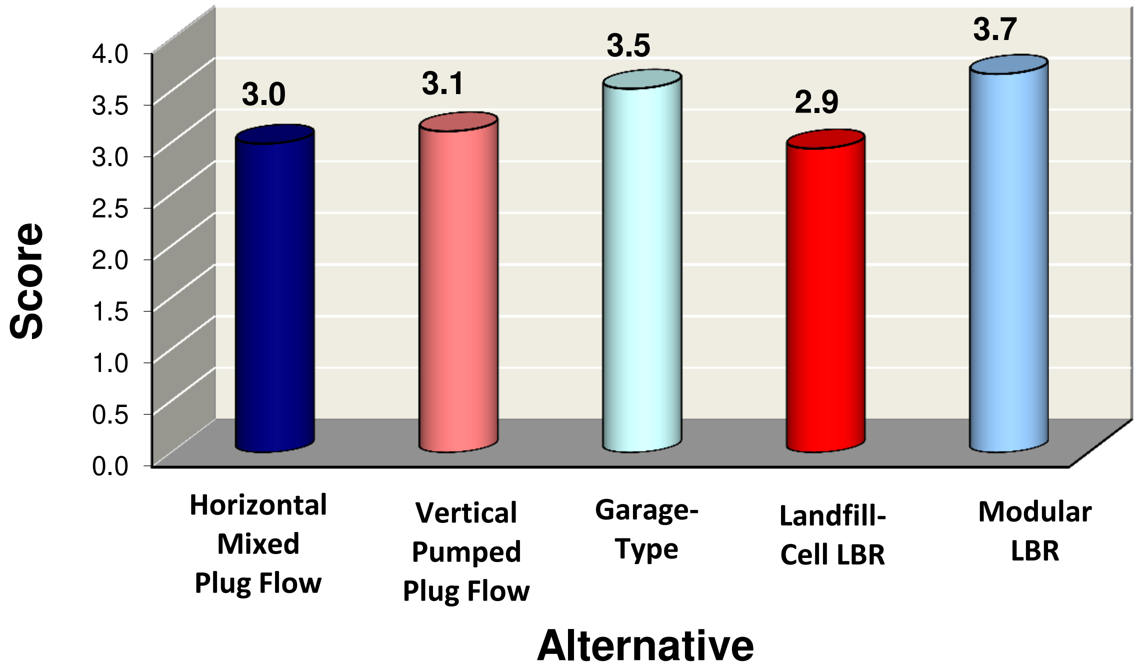


Figure 12 - MCDA Ratings for Technology Alternatives. Note: A higher rating represents a more favorable alternative

Under equal criteria weighting, the MSAD system received the highest rating due to its strong hydraulic performance, operational control, and process efficiency, whereas it was less competitive with respect to capital and operational requirements (Figure 13). Due to the lower scores for capital and operational requirements, it is recommended that future development efforts continue to focus on minimizing equipment and operating expenses.

The garage-type LBR technology was the second highest rated alternative with a score of 3.5 out of 5 (Figure 12). It had very favorable ratings for capital requirements and feedstock fit (Figure 13). In addition, this technology had relatively favorable ratings for operational control, impact of hydraulic failure, and process efficiency. The garage-type LBR had a relatively low rating for operational requirements due to its substantial material handling requirements.

The vertical pumped plug flow technology was the third highest rated alternative with a score of 3.1 out of 5 (Figure 12). It had favorable ratings in operational requirements and process efficiency, whereas it had unfavorable ratings in operational control and feedstock fit (Figure 13). The horizontal mixed plug flow technology was the second lowest rated alternative with a score of 3.0 out of 5 (Figure 12). It had a relatively favorable rating for capital requirements, an unfavorable rating for feedstock fit, and mid-range ratings for the other criteria (Figure 13).

The landfill-cell LBR technology was the lowest rated alternative with a score of 2.9 out of 5 (Figure 12). It had very favorable ratings for operational requirements and feedstock fit due to its low material handling requirements and ability to tolerate feedstock with high contamination of inert particles (Figure 13). However, the landfill-cell LBR's low ratings for all of the other criteria led to its low overall score.

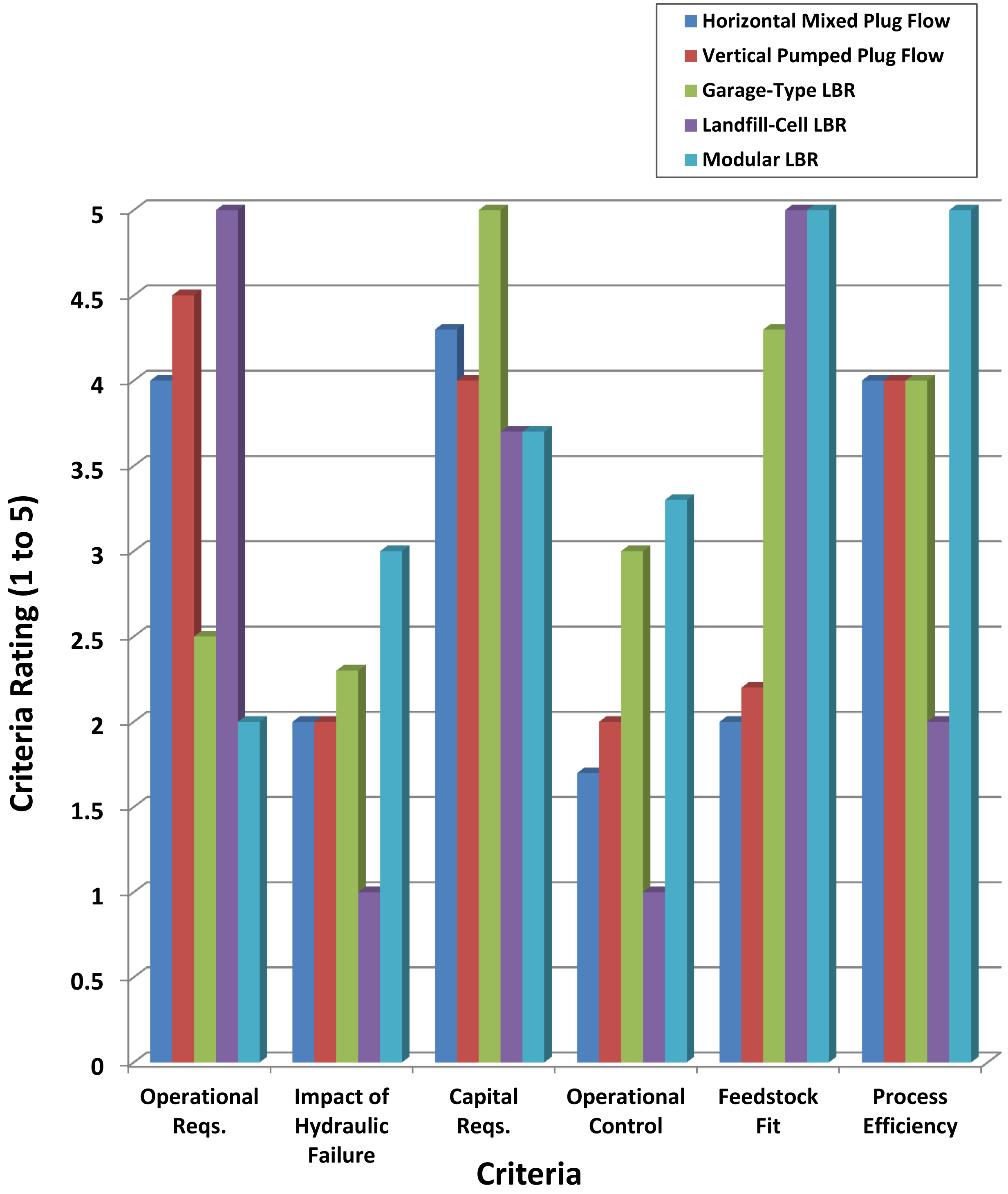


Figure 13 - Criteria Ratings for Technology Alternatives. Note: A higher rating represents a more favorable alternative

The above results were obtained under equal criteria weighting (Figure 12 and Figure 13). A sensitivity analysis can be used to understand the effect that variations in weighting have on the outcome of the MCDA (Figure 14). To perform the sensitivity analysis, one criterion weighting was increased to 3 (on a scale of 1 to 4) while the other criteria weightings remained at 1. The analysis was carried out in 6 runs, such that each criterion had a run where its weighting was increased to 3 (Figure 14).

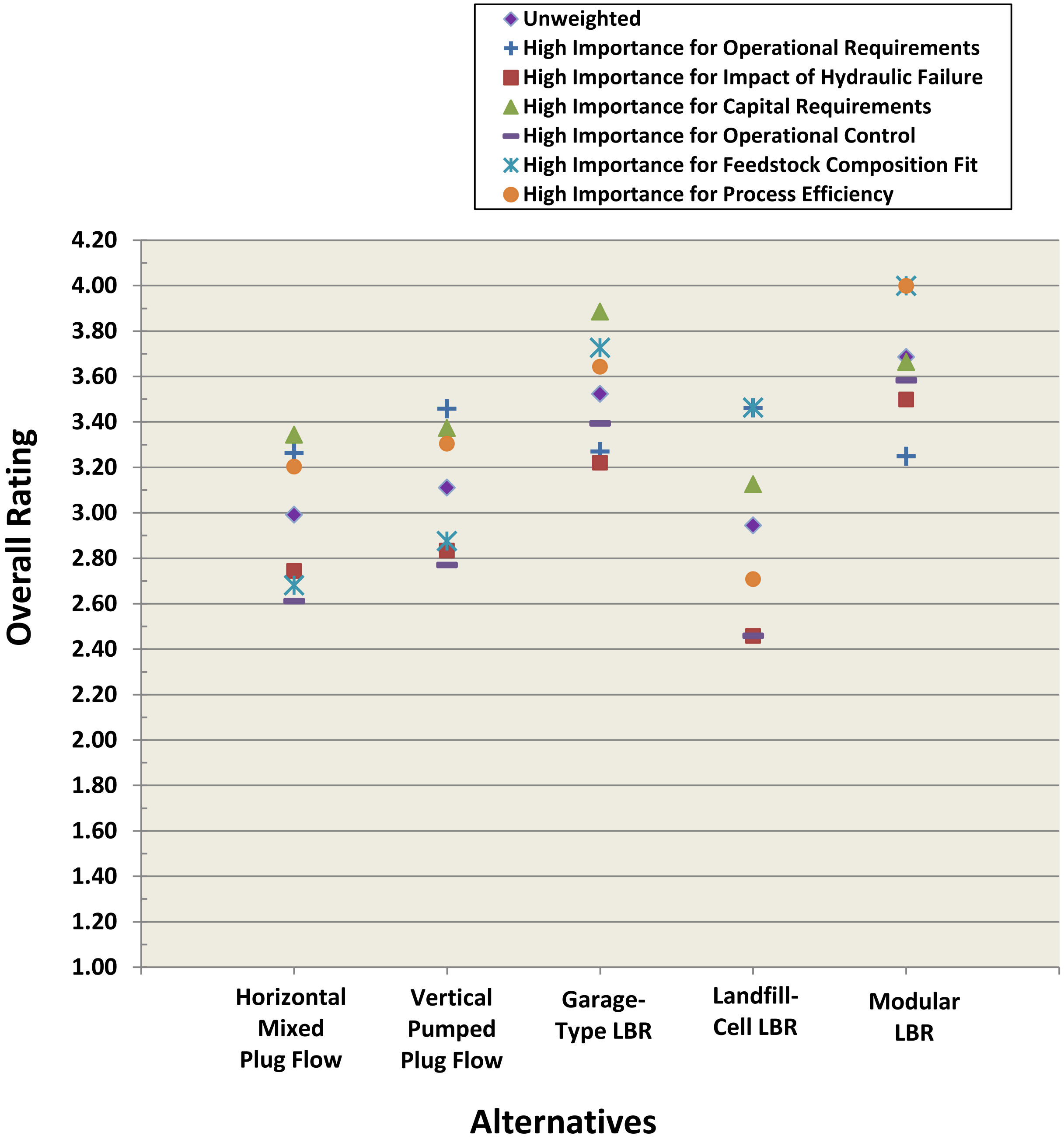


Figure 14 – Sensitivity Analysis of Overall Rating. Note: A higher rating represents a more favorable alternative

The modular LBR had its best overall rating under scenarios with increased weighting for feedstock fit and process efficiency (Figure 14). The modular LBR had its worst overall rating under the scenario where the weighting for operational requirements was increased (Figure 14). These sensitivity analysis results are logical due to the fact that the modular LBR has the best unweighted criteria ratings for feedstock fit and process efficiency, while it has the worst unweighted criterion rating for operational requirements.

It is worth noting that even though the landfill-cell LBR has the lowest reactor materials cost, it remains the weakest alternative even when the weighting for capital requirements is increased. This occurs because its extremely long retention time (365 days) relative to other technologies (14-28 days) negates the advantage of its low material cost. This indicates that the overall viability of a technology is influenced by the amount of material the technology can degrade over its lifetime, normalized by the cost of building the reactor. The sensitivity analysis demonstrates that the fundamental relationships in the reactor design space are typified by trade-offs between the benefits of increased performance achieved through enhanced process control and efficiency and the increased operational and capital costs required to implement these higher performing system alternatives.

The average rank of the modular LBR was 1.7 (Figure 15). The least favorable rank of the modular LBR was 4, which occurred when the weighting of the operational requirements criterion was increased (Figure 15). The most favorable rank of the modular LBR was 1, which occurred when the criteria weighting of the hydraulic failure impact, operational control, feedstock fit, and process efficiency were increased, respectively (Figure 15).

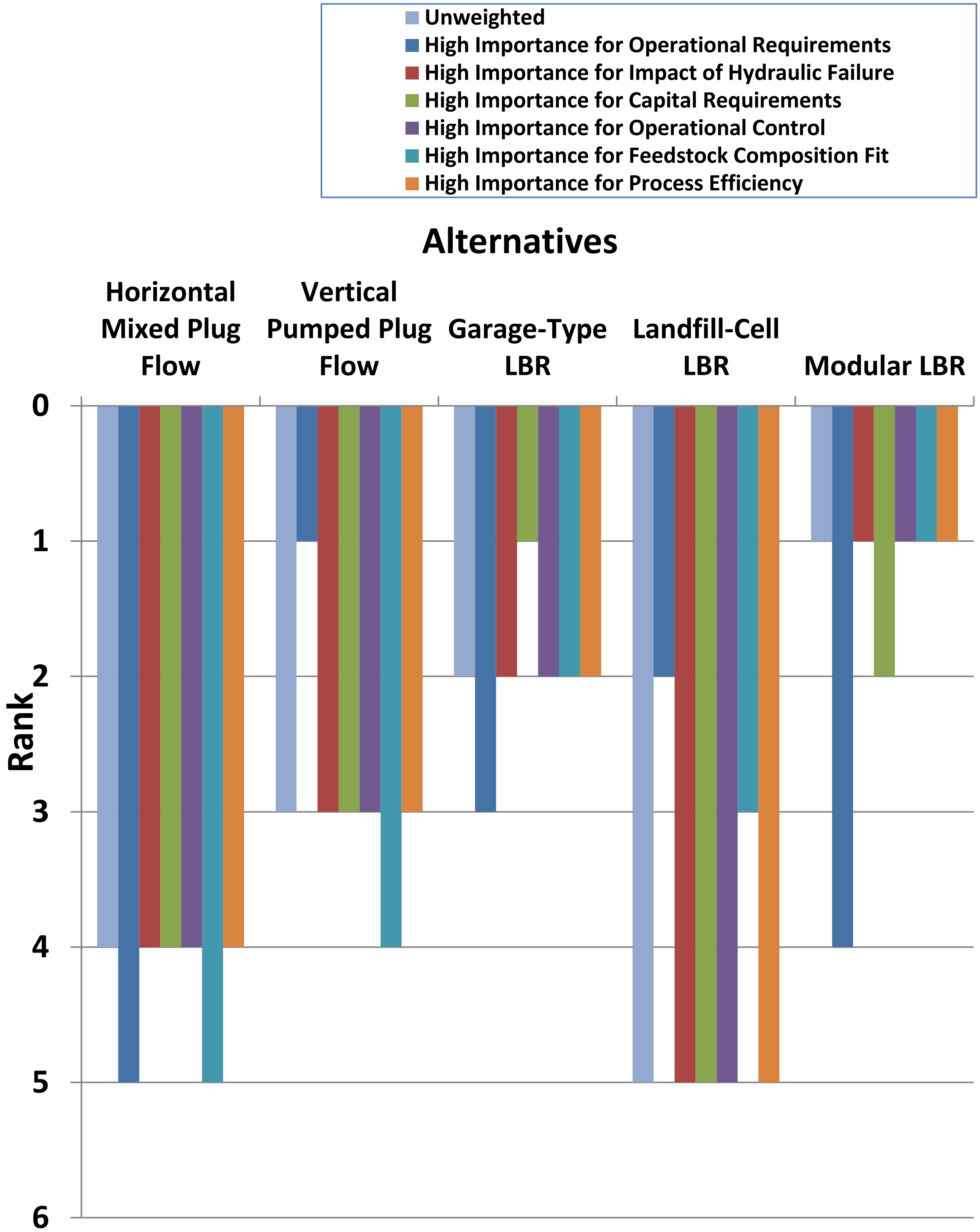


Figure 15 – Sensitivity Analysis of Overall Rank. Note: a rank of 1 represents the most favorable alternative, while a rank of 5 represents the least favorable alternative.

The modular LBR (MSAD system) compares favorably with the other system alternatives (Figure 15). Due to its high number of LBRs, the MSAD has advantages with respect to resilience to hydraulic failure. It also competes well with respect to operational control, due to its customizable operating conditions and retention time for each batch of waste. The MSAD also compares favorably to the other alternatives with respect to process efficiency, due to its high degree of volatile solids reduction and biogas production stability.

Summary

The MCDA indicated that under a scenario with unweighted criteria, the MSAD system received the most favorable rating of all the alternatives with a score of 3.7 out of 5. Results of the sensitivity analysis indicated that the MSAD was ranked as the most favorable alternative for all but 2 of the scenarios.

Ideal research and development pathways should be selected based on their potential to increase the overall commercial viability of the MSAD system. The overall viability of a digester is strongly determined by the quantity of material it can degrade over its lifetime, normalized by the costs associated with the reactor. Results from the sensitivity analysis suggest that the central relationships in the reactor design space are characterized by trade-offs between the benefits of increased productivity achieved through enhanced reactor performance and the increased operational and capital costs required to implement these higher performing system alternatives.

While future MSAD studies may progress by focusing on LBR design strategies that strike the optimal balance between increased reactor performance and increased capital and operating costs, it is recommended that strategies for mitigating hydraulic failure in LBRs be explored as well. This thesis particularly recommends that future research explore the development of hydraulic control strategies, which may have the potential to increase reactor performance by promoting flow through the static pile waste beds of LBR-based digester systems. LBRs are typically lower-cost technologies compared to systems with extensive pumping or mechanical mixing. If hydraulic control strategies can be employed through low-cost biological additives or modification of the operating procedures of existing equipment, it may be possible to improve performance without substantially increasing costs. This approach may provide a pathway to increased commercial viability of the MSAD system, which would not be possible solely through optimization of reactor design trade-offs.

CHAPTER 3: OPERATION OF PROTOTYPE LEACH BED REACTOR

3.1 Introduction and Background

The LBR is a critical part of the MSAD system since hydrolysis can be a rate-limiting step in the anaerobic digestion of HSCM (Hinds 2015; Veeken and Hamelers 1999). To ensure that hydrolysis is occurring properly within the reactor, leachate injection and reactor operation must proceed in a manner that facilitates uniform distribution of leachate through the manure waste bed. Since the leachate must be recirculated through the LBR for the entirety of the batch digestion time, any phenomena that disrupt the duration or uniformity of leachate distribution must be addressed. At commercial scale, hydraulic failure of LBRs would lead to reduced biogas and agricultural product generation and increased operating costs. Since commercial processes are reliant on consistent output, a high level of LBR dependability is required to achieve technical and economic viability. Therefore, control over the hydraulic performance of LBRs is crucial for commercialization of the MSAD system. This chapter presents work at the prototype scale aimed at addressing problems related to clogging and preferential pathways in the LBR. The experiments were aimed at characterizing the flow of leachate through the HSCM to understand how hydraulic performance in the LBR influences overall operation of the MSAD system.

The Sharvelle Research Group has conducted multiple rounds of experimentation to develop the MSAD system's ability to treat HSCM. Wasserbach (2013) evaluated the use of straw and wood bulking agents, as well as removal of small manure agglomerations. Straw was reported to result in the largest increase in permeability of the manure. Tracer tests were conducted to evaluate the mean residence time of leachate percolating through the manure. "Tailing of residence time distribution curves and inability to recover all injected salt indicates the likelihood of dead zones within reactors (Wasserbach 2013)." To address clogging issues in the LBR, Hanif (2013) evaluated the use of sand as a dispersion layer on top of the LBR manure bed (Figure 16). The dispersion layer was reported to promote improved hydraulic flow and reduce clogging problems.

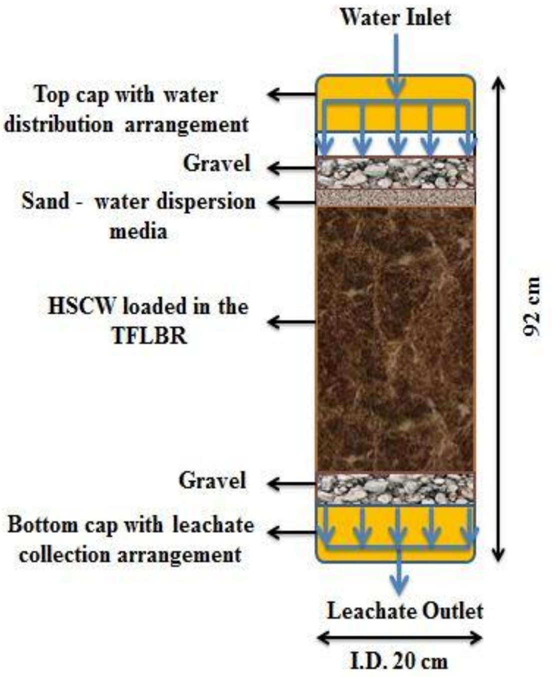


Figure 16 - LBR Column Schematic (Hanif 2013)

Wu (2017) evaluated additional natural and geosynthetic materials for effectiveness as dispersion layers in LBRs. Column studies were conducted to evaluate top and bottom packing materials in the LBR (Wu 2017). Materials were selected for testing of their efficacy as a dispersive layer that would facilitate the unroiled distribution of leachate through the HSCM. In the initial LBR configuration, leachate was introduced from a nozzle located at the top of the reactor. The leachate trickled down through the HSCM in the reactor and leached organic matter out of the solid phase and into the liquid phase. In this configuration the reactor was termed a Trickle Flow

Leach Bed Reactor (TFLBR). A number of different materials were assessed as potential reusable dispersion layers, which were hypothesized to be capable of preventing the formation of an impermeable crust at the infiltrative surface of the manure. The materials that were tested in column studies included: sand, gravel, a non-woven monofilament geonet composite, an 8 ounce geotextile, a geotextile bag filled with sand, and various size distributions of agglomerated manure particles (Wu 2017). Wu (2017) found that none of these materials were effective for maintaining hydraulic flow, but that using an upward flow configuration enabled leachate flow in the LBR to be sustained for longer average durations during batch digestion (Figure 17). (Wu 2017)

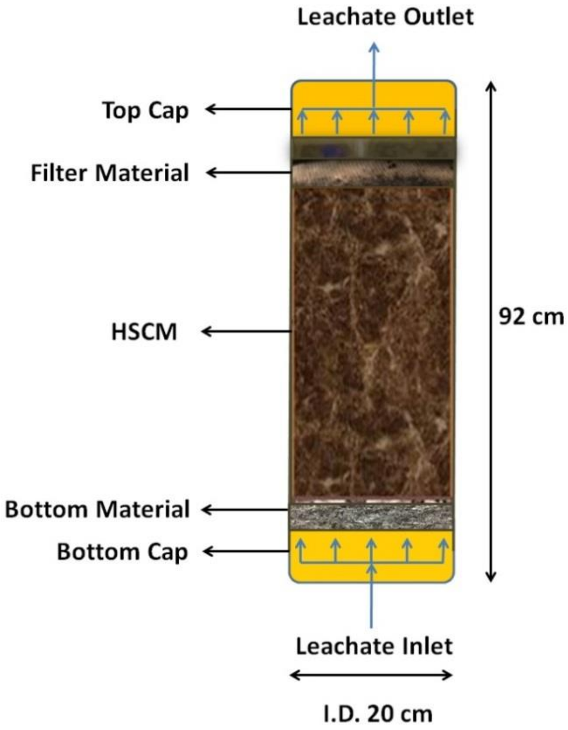


Figure 17 - Upflow LBR Reactor Schematic

In this research, a prototype LBR was constructed to evaluate—at a larger scale—the findings from the column LBRs. The operational objectives were to test the hydraulic performance of the upward flow configuration LBR prototype and to evaluate any issues that presented themselves as part of the scaling-up process.

3.2 LBR Prototype Methods

Design of Prototype-Scale Upflow Leach Bed Reactor

The prototype LBR, referred to as a leachate module (LM) used a four cubic yard metal dumpster prefabricated by WastEquip (Arvada, CO) as the primary reactor vessel. The CSU Engineering Research Center Machine Shop (Figure 18) fabricated a movable support structure with a built-in battery-powered tipping mechanism. The dumpster was structurally reinforced and fashioned with a load-bearing centrally mounted torque shaft, which allowed an electric motor to rotate the dumpster upside-down when the processed manure residual solids needed to be emptied.

Figure 18 - Picture of LBR Prototype

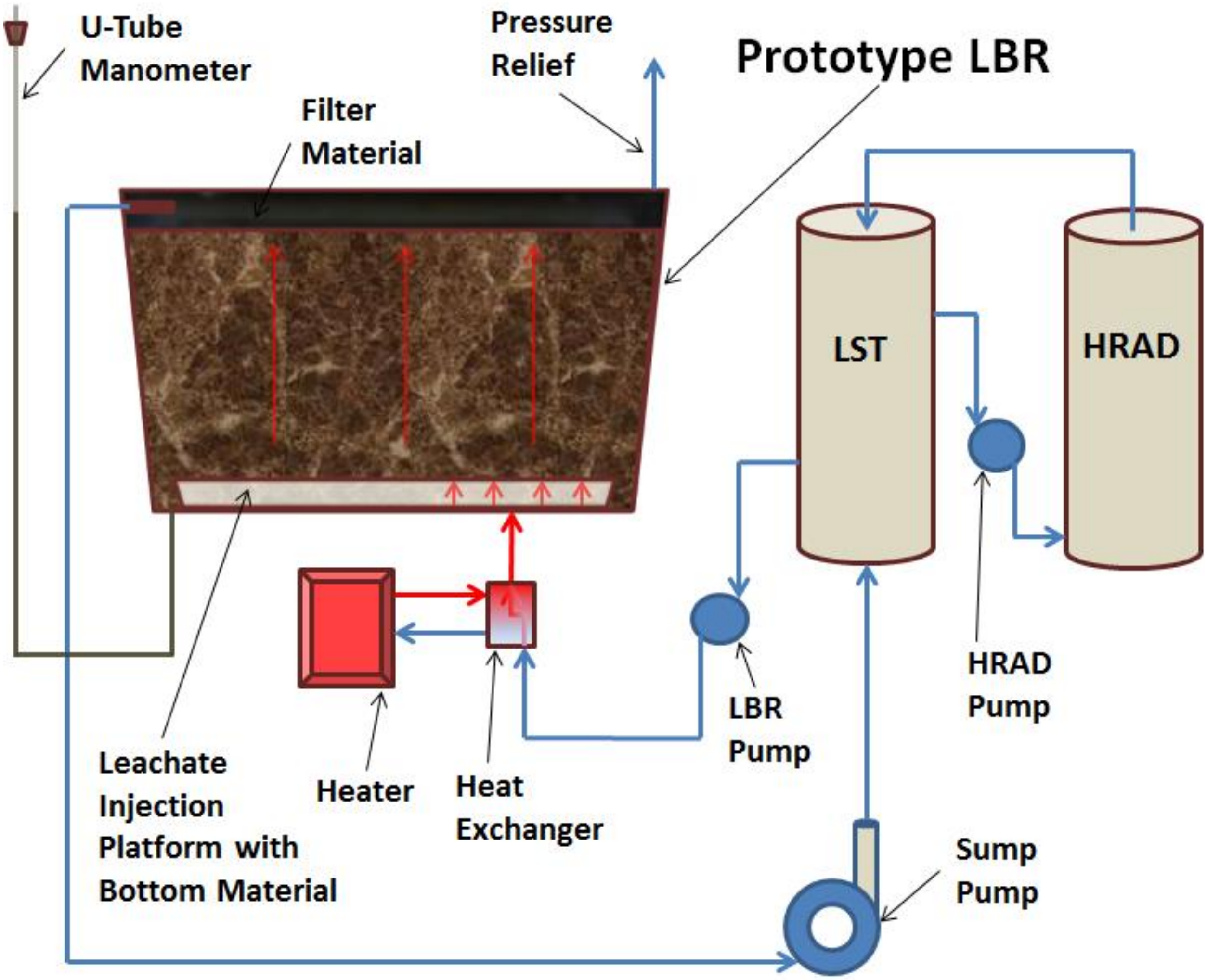


Figure 19 - Prototype LBR and MSAD System Schematic

The reactor was designed to be easily filled with a small skid-steer loader. This configuration allowed a very close simulation of how manure would be loaded at a commercial facility. The reactor design worked effectively as the vessel was easily filled and emptied during routine operation. To empty the reactor, the valves to the leachate tubing were closed and the union fitting was disconnected from the vessel. The vessel was allowed to drain by gravity through the ports located at the bottom for approximately 15 minutes. The electric motor was then used to rotate the vessel upside-down so the residual solids could be collected with a small skid-steer loader.

The prototype used a 7 kW SH07 electric on-demand water heater (Seisco) to heat a ½” PEX tubing (Mr. PEX) hydronic loop that included an 8 plate braze plate heat exchanger (GEA Systems), which the leachate passed through before being added to the reactor (Figure 19). The intent of the heating system was to make sure that the waste bed was permeated with a constant temperature leachate. This ensured that the waste bed would reach operating temperature quickly after initiation of digestion.

Leachate tubing, made from clear 1” braided vinyl style 3150 tubing (Kuriyama), was introduced through the bottom of the reactor and the leachate was injected into the reactor through a manifold (Figure 20). Leachate was pumped using a low-voltage DC pressure-demand equipped diaphragm pump (NorthStar). The manifold was constructed by drilling holes in a piece of clear 1” braided vinyl style 3150 tubing (Kuriyama). The manifold was located in a space underneath the leachate injection platform. The leachate injection platform was constructed out of a plastic nestable ProStack distribution pallet (Polymer Solutions International), which had numerous holes drilled so that leachate could permeate through while still supporting the weight of the waste bed. The bottom layer used in the prototype reactor was a non-woven monofilament geonet composite synthetic material (unknown manufacturer) (Figure 20) attached to the platform with 8” nylon cable ties (Boen).

Figure 20 - Leachate Injection Platform

Left: Non-Woven Monofilament Geonet Composite Bottom Layer Material.

Right: Bottom Layer Material Attached to Leachate Injection Platform

The leachate permeated up through the waste bed and was removed from the reactor through a leachate collection filter made of 4” Filter Fabric Sock (Drain-Sleeve). Once the leachate passed through the filter, it flowed by gravity to a 1/3 HP Model 237 Sump Pump (Liberty Pumps), which moved it back to the Leachate Storage Tank (LST). Gas was vented out of the reactor through a liquid gas barrier (constructed of PVC piping). U-tube manometers were constructed from clear 1” braided vinyl style 3150 tubing (Kuriyama) and used to monitor liquid level and gas pressure within the reactor (Figure 19).

Experiment Design and Analysis of Performance

One experiment with a duration of 14 days was conducted with the prototype LBR. The flow rate was approximately 1 liter per minute. It was selected to provide a hydraulic loading rate comparable to that used in the column experiments (Wu 2017). The hydraulic loading rate was approximately 518 liters per m^2 per day. As discussed above, the liquid distribution system for the LBR was modified to an “up-flow” configuration to help mitigate clogging issues. At the prototype scale, the liquid distribution system was fed from the inlet port located at the bottom right of the reactor (Figure 19). The leachate was fed into a diffusion space that was designed to promote homogeneous flow up through the bottom material and into the manure.

Collection of leachate from the prototype was performed daily by collection of 1 liter samples from ports located on both the influent and effluent tubing. COD data was not analyzed because it was realized that the random addition of water needed to maintain consistent pumping meant that samples would not provide reliable COD values.

Upon completion of the batch digestion time, it was discovered through visual observation that the manure on the right side of the reactor (directly above the leachate inlet) had noticeably more interaction with the permeating leachate, while the manure on the left was markedly less processed. The reactor was allowed to drain of excess leachate and was rotated nearly on its side using the electric motor. Three samples from the left side of the dumpster and three samples from the right side of the dumpster were taken after completion of digestion and VS measurements were performed.

TS was defined as the mass of solids remaining in a sample after all moisture was evaporated by placing the samples in an oven at 110 degrees C for 2-6 hours (Wu 2017). 5-10g samples of homogenized pre-digestion and post-digestion HSCM were placed in aluminum dishes (Wu 2017). The value for TS of the sample equals the mass of the sample and the dish after evaporation minus the mass of the dish (Wu 2017). Fixed Solid (FS) was defined as the mass of solids remaining after the samples were heated in a furnace for one hour at 550 degrees C. The value for FS equals the mass of the sample and the dish after heating in the furnace minus the mass of the dish (Wu 2017). VS was defined as the mass of solids that were volatilized in the furnace. VS was calculated by taking the value for TS and subtracting the value for FS (Wu 2017).

$$VS\,\% = \frac{mass\ of\ sample\ after\ drying - mass\ of\ sample\ after\ furnace}{mass\ of\ sample\ after\ drying} * 100$$

(Rice et al. 2012)

In addition to the upflow configuration discovered during column scale operations, top and bottom layers for the LM were also investigated. However, the reconfiguration of the liquid distribution system to upflow affected the required functions of the top material. In the modified configuration the top layer must, at minimum, serve to filter the leachate to prevent larger insoluble manure particles and inert materials from moving out of the reactor. Commercially available French Drain cover (Drain-Sleeve) was used as a filter material, which worked well at both the column and prototype scales during the course of the experiments.

3.3 LBR Prototype Results

Liquid flow was sustained through the LM without clogging over the duration of operations (14 days). Upon completion of the batch digestion, it was discovered through visual observation that the manure on the right side of the reactor (directly above the leachate inlet) had noticeably more interaction with the permeating leachate, while the manure on the left was markedly less processed. This observation was supported by measurements of initial and final volatile solids. The final VS of the manure on the left side had 15% VS, while the right side had manure with a final level of 10% VS after a digestion time of 14 days (Figure 21); There is a significant difference between the final VS on the right and the final VS on the left based on a two-sample t-test (P(T<=t) two-tail = 0.013, α = 0.5). Many of the columns ended up with roughly 10% volatile solids at similar digestion times, so it was concluded that the liquid distribution system worked better on the right side of the reactor. Further optimization efforts should examine leachate injection spacing as a key design criterion.

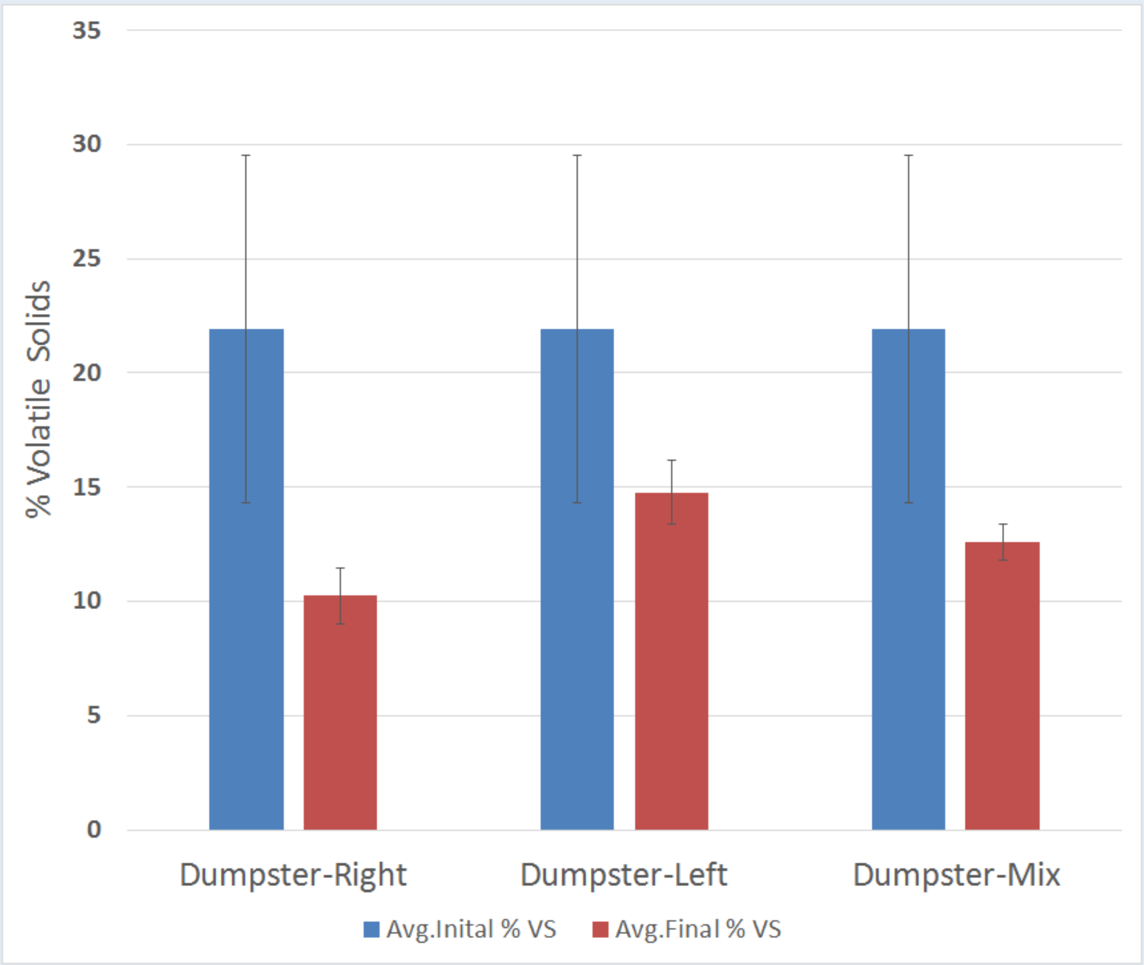


Figure 21 - Average Initial and Final Volatile Solids in Prototype Experiment

The upflow configuration validated via column studies was also successful to sustain liquid flow in the LBR prototype. This was demonstrated via duration of liquid flow (14 days) and successful breakdown of volatile solids in the LBR prototype (Figure 21). Collection of leachate from the prototype was performed; however, COD data was not analyzed due to the random addition of water needed to maintain consistent pumping. This occurred because the size of the prototype was so much larger than the columns that water had to be added to the LST to keep it full as leachate was initially introduced to the prototype. The issue of managing liquid in the system also led to irregular leachate recirculation flow, as leachate would exit the prototype intermittently, apparently as a result of corresponding pressure fluctuations observed via the u-tube manometers.

A secondary function of the top layer may be to hold the manure in an intact structure so that it is not fluidized into slurry by the permeating leachate. This secondary function requires more research because it affects the solid content of manure substrate during reactor operations. Careful management of the amount of solids and liquid in the reactor and the overall system are important to the optimization of the MSAD, since the system is designed to treat manure with minimal water input. Further investigation should focus on the useful life and cost of the filter material to gain a better understanding of reactor operating costs.

The bottom layer used in the prototype reactor was a non-woven monofilament geonet composite synthetic material. It was an ideal material for allowing the leachate to permeate the manure in a homogeneous manner. Future research may focus on the physical layout of the structural support that undergirds the non-woven monofilament geonet composite. Future designs must trade-off between supporting the weight of the manure above, while ensuring that leachate is homogeneously distributed from the dispersion area to the synthetic bottom material. While the prototype's bottom layer worked well, further research may be able to develop a bottom layer substructure that can be easily mass-produced.

3.4 Issues to Address with Prototype LBR

Issues encountered with regard to prototype operation included problems with the anchoring of the leachate injection apparatus, a need to optimize leachate injection spacing, and intermittent exiting of leachate. It may also be possible to improve the prototype heating system. To improve the functioning of the Prototype LBR, the following modifications are recommended: anchoring of the leachate injection apparatus, addition of a top layer, optimization of leachate injection spacing, replacement of sump pump with continuous pump, and modification of the heating system.

Leachate Distribution

The leachate injection apparatus should be anchored to the bottom of the reactor. The injection platform floated to the top after the manure bed became liquefied. A top layer should be added to keep the manure bed intact so that optimal leaching can occur and the liquefaction of manure can be prevented. Additionally, the distribution of leachate injection spacing should be optimized so that leachate distribution can occur to the maximum extent feasible, while maintaining a cost-effective design. It was observed that the manure bed underwent a higher degree of degradation directly above the leachate injection manifold, whereas the manure farthest from injection was less degraded. This was a visual observation, which prompted additional scrutiny of spatially resolved VS degradation measurements. The leachate injection manifold was positioned under the right side of the prototype. The final VS of the manure on the left side had 15% VS, while the right side had manure with a final level of 10% VS after a digestion time of 14 days (Figure 21).

Leachate Circulation, Pressure, and Flow

The flow rate was through the LBR was set at approximately 1 liter per minute. It was selected to provide a hydraulic loading rate comparable to that used in the column experiments (Wu 2017). Since complete clogging was not observed during operation of the prototype, the intermittent nature of leachate effluent flow from the LBR suggests that more attention may need to be paid to the possibility that intermittent operation of the downstream sump pump is preventing continuous, steady-state flow of leachate through the system.

Further research may need to undertake an evaluation of how well the sump pump is working within the process and assess how well (hydraulic) steady-state operation is achieved. Sump pump related back-pressure was suspected of causing intermittent exiting of leachate from the prototype LBR, which was visually observed during operation. Little to no leachate would exit the prototype for approximately 30 minutes, and then leachate would exit rapidly over the course of a few minutes.   An assessment of the system should evaluate whether or not the intermittent operation of the sump pump could be creating back-pressure that may decrease leachate permeation once the hydraulic conductivity of the waste bed has decreased. This may be occurring because the sump pump does not begin pumping until a certain amount of leachate has drained into it by gravity (Figure 19).   Leachate is more likely to be exiting the LBR at a higher rate if the sump pump is on compared to when the sump pump is off, since the downstream pressure (with respect to the LBR leachate effluent port) should be reduced when the pump is on. If the sump pump happens to be off, this may reduce the pressure differential that drives leachate flow out of the LBR. If the hydraulic conductivity of the waste bed has decreased, the reduced pressure differential caused by the sump pump being off may be critical to whether significant volumes of leachate continue to exit the LBR or not. If a significant volume of leachate (relative to the volume of liquid required to activate the sump pump) does not exit the LBR, the sump pump will not be turned on, which may prolong the period of leachate stagnation.

Replacing the sump pump with a continuously operating pump may reduce intermittency of the prototype's leachate effluent flow. A pump with energy use logging may be useful for correlating the degree of waste degradation achieved with the parasitic energy requirements of the system. The energy required to move leachate through the LBR prototype (in the upflow configuration) relates to the hydraulic conductivity of the waste bed. From a systems perspective, a deeper waste bed may enable more waste to be treated in a smaller footprint, however the power required to drive flow through a deeper waste bed should be evaluated as a future design criteria. Measurement and data logging of flow, pressures, and fluid addition at key points throughout the system could be helpful in understanding the total power required to drive flow through the system, as well as whether or not there are any bottlenecks in the system, which are reducing flow or increasing the overall power required to operate the system.

Also, an upgraded gas handling system with pressure release valves that can be set at a very low pressure may be helpful compared to the existing system that requires the displacement of water to allow gas to escape. The buildup of any additional gas pressure in the LBR may negatively affect the movement of leachate through the waste bed (Section 4.1.6 Gas Clogging).

LBR Heating

Future development efforts should undertake an evaluation of how well the LBR heating system is working. There were difficulties with leachate pre-injection heat exchange due to questionable thermistor readings and excessively frequent heating loop solenoid valve cycling. Additionally, putting the reactor in an enclosure that is kept at the same temperature as the reactor may help to maintain a constant, evenly-distributed vessel temperature. This may require a heat recovery ventilator for the enclosure space in addition to the existing pressure relief port**.** It is recommended that LBR operation be evaluated at the thermophilic temperature range (55 °C).

3.5 Summary of Prototype Findings

Column experiments and prototype operation showed some successful operation of LBRs for treating HSCM. However, there were a considerable amount of hydraulic failures or examples of sub-optimal hydraulic performance. There were multiple rounds of experimentation where at least one of three LBR columns either clogged completely or required a high amount of pressure to maintain flow (Wu 2017). Due to the continued risk of hydraulic failure, further research is needed to understand mechanisms for hydraulic failure and determine approaches to overcome this issue. At commercial scale, hydraulic failure of LBRs would result in decreased energy and agricultural product output and increased operating costs. Since commercial processes rely on reproducible results, a high degree of LBR reliability is required to achieve technical and economic feasibility. Therefore, control over the hydraulic performance of LBRs is critical for commercialization of the MSAD system. To this end, an experimentation strategy has been developed, which is intended to elucidate the mechanisms behind the hydraulic failures occurring in the LBR (Chapter 4).

CHAPTER 4: EXPERIMENTATION STRATEGY TO IMPROVE HYDRAULIC PERFORMANCE IN THE LBR

The LBR is a particularly important element of the MSAD system since hydrolysis can be a rate-limiting step in the anaerobic digestion of HSCM (Hinds 2015; Veeken and Hamelers 1999). For hydrolysis to occur effectively within the reactor, leachate injection and reactor operation must take place in a manner that facilitates uniform distribution of leachate through the manure waste bed. The leachate must be recirculated through the LBR for the entire duration of the batch digestion time. Accordingly, any phenomena that disrupt the duration or uniformity of leachate distribution must be addressed. A minimum acceptable level of hydraulic performance and reliability must be achieved in the LBR for the MSAD system to be a technically and economically feasible option for the treatment of HSCM.

It is likely that a number of coupled physical, chemical, and biological phenomena affect the hydraulic conductivity of the manure bed. The following is a non-exhaustive list of some of the types of hydraulic failure: biofilm clogging "closed pore model", biofilm clogging "open pore model", pore collapse by agglomeration deformation, colloidal particle pore-throat blockage, precipitation of insoluble salts, gas clogging, preferential pathways, and slurry formation.
This chapter explains possible types of hydraulic failure that may occur in the LBR, and the coupled physical, chemical, and biological mechanisms that may be causing the failures. The term hydraulic failure refers, not only to complete clogging of the LBR (in either the upflow or downflow configuration), but also to any pattern of leachate flow through the HSCM which results in inadequate production and discharge of hydrolysis products from the LBR. At commercial scale, hydraulic failure of LBRs would result in decreased energy and agricultural

product output and increased operating costs. Since commercial processes rely on reproducible results, a high degree of LBR reliability is required to achieve technical and economic feasibility. It is suggested that future research attempt to determine whether distinct "characteristic hydraulic failure modes" can be identified based on the presence of unique pore space network geometries, chemical oxygen demand (COD) output, and flow rate of LBR leachate effluent. An attempt should be made to determine if these patterns of hydraulic failure can be related to—and reproduced under—certain operating conditions, so that the mechanisms that cause these types of failure can be understood. When the mechanisms of hydraulic failure are better characterized, it is more likely that reactor design and operating conditions that avoid these types of problems can be developed.

4.1 Types of Hydraulic Failure

For the LBR to operate effectively there must be adequate contact between the leachate, feedstock, and anaerobic microorganisms. This requires leachate distribution through the macro-pores of the entire reactor, as well as, homogeneous distribution through the waste bed's capillary pore space. An attempt to describe possible mechanisms and control strategies for the types of hydraulic failures is given below in Table 4, however an a priori description is difficult and thus these mechanisms and strategies are presented as hypothetical.

Table 4 - Hydraulic Failure Mechanisms and Control Strategies

Hydraulic Failure Type	**Possible Hydraulic Failure Mechanism**	**Possible Hydraulic Control Strategy**
Biofilm Clogging “Closed Pore Model”	Slightly permeable biofilm clogs entire pore space	Quorum-sensing antagonists; Discontinuous leachate injection; Flow direction alternation
Biofilm Clogging “Open Pore Model”	Impermeable biofilm grows and decreases the effective cross-sectional area available for flow	Quorum-sensing antagonists; Discontinuous leachate injection; Flow direction alternation
Pore Collapse by Agglomeration Deformation	Manure agglomerations deform, pressing into each other and collapsing pore space	Decrease digestion time with thermophilic operation
Colloidal Particle Pore-Throat Blockage	A colloidal particle blocks the pore-throat, which prevents flow	Flow direction reversal
Mineral Precipitation	Insoluble salt precipitate forms in the pore space, which prevents flow	Change pH Critical imposed pressure head
Gas Clogging	Gas pockets form in the manure bed creating two phase flow in three dimensional porous media	Gas extraction wells
Slurry Formation	A slurry forms that negatively affects the rheological properties of the leachate	Aqueous chemistry additive and divalent cationic bridging theory
Preferential Pathways	Preferential pathways form reducing the active volume in the LBR	Leachate injection wells; Flow direction reversal; Quorum-sensing antagonists

The following subsections describe types of hydraulic failure that may be affecting the hydraulic performance of the LBR.

4.1.1 Biofilm Clogging

The growth of biofilms can have a drastic effect on the geometric and topological nature of the interstitial space within porous media (Kapellos et al. 2015). “As a consequence, the values of various transport coefficients, including the hydraulic permeability, the coefficients of diffusion, dispersion, mass transfer, adsorption, etc., will also be affected to a certain extent (Kapellos et al. 2015).” Biofilm growth has been observed to decrease the hydraulic permeability of porous media by a factor of “three or four orders of magnitude” (Kapellos et al. 2015). The extent to which permeability decreases is often strongly related to the interplay of genetic and phenotypic composition of biofilm microbial consortia, availability of nutrients, and the chemical characteristics of the gaseous, liquid, and solid constituents of the porous medium (Kapellos et al. 2015). These factors also interact with the geometric structure and the hydrodynamic characteristics resulting from flow through the medium (Table 4) (Kapellos et al. 2015).

Wimpenny and Colsanti 1997 reported a significant relationship between the availability of nutrients and biofilm morphology (Kapellos et al. 2015). “High nutrient concentration resulted in compact biofilms, while low nutrient concentration resulted in porous biofilms with dendritic structure (Kapellos et al. 2015).” This phenomenon could explain a possible scenario in the LBR in which the hydraulic performance of the reactor decreases due to biofilm activity. If a certain microbial community with a compact biofilm structure flourishes in the initial days of batch digestion due to the high concentration of readily solubilized substrate, then the hydraulic performance of the LBR may be diminished as decreasing nutrient concentrations lead to spatially expansive biofilm structures.

4.1.1.1"Closed Pore Model" Biofilm Clogging

The "closed pore model" of biofilm clogging is a proposed mechanism of hydraulic failure in which a slightly permeable biofilm clogs the entire pore space causing a reduction in the ability of liquid to flow through a porous medium. "Within the permeable biofilm, Brinkman's extension of Darcy's Law is considered as an appropriate equation to describe the flow along with the conservation of total fluid mass" (Kapellos et al. 2015; Appendix C). A similar phenomenon known as the formation of biofilm streamers could also result in a condition that could also be described as closed pore biofilm clogging (Drescher et al. 2013). A hydraulic control strategy that may be applicable is the alternation of leachate flow direction to disrupt formation of biofilms (Table 4).

4.1.2.2 "Open Pore Model" Biofilm Clogging

The open pore model of biofilm clogging is a proposed mechanism of hydraulic failure in which an impermeable biofilm grows on pore channel walls, effectively narrowing the cross-section available for flow. At constant pressure, this reduction in cross-section available for flow will decrease the flow rate of liquid through the porous medium. It is likely that some of the biofilm will detach during growth; this means that the effective channel diameter will be dictated by a balance between biofilm growth rate and biofilm detachment rate. A hydraulic control strategy that may be applicable is the alternation of leachate flow direction to disrupt formation of biofilms (Table 4). (Kapellos et al. 2015)

4.1.3 Pore Collapse by Manure Agglomeration Deformation

In this type of hydraulic failure, the manure agglomerations in the LBR deform under compaction and the pore collapses such that the effective diameter of the flow channel is reduced or completely eliminated. If found to be occurring, this mechanism is likely to happen after the manure agglomerations have become sufficiently saturated, such that they begin to soften and become susceptible to compressive forces. (Keyes et al. 2017; Garcia-Bernet et al. 2011)

A hydraulic control strategy that may be applicable is to decrease digestion time with thermophilic operation (Table 4).

4.1.4 Colloidal Particle Pore-Throat Blockage

Particles may dislodge from their original location and travel in the flowing fluid until they reach a narrow pore-throat farther downstream in the porous medium. Figure 22 below illustrates the concept of a narrow pore-throat (Dong 2007). This type of hydraulic failure may be caused by detached biofilm, eroded manure agglomeration, or by inerts such as sand. A hydraulic control strategy that may be applicable is the alternation of leachate flow direction (Table 4).

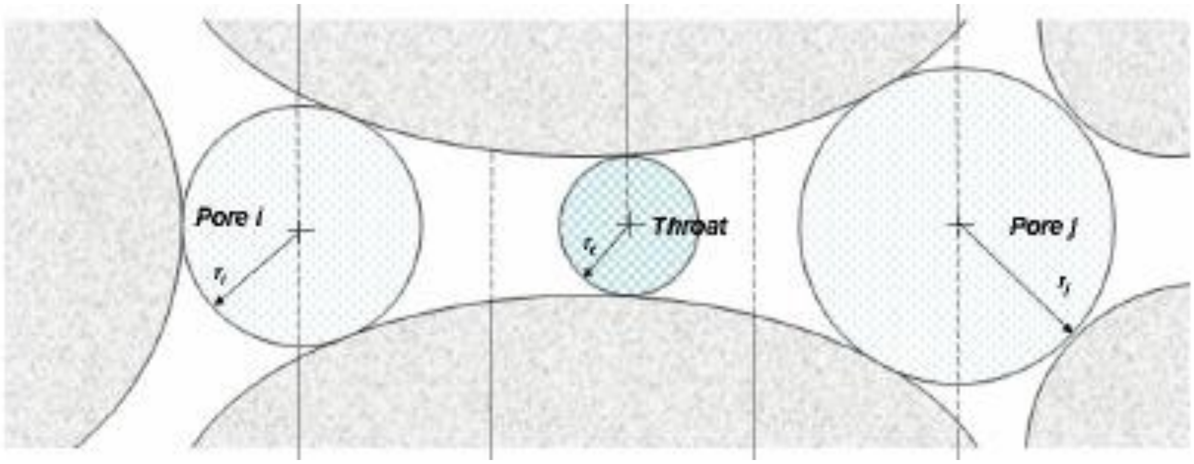


Figure 22 - Illustration of Pore and Throat Geometry (Dong 2007)

4.1.5 Mineral Precipitation

When microorganisms are growing in porous media they can cause an increase in pH that can cause mineral precipitation, particularly with respect to carbonates. Under certain conditions in porous media, chemical, physical, and microbiological processes interact enable the formation of solid mineral deposits. The presence of biofilms that facilitate precipitation can lead to mineral accumulations, which fill pore space and disrupt flow. A hydraulic control strategy that may be applicable is the alternation of reactor pH (Table 4). (Zhang and Klapper 2014)

4.1.6 Gas Clogging

Gas Clogging could potentially occur in which gas pressure exerts a force within the pore space, which makes it difficult for fluid to continue flowing. This is less likely to occur in the upflow LBR configuration, but gas could still potentially restrict leachate flow laterally within the LBR. This type of clogging may result in pore space that appears to be open, but does not have liquid flowing through. A hydraulic control strategy that may be applicable is the use of gas extraction wells (Table 4). (Sinha et al. 2017; Kapellos et al. 2015)

4.1.7 Slurry Formation

A slurry can be described as a two-phase liquid with non-Newtonian flow properties (Chen 1986). The rheological behavior during flow of a slurry is affected by, “the interaction between particles, interactions of particles with the solution, and particle deformation” (Chen 1986). “When there is structural formation of the particles, the liquid may require initial stress before it starts to flow (Chen 1986).” If a slurry forms, the viscosity of the liquid phase may become too high for it to flow through the intact porous media (Chen 1986). This situation may lead to a condition in which clogging will occur unless the pressure driving the flow can be increased

(Chen 1986). Even if flow can be maintained in such a situation, it is possible that unhydrolyzed material will be moved into the next stage of the reactor, resulting in suboptimal reactor operation (Garcia-Bernet et al. 2011). Another mechanism that can lead to inability of water to move through organic material is due to the relative presence of monovalent and divalent cations (Higgins and Novak 1997; Wang et al. 2013). A hydraulic control strategy that may be applicable is the use of a chemical additive that affects the relative presence of monovalent and divalent cations (Table 4).

4.1.8 Preferential Pathways

Another mechanism of hydraulic failure is the development of preferential pathways for leachate flowing through the waste bed. In this case, the LBR does not clog; instead, the majority of the leachate flows through preferential pathways that run through part of the waste bed, while the remainder experiences stagnation or minimal flow (Mooney and Morris 2008). This leads to a reduction in the active volume of the LBR (Sharvelle et al. 2008). The areas of the LBR that experience stagnation due to non-uniform leachate flow may be considered to be outside of the reactor's active volume (Andre et al. 2015). The areas outside of the active volume will likely experience suboptimal waste degradation compared to the areas inside the reactor that experience homogenous leachate distribution (Andre et al. 2015). A hydraulic control strategy that may be applicable is the use of gas extraction wells (Table 4).

4.2 Purpose of Experimentation Strategy

Column experiments and prototype operation showed some successful operation of LBRs for treating HSCM. However, hydraulic failures due to clogging and preferential pathway formation were observed. Due to the continued risk of hydraulic failure, further research was needed to understand mechanisms for hydraulic failure and to determine approaches to overcome these issues. The experimentation strategy is designed to characterize the types of hydraulic failure, identify characteristic failure modes (a reproducible pattern wherein a type of hydraulic failure occurring at a particular time and location within the LBR can be linked to a particular set of operating conditions), and elucidate the mechanisms leading to each type of failure. The goal of the experimentation strategy is to establish an understanding of the relationship between hydraulic failure mechanisms and reactor operating conditions which facilitates the development of hydraulic control strategies. Hydraulic control strategies include any modification of reactor design or operating conditions that enable sustained, uniform distribution of leachate through the waste bed in a manner that maximizes the hydrolytic productivity of the LBR.

The term hydraulic failure refers, not only to complete clogging of the LBR, but also to any pattern of leachate flow through the HSCM which results in inadequate production and discharge of hydrolysis products from the LBR. It is suggested that future research attempt to determine whether distinct “characteristic hydraulic failure modes” can be identified based on the presence of unique pore space network geometries, soluble chemical oxygen demand (SCOD) output, and flow rate of LBR leachate effluent. An attempt should be made to determine if these patterns of hydraulic failure can be related to—and reproduced under—certain operating conditions, so that the mechanisms that cause these types of failure can be understood. When the mechanisms of hydraulic failure are better characterized, it is more likely that reactor design and operating conditions that avoid these types of problems can be developed.

The complexity of the problem of maintaining leachate flow through an LBR treating HSCM can be understood by the following quote from Kapellos et al. 2015:

> **"The analysis of biofilm growth in porous media is challenging because the structure of the system exhibits a hierarchy of characteristic length scales that span several orders of magnitude (for example, from several nanometers in the EPS up to a few hundreds of meters at the aquifer scale) and, further, there exists an intricate interplay of hydrodynamic, physicochemical, and biological processes occurring at different characteristic time scales (Figure 8.4) (Kapellos et al 2015)"**

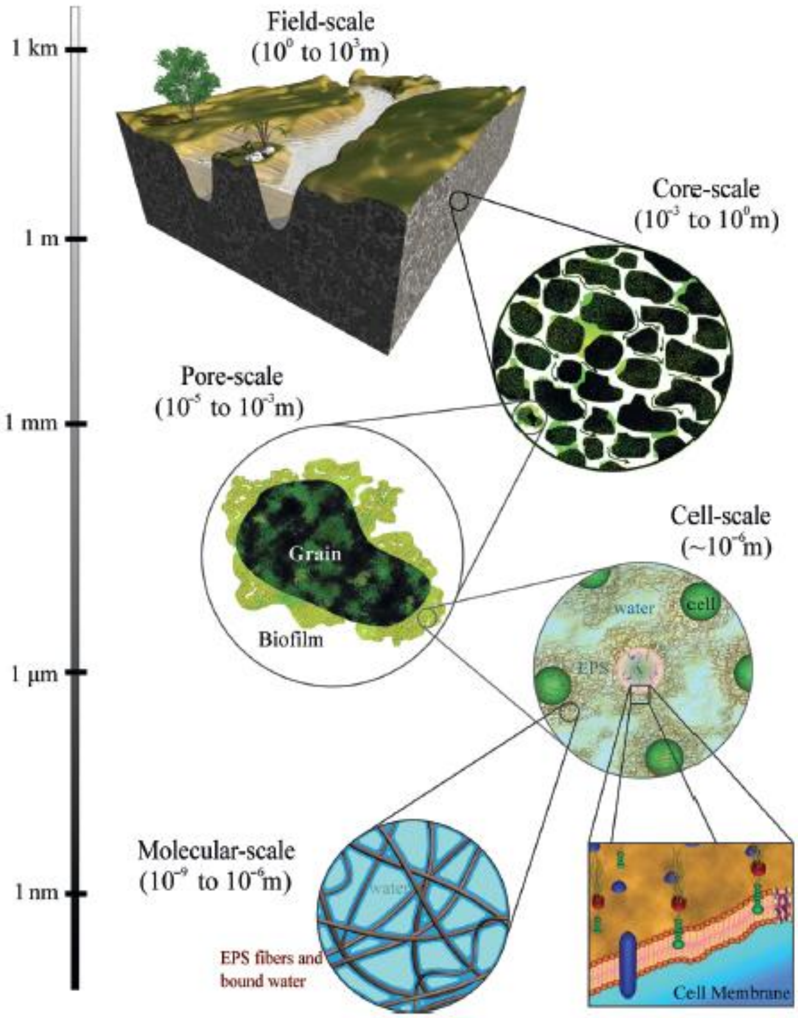


Figure 23 - Porous Media at Different Scales (Kapellos et al. 2015, figure 8.4)

In addition to the challenges of understanding the interaction of hydrodynamics and biofilm growth in 'inert' porous media, flow through the LBR has the additional confounding factor of a very high organic content (relative to typical soil and geological formations). The high degree of organics in the LBR means that biofilms attach to the solid porous media and consume it as a biochemical substrate (rather than serving solely as physical loci for anchoring of sessile microorganisms around which the Exocellular Polymeric Substances of biofilms are secreted). The fact that the organic solid porous medium is a substrate that is being consumed and solubilized means that the pore space network geometry in the LBR is changing with respect to time, due to the structural degradation of organic matter, and not solely due to biofilm growth (as is the case when the solid porous medium itself is biochemically inert). In addition to being consumed biologically, the high organic content solid porous medium composed of manure agglomerations in the LBR can chemically dissolve into the leachate and may physically deform, both of which are mechanism that may alter the pore space network geometry, which may lead to clogging and hydraulic failure irrespective of biofilm growth.

This thesis proposes a series of tests and experiments which are intended to increase our understanding of the mechanisms of hydraulic failure occurring in the LBR and guide the optimization of LBR design and operation strategies. Due to the complexity and interdependency of the possible mechanisms of failure, experiments are proposed that combine existing experimental methods with a variety of three-dimensional imaging and visualization techniques to extend our insight into the hydraulic performance of the LBR.

4.3 Electrical Resistivity Tomography (Assess Reactor-Scale Hydraulics)

4.3.1 Columns with Optimal Hydraulics versus Columns with Preferential Pathways

This project proposes a sequence of experiments designed to determine how well LBRs are performing with respect to hydraulic conductivity, rates of hydrolysis, and the degree of waste degradation achieved. In these experiments, a primary objective is to compare columns with optimal hydraulic and biological performance to columns with substantial preferential pathways, which are reducing the active volume (Sharvelle et al. 2008) of the reactor (and likely the productivity of hydrolysis products with respect to reactor volume). This can be done using a technique called Electrical Resistivity Tomography (ERT) as explained in Degueurce et al. (2016) and Andre et al. (2016).

ERT is a non-invasive, non-destructive approach to measuring infiltration of liquid into porous media. It is performed by placing a set of electrodes in the waste and running a current of known value between the electrodes, while using a second set of electrodes to measure the electrical potential (Degueurce et al. 2016). A low measured electrical potential correlates with high electrical resistance in the medium. An increase in measured electrical resistivity generally indicates a decrease in water contained in the medium, while a decrease in measured electrical resistivity generally indicates increased distribution of water into the medium (Degueurce et al. 2016). ERT could be used to measure the water content of the medium before, during, and after leachate injection**.** Illustrations of electrode placement geometry and leachate injection profiles can be generated with this method (Figure 24; Degueurce et al. 2016).

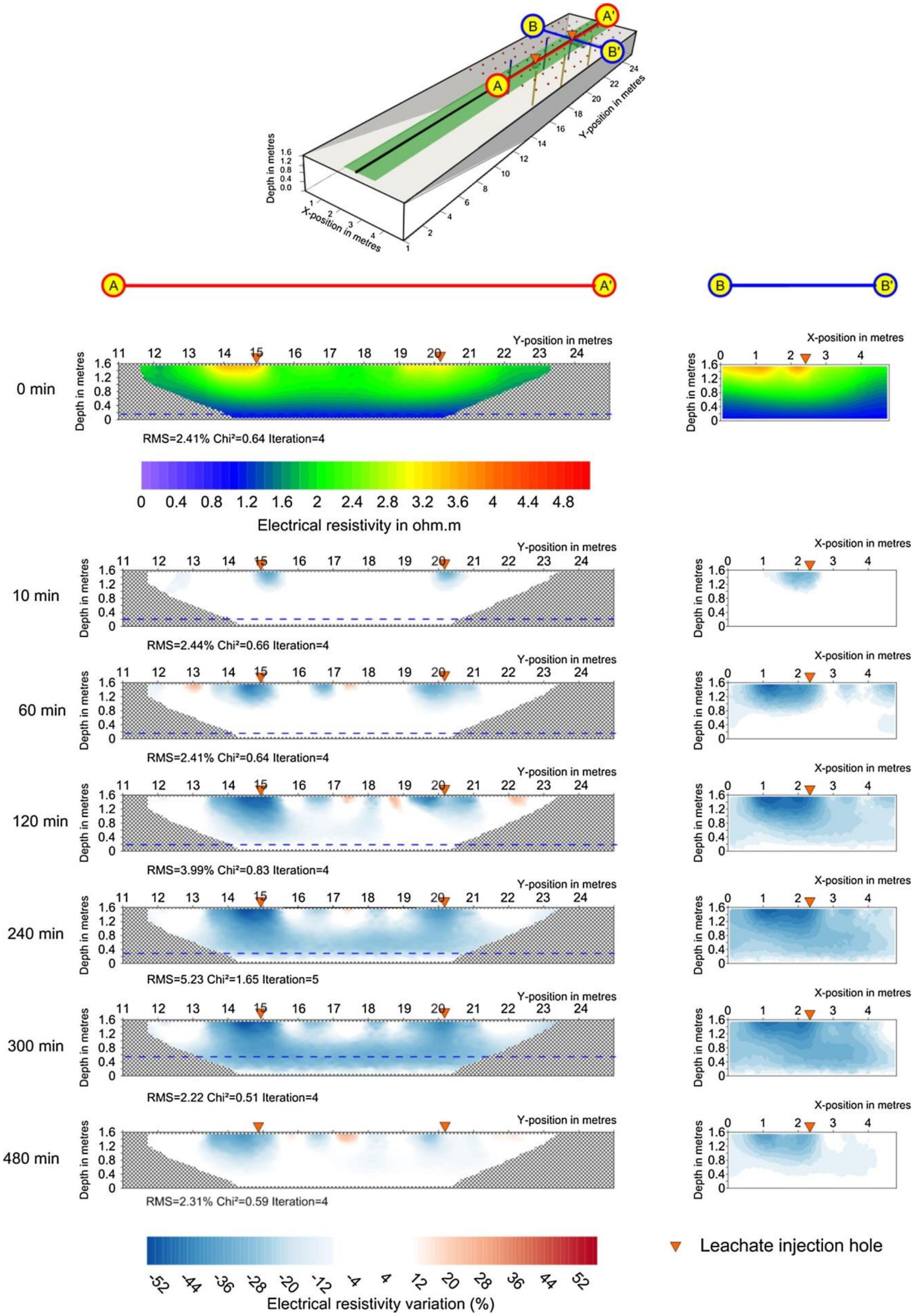


Figure 24 - Illustration of Electrical Resistivity Tomography (Degueurce et al. 2016)

We can use ERT to understand the patterns of leachate distribution through the waste bed. An understanding of these patterns may provide distinct insight regarding the hydraulic performance of the LBR. The ERT visualizations may enable an immediate assessment of whether the LBR is operating near-optimally with uniform, homogeneous leachate distribution or whether significant preferential pathways have formed. This may be useful for real-time early detection and mitigation of hydraulic problems occurring in the LBR.

ERT is a valuable technique because it allows an understanding of hydraulic failures occurring in the LBR that are not as obvious as complete clogging, but just as critical to the technical and economic success of MSAD system operation. ERT visualizations can be used in conjunction with regularly collected data such as effluent COD and volatile solids measurements to provide a more thorough assessment of LBR hydraulic performance. This information can be used to assess the design of the leachate injection system and develop operational strategies that seek to maximize the active volume of the LBR. A successful hydraulic control strategy should allow a higher level of volatile solids reduction to be achieved in the LBR by ensuring that the HSCM is degraded as fully and uniformly as possible.

4.3.2 Comparison of Columns with Optimal Hydraulics to Clogged Columns

In these experiments, a primary objective is to compare LBR columns that have optimal hydraulic and biological performance to columns that have clogged, to assess the location of hydraulic failures and to determine if characteristic modes of hydraulic failure can be identified. To this end, ERT visualizations can provide a four-dimensional description of flow patterns that illustrate how hydrodynamic conditions evolved from initiation of digestion until complete clogging of the LBR. The ERT visualizations can also be used to test hydraulic control strategies aimed at preventing clogging, such as reversal or alternation of leachate flow direction, to assess whether or not hydraulic performance improves.

4.4 Assess Microscale Differences in HSCM Samples

ERT visualizations can be used to guide sampling efforts wherein microscale structural differences are evaluated between HSCM samples taken from columns that have optimal performance, columns that have clogged, and columns with preferential pathways. Using ERT visualizations to guide the location and timing of sample collection may be critical for connecting HSCM properties and hydrodynamics to reactor operation because the ERT visualizations provide a distinct representation of the overall hydraulic regime that exists in the LBR for a given characteristic failure mode.

With the relationship between an HSCM sample and the overall hydraulic regime known, the sample's microscale structure can be imaged using X-ray Computed Microtomography, Nuclear Magnetic Resonance Microscopy, or other techniques. These imaging techniques can provide representations of the pore space network geometries—along with other characteristics—that may elucidate the microscale dissimilarities that exist between HSCM samples with different hydraulic properties. (Xiong et al. 2016; Davit et al. 2010; Dong 2007; Zhou et al 2018; Mooney et al. 2008; Cnudde and Boone 2013; Neu et al. 2010)

4.4.1 X-ray Computed Microtomography

X-ray computed microtomography is an imaging method that can provide visualizations of the internal structure of an opaque porous material in a non-invasive manner. Cross-sectional X-ray images are taken from multiple angles and reconstructed into 3D images which map "the real interior structure of original samples" (Xiong et al. 2016). The two types of X-ray microtomography that would be appropriate for this type of experimentation would be industrial X-ray generation tube and synchrotron microtomography. Most industrial systems have resolutions ranging from 50 to 100 micrometers, while synchrotron systems have resolutions ranging from 1 to 50 micrometers, with some specialized laboratory synchrotron systems having "submicron capabilities" (Xiong et al. 2016). Microtomographs provide a representation of the structural heterogeneity present at the microscale (Figure 25; Zhou et al. 2018).

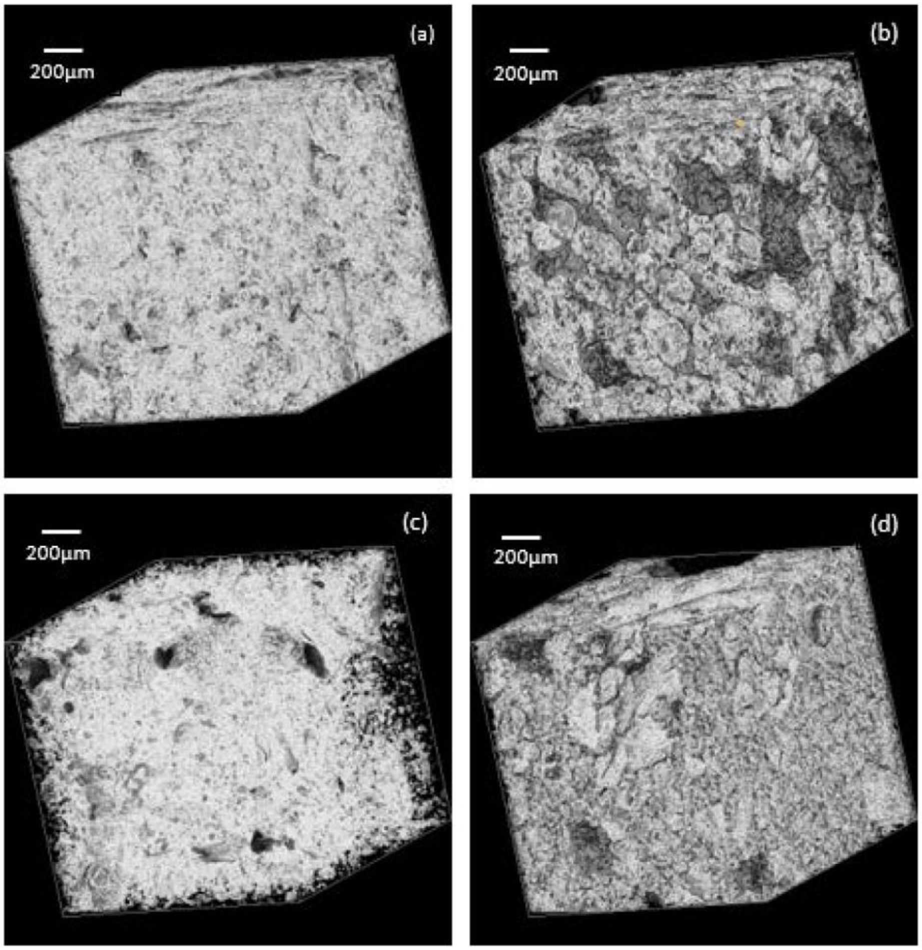


Figure 25 - Example of an X-ray Microtomograph (Zhou et al. 2018)

4.4.2 Nuclear Magnetic Resonance Microscopy

Imaging using Nuclear Magnetic Resonance (NMR), also known as Magnetic Resonance Imaging (MRI) is a non-invasive imaging technique that (unlike X-ray based techniques) does not use ionizing radiation. NMR uses the property of hydrogen atoms wherein their "nuclei, when placed in a magnetic field, are able to absorb energy from an electro-magnetic field oscillating at a particular frequency (the resonance frequency)" (Brown et al. 2007). This energy can then be measured by a detector coil. MRI uses a gradient field to give spatial resolution to the magnetic resonance signal, which can be subsequently represented as an image (Brown et al. 2007). NMR can be used to map the interior of a leachate-saturated waste bed using the diffusion diffraction phenomenon (Xiong et al. 2016). This is possible "since the water molecules in the porous material will move randomly" and "will probe the pore structure" (Xiong et al. 2016). There are multiple NMR techniques that can be used to characterize a pore network. Information on these techniques can be found in (Xiong et al. 2016).

4.5 Pore Network Extraction

The microscale images can be used to perform a pore network extraction on the various HSCM samples to create 3-/4-dimensional models of their pore space geometries. This can be accomplished by using a "maximal ball algorithm to extract topologically equivalent networks of pores and throats from images of porous media that can be used as input to network models" (Dong 2007). It is suggested that this type of analysis be used to mathematically describe pore space networks that characteristically represent modes of hydraulic failure, modes of optimal hydraulics, and modes of preferential pathway flow. Pore space mathematical description properties may correlate with some observed flow properties. (Xiong et al. 2016)

4.6 Simulation of Flow in Porous Media with Biofilm Growth

The mathematical pore space models may be used for simulation of LBR hydraulic performance (Figure 26; Sinha et al. 2017).

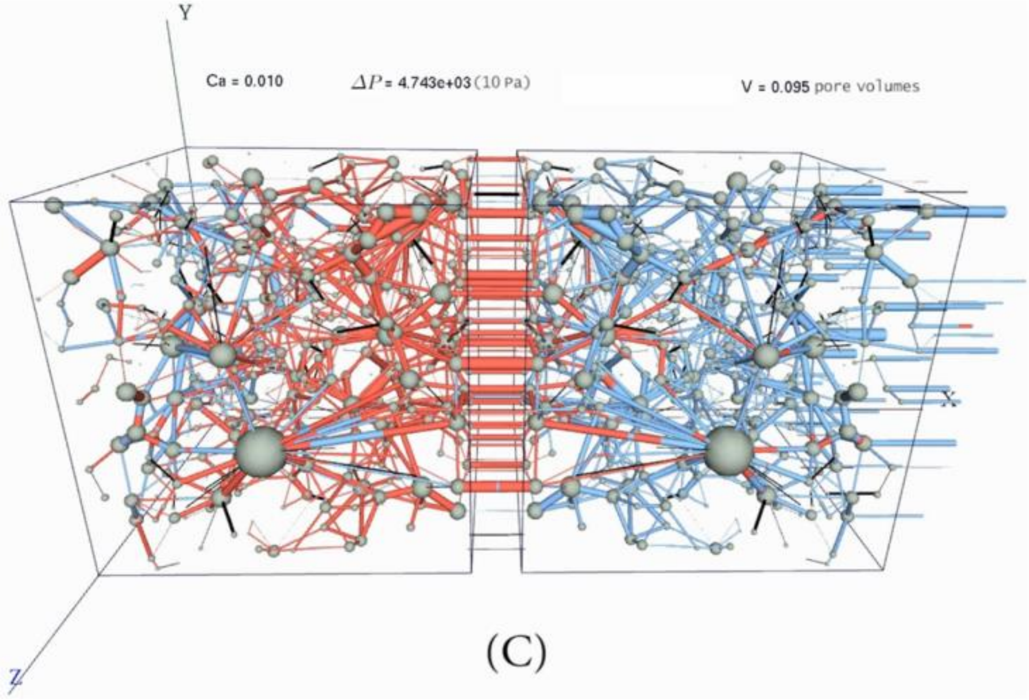


Figure 26 - Simulation of Two-Phase Flow in Three-Dimensional Porous Media (Sinha et al. 2017)

Creation of such simulations can further the conceptualization of mechanisms of hydraulic failure by elucidating the relationship between pore structure, hydrodynamics, biofilm growth, and biochemical phenomena. The creation and validation of LBR models and simulations may also further development of hydraulic control strategies by linking knowledge of hydraulic failure mechanisms to reactor design and operation approaches. (Sinha et al. 2017; Kapellos et al. 2015)

4.7 Summary of Experimentation Strategy

This chapter explained possible types of hydraulic failure that may occur in the LBR, and the coupled physical, chemical, and biological mechanisms that may be causing the failures. The term hydraulic failure refers, not only to complete clogging of the LBR, but also to any pattern of leachate flow through the HSCM which results in inadequate production and discharge of hydrolysis products from the LBR. It is suggested that future research attempt to determine whether distinct “characteristic hydraulic failure modes” can be identified based on the presence of unique pore space network geometries, organic matter output, and flow rate of LBR leachate effluent. An attempt should be made to determine if these patterns of hydraulic failure can be related to—and reproduced under—certain operating conditions, so that the mechanisms that cause these types of failure can be understood. When the mechanisms of hydraulic failure are better characterized, it is more likely that reactor design and operating conditions that avoid these types of problems can be developed.

The experimentation strategy outlined in this chapter may provide additional insight with respect to the hydraulic performance of LBRs. The mechanisms of hydraulic failure provided in this chapter are not exhaustive. It is recommended that future research explore the possibility of additional mechanisms and experimental methods, including those involving spatially resolved metabolomics techniques (Spur et al. 2013)

ERT visualizations have been used by researchers to evaluate leachate distribution in LBRs (Degueurce et al. 2016; Andre et al. 2016). Application of this technique may provide valuable information regarding mechanisms of hydraulic failure occurring in the LBR. Using this knowledge, further characterization of the pore space network geometry at the microscale using either Magnetic Resonance Imaging (MRI) or X-ray Computed Tomography (X-ray CT) is recommended. The extent to which permeability decreases is often related to the composition of biofilm microbial consortia, availability of nutrients, and the chemical characteristics of the gaseous, liquid, and solid constituents of the porous medium (Kapellos et al. 2015). These factors also interact with the geometric structure and the hydrodynamic characteristics resulting from flow through the medium (Kapellos et al. 2015). Microscale characterization of the process may yield insight for conceptualizing and modeling the dynamic conditions in the LBR. The recursive process of creating and refining a detailed mathematical model of the system may prompt an increased level of analytical thinking about the coupled physical, chemical, and biological phenomena occurring in the LBR. Moreover, the creation and validation of LBR models and simulations may further the development of hydraulic control strategies by linking knowledge of hydraulic failure mechanisms to reactor design and operation approaches.

CHAPTER 5: SYNTHESIS

This project reviewed the main aspects of the MSAD system environment along with information on the needs of AFOs for more effective waste management practices. It then applied a MCDA tool to assess the MSAD relative to other prominent HSAD technologies. The modular LBR (MSAD system) received the highest rating of all the technologies with a score of 3.7 out of 5 (Figure 12 and Figure 13). The MSAD compares favorably with the other system alternatives. Due to its high number of LBRs, the MSAD has advantages with respect to resilience to hydraulic failure. It also competes well with respect to operational control, due to its customizable operating conditions and retention time for each batch of waste. The MSAD also compares favorably to the other alternatives with respect to process efficiency, due to its high degree of volatile solids reduction and biogas production stability.

Under equal criteria weighting, the MSAD system was the most favorable alternative due to its strong hydraulic performance, operational control, and process efficiency, whereas it was less competitive with respect to capital and operational requirements. Under a sensitivity analysis, the average rank of the modular LBR was 1.7 (Figure 15). The least favorable rank of the modular LBR was 4, which occurred when the weighting of the operational requirements criterion was increased (Figure 15). The most favorable rank of the modular LBR was 1, which occurred when the criteria weighting of the impact of hydraulic failure, operational control, feedstock fit, and process efficiency were increased, respectively (Figure 15).

It is recommended that future studies pay particular attention to LBR design strategies which seek to minimize capital and operating costs over the lifecycle of the system. In addition, future research on developing hydraulic performance control strategies should also take into consideration the costs and benefits of each identified approach.

The LBR is a critical part of the MSAD system since hydrolysis can be a rate-limiting step in the anaerobic digestion of HSCM (Hinds 2015; Veeken and Hamelers 1999). Since leachate must be recirculated through the LBR for the entirety of the batch digestion time, any phenomena that disrupt the duration or uniformity of leachate distribution must be addressed. This thesis presented work aimed to address problems related to clogging and preferential pathways, which have caused hydraulic failure in the LBR. The flow of leachate was evaluated to understand how the movement of fluid through the HSCM affected LBR performance. The overarching goal of this thesis project was to improve the LBR stage of the MSAD.

Throughout this project, information gained through laboratory and prototype-scale LBR experimentation was used to establish possible improvements to LBR design. The primary improvement to the LBR was the modification from a downflow to an upflow configuration. The prototype LBR was operated in the upflow configuration to facilitate longer durations of undisrupted leachate permeation. In addition, it was determined that leachate injection spacing should be studied further as results from operation of the prototype LBR suggested that higher volatile solids reduction occurred closer to the leachate influent manifold.

The intermittent nature of LBR leachate effluent flow caused a de facto discontinuous leachate recirculation operational condition. The replacement of the sump pump with a continuously operating pump may reduce intermittency of the prototype's leachate effluent flow. However, along with the recommended improvements (section 3.4), future pumping systems should be designed with the ability to program in a discontinuous leachate recirculation regime. It is recommended that leachate sample collection and measurement of organic content be implemented only after leachate recirculation and supplementary liquid addition can be reliably controlled and quantified. It is also recommended that a pump with energy logging capabilities be installed.

Column experiments and prototype operation showed some successful operation of LBRs for treating HSCM. However, there were a considerable amount of hydraulic failures or examples of sub-optimal hydraulic performance. There were multiple rounds of experimentation where at least one of three LBR columns either clogged completely or required a high amount of pressure to maintain flow (Wu 2017). Due to the continued risk of hydraulic failure, further research was needed to understand mechanisms for hydraulic failure and determine approaches to overcome this issue. At commercial scale, hydraulic failure of LBRs would result in decreased energy and agricultural product output and increased operating costs. Since commercial processes rely on reproducible results, a high degree of LBR reliability is required to achieve technical and economic feasibility. Therefore, control over the hydraulic performance of LBRs is critical for commercialization of the MSAD system. To this end, an experimentation strategy was developed, with the goal to elucidate the mechanisms behind hydraulic failures occurring in the LBR.

The experimentation strategy recommended the use of electrical resistivity tomography (ERT) to render visualizations of leachate distribution throughout the waste bed. This would allow an understanding of reactor-scale flow patterns in the LBR. After ERT visualizations are conducted, further characterization of the pore space network geometry at the microscale using either Magnetic Resonance Imaging (MRI) or X-ray Computed Tomography (X-ray CT) was recommended. These approaches form the basis for more detailed analysis of flow through the decomposing manure waste bed, which may inform future LBR-related research and development.

REFERENCES

André, L., et al. "Quantifying physical structure changes and non-uniform water flow in cattle manure during dry anaerobic digestion process at lab scale: Implication for biogas production." *Bioresource technology* 192 (2015): 660-669.

André, L., et al. "Electrical resistivity tomography to quantify in situ liquid content in a full-scale dry anaerobic digestion reactor." *Bioresource technology* 201 (2016): 89-96.

Blanchard, Benjamin S., Wolter J. Fabrycky. *Systems engineering and analysis*. Vol. 5. Englewood Cliffs, NJ: Prentice Hall, 2011.

Bracmort, Kelsi S. "Anaerobic digestion: Greenhouse gas emission reduction and energy generation." Congressional Research Service, Library of Congress, 2009.

Brown, Gregory G., et al. "A primer on functional magnetic resonance imaging." *Neuropsychology review* 17.2 (2007): 107-125.

Carrel, Maxence, et al. "Biofilms in 3D porous media: Delineating the influence of the pore network geometry, flow and mass transfer on biofilm development." *Water research* 134 (2018): 280-291.

Colorado Department of Commerce Advanced Industries Grant Program: Demonstration of a Prototype Leach-Bed Reactor for Anaerobic Digestion of Dry Waste, Final Report 2016

Chaudhary, Binod Kumar. "Dry continuous anaerobic digestion of municipal solid waste in thermophilic conditions." *ME Thesis. Asian Institute of Technology* (2008).

Chen, Y. R. "Rheological properties of sieved beef-cattle manure slurry: Rheological model and effects of temperature and solids concentration." *Agricultural wastes* 15.1 (1986): 17-33.

Cnudde, Veerle, and Matthieu Nicolaas Boone. "High-resolution X-ray computed tomography in geosciences: A review of the current technology and applications." *Earth-Science Reviews* 123 (2013): 1-17.

Daniel, T. C., and J. Bouma. "Column studies of soil clogging in a slowly permeable soil as a function of effluent quality." *Journal of Environmental Quality* 3, no. 4 (1974): 321-326.

Davit, Yohan, et al. "Imaging biofilm in porous media using X-ray computed microtomography." *Journal of Microscopy* 242.1 (2011): 15-25.

Degueurce, Axelle, et al. "On the value of electrical resistivity tomography for monitoring leachate injection in solid state anaerobic digestion plants at farm scale." *Waste Management* 56 (2016): 125-136.

Degueurce, Axelle, et al. "Biotic and abiotic roles of leachate recirculation in batch mode solid-state anaerobic digestion of cattle manure." *Bioresource technology* 200 (2016): 388-395.

Degueurce, Axelle, Anne Trémier, and Pascal Peu. "Dynamic effect of leachate recirculation on batch mode solid state anaerobic digestion: Influence of recirculated volume, leachate to substrate ratio and recirculation periodicity." *Bioresource technology* 216 (2016): 553-561.

Drescher, Knut, et al. "Biofilm streamers cause catastrophic disruption of flow with consequences for environmental and medical systems." *Proceedings of the National Academy of Sciences* 110.11 (2013): 4345-4350.

Dong, Hu, and Martin J. Blunt. "Pore-network extraction from micro-computerized-tomography images." *Physical review E* 80.3 (2009): 036307.

EPA 2017 Anaerobic Digester Basics. Accessed 7 November 2017
https://www.epa.gov/agstar/recovering-value-waste-anaerobic-digester-system-basics

EPA 2011 AgSTAR Recovering Value from Waste: Anaerobic Digester System Basics. Accessed 7 November 2017
https://www.epa.gov/agstar/recovering-value-waste-anaerobic-digester-system-basics

Fontane and Sharvelle (2014). Multi-Criterion Decision Analysis. CIVE 575, Colorado State University. Fort Collins, CO

Garcia-Bernet, D., et al. "Rapid measurement of the yield stress of anaerobically-digested solid waste using slump tests." *Waste management* 31.4 (2011): 631-635.

García-Bernet, Diana, et al. "Water distribution in biowastes and digestates of dry anaerobic digestion technology." *Chemical engineering journal* 172.2-3 (2011): 924-928.

Geesey, Gill G., and Andrew C. Mitchell. "Need for direct measurements of coupled microbiological and hydrological processes at different scales in porous media systems." *Journal of hydrologic engineering* 13.1 (2008): 28-36.

Hanif Abdul Karim, Asma. "Evaluation of a trickle flow leach bed reactor for anaerobic digestion of high solids cattle manure." Thesis, Colorado State University, 2013.

Herrero, Mario, and Philip K. Thornton. "Livestock and global change: emerging issues for sustainable food systems." Proceedings of the National Academy of Sciences Dec 2013, 110 (52) 20878-20881; DOI: 10.1073/pnas.1321844111

Higgins, Matthew J., and John T. Novak. "The effect of cations on the settling and dewatering of activated sludges: laboratory results." *Water Environment Research* 69.2 (1997): 215-224.

Hinds, Gregory Richard. *High-Solids Anaerobic Digestion of the Organic Fraction of Municipal Solid Waste State of the Art, Outlook in Florida, and Enhancing Methane Yields from Lignocellulosic Wastes*. Thesis, University of South Florida, 2015.

Kapellos, George E., Terpsichori S. Alexiou, and Stavros Pavlou. "Fluid-Biofilm Interactions in Porous Media." *Heat transfer and fluid flow in biological processes*. 2015. 207-238.

Kapellos, George E., Terpsichori S. Alexiou, and Alkiviades C. Payatakes. "A multiscale theoretical model for fluid flow in cellular biological media." *International Journal of Engineering Science* 51 (2012): 241-271.

Kapellos, George E., Terpsichori S. Alexiou, and Alkiviades C. Payatakes. "Theoretical modeling of fluid flow in cellular biological media: An overview." *Mathematical biosciences* 225.2 (2010): 83-93.

Karak, Tanmoy, R. M. Bhagat, and Pradip Bhattacharyya. "Municipal Solid Waste Generation, Composition, and Management: The World Scenario." *Critical Reviews in Environmental Science and Technology* 43.2 (2013): 215-215.

Keyes, S. D., et al. "Measurement of micro-scale soil deformation around roots using four-dimensional synchrotron tomography and image correlation." *Journal of The Royal Society Interface* 14.136 (2017): 20170560.

Kjeldsen, Peter, et al. "Present and long-term composition of MSW landfill leachate: a review." *Critical reviews in environmental science and technology* 32.4 (2002): 297-336.

Lasker, Jeff. "Decision support for anaerobic digestion installations at cattle operations in Colorado." Thesis, Colorado State University, 2013.

Lewis, Matthew A. 2017a. Sustainable Energy in Remote Alaskan Villages. CIVE 578 Colorado State University, Fort Collins, CO.

Lewis, Matthew A. 2017b. Term Paper. ENGR 530 Colorado State University, Fort Collins, CO

Lewis, Matthew A. 2017c. Assignment 1. ENGR 530 Colorado State University, Fort Collins, CO.

Lewis, Matthew A. 2017d. Assignment 2. ENGR 530 Colorado State University, Fort Collins, CO.

McLean, Jeffrey S., Ositadinma N. Ona, and Paul D. Majors. "Correlated biofilm imaging, transport and metabolism measurements via combined nuclear magnetic resonance and confocal microscopy." *The ISME journal* 2.2 (2008): 121.

Mooney, Sacha J., and Catherine Morris. "A morphological approach to understanding preferential flow using image analysis with dye tracers and X-ray computed tomography." *Catena* 73.2 (2008): 204-211.

Myint, M., and N. Nirmalakhandan. "Evaluation of first-order, second-order, and surface-limiting reactions in anaerobic hydrolysis of cattle manure." *Environmental engineering science* 23.6 (2006): 970-980.

Myint, M., N. Nirmalakhandan, and R. E. Speece. "Anaerobic fermentation of cattle manure: modeling of hydrolysis and acidogenesis." *Water Research* 41.2 (2007): 323-332.

Myint, M. T., and N. Nirmalakhandan. "Enhancing anaerobic hydrolysis of cattle manure in leachbed reactors." *Bioresource technology* 100.4 (2009): 1695-1699.

Neu, Thomas R., et al. "Advanced imaging techniques for assessment of structure, composition and function in biofilm systems." *FEMS microbiology ecology* 72.1 (2010): 1-21.

Pintelon, Thomas RR, et al. "The effect of biofilm permeability on bio-clogging of porous media." *Biotechnology and bioengineering* 109.4 (2012): 1031-1042.

Place, Sara E., and Frank M. Mitloehner. "The nexus of environmental quality and livestock welfare." *Annu. Rev. Anim. Biosci.* 2.1 (2014): 555-569.

Rapport et al. 2008. CalRecycle "Current Anaerobic Digestion Technologies for Treatment of Municipal Organic Solid Waste" *https://www2.calrecycle.ca.gov/Publications/Download/1099*

Rice, Eugene W., et al. "Standard methods for the examination of water and wastewater." *Washington: APHA, AWWA, WPCR* (2012): 1496.

Sandefur, Julie. "Anaerobic Post-Processing of Digestate From A Multi-Stage Anaerobic Digester." Thesis, Colorado State University, 2017.

Self, James Robert, and R. M. Waskom. "Nitrates in drinking water." *Service in action; no. 0.517* (1992).

Sinha, Santanu, et al. "Effective rheology of two-phase flow in three-dimensional porous media: experiment and simulation." *Transport in porous media* 119.1 (2017): 77-94.

Sharvelle, Sybil, Eric McLamore, and M. Katherine Banks. "Hydrodynamic characteristics in biotrickling filters as affected by packing material and hydraulic loading rate." *Journal of Environmental Engineering* 134.5 (2008): 346-352.

Sharvelle, S., Keske, C., Davis, J., & Lasker, J. (2011a). Guide for Assessing Feasibility of On-Farm AD at Cattle Operations in Colorado. NRCS Colorado Engineering Technical Note 28 https://www.nrcs.usda.gov/wps/portal/nrcs/detail/co/technical/engineering/?cid=nrcs144p2_063015

Sharvelle et al 2011b, Technical Guide for the use of an Online AD Feasibility Tool for Colorado https://erams.com/static/map/css/AD_feasibility/files/Technical%20Guide%20for%20the%20use%20of%20an%20Online%20AD%20Feasibility%20Tool%20for%20Colorado_FINAL.pdf

Spur, Eva-Margarete, Emily A. Decelle, and Leo L. Cheng. "Metabolomic imaging of prostate cancer with magnetic resonance spectroscopy and mass spectrometry." *European journal of nuclear medicine and molecular imaging* 40.1 (2013): 60-71.

Tejedor-Sanz, Sara, et al. "The Planktonic Relationship Between Fluid-Like Electrodes and Bacteria: Wiring in Motion." *ChemSusChem* 10.4 (2017): 693-700.

Tejedor-Sanz, Sara, et al. "Geobacter dominates the inner layers of a stratified biofilm on a fluidized anode during brewery wastewater treatment." *Frontiers in microbiology* 9 (2018): 378.

United States Department of Agriculture, Natural Resources Conservation Service. (2011). Agricultural Waste Management Field Handbook. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/ecoscience/mnm/?cid=stelprdb1045935

Veeken, Adrie, and Bert Hamelers. "Effect of temperature on hydrolysis rates of selected biowaste components." *Bioresource technology* 69.3 (1999): 249-254.

Vogt, Sarah J., et al. "Permeability of a growing biofilm in a porous media fluid flow analyzed by magnetic resonance displacement-relaxation correlations." *Biotechnology and bioengineering* 110.5 (2013): 1366-1375.

Wagner, John J., Shawn L. Archibeque, and Dillon M. Feuz. "The modern feedlot for finishing cattle." *Annu. Rev. Anim. Biosci.* 2.1 (2014): 535-554.

Wagner, Michael, and Harald Horn. "Optical coherence tomography in biofilm research: a comprehensive review." *Biotechnology and bioengineering* 114.7 (2017): 1386-1402.

Wang, Xiaofan, et al. "Cation bridging studied by specular neutron reflection." *Langmuir* 29.18 (2013): 5520-5527.

Wasserbach, Kelly "Hydraulic Characteristics of Feedlot Manure In An Anaerobic Leach Bed Reactor" Thesis, Colorado State University, 2013.

Werth, Charles J., et al. "A review of non-invasive imaging methods and applications in contaminant hydrogeology research." *Journal of contaminant hydrology* 113.1-4 (2010): 1-24.

Wilson, L. Paige, Sybil E. Sharvelle, and K. Susan. "Enhanced anaerobic digestion performance via combined solids-and leachate-based hydrolysis reactor inoculation." *Bioresource technology* 220 (2016): 94-103.

Wimpenny, Julian WT, and Ric Colasanti. "A more unifying hypothesis for biofilm structures–a reply." *FEMS microbiology ecology* 24.2 (1997): 185-186.

Wu, R. and Lewis, M. Multi-Stage AD Technology For Dry Lot Animal Feeding Operations. Presentation at BioCycle REFOR17, Portland, Oregon, 17-18 October.

Wu, Rong Xi. “Enhancement of Liquid Flow Through a Leach Bed Reactor for Anaerobic Digestion of High Solids Cattle Manure” Thesis 2017 Colorado State University

Xie, Sihuang, et al. "Hydrolysis and acidification of grass silage in leaching bed reactors." *Bioresource technology* 114 (2012): 406-413.

Xu, Su Yun, et al. "Microbial community distribution and extracellular enzyme activities in leach bed reactor treating food waste: Effect of different leachate recirculation practices." *Bioresource technology* 168 (2014): 41-48.

Xiong, Qingrong, Todor G. Baychev, and Andrey P. Jivkov. "Review of pore network modelling of porous media: experimental characterisations, network constructions and applications to reactive transport." *Journal of contaminant hydrology* 192 (2016): 101-117.

Zhou, Hongxiang, et al. "Evaluating Hydraulic Properties of Biochar-Amended Soil Aggregates by High-Performance Pore-Scale Simulations." *Soil Science Society of America Journal* (2018).

APPENDIX A: MCDA RAW DATA

Criteria	Sub-Criteria	Max/Min	Horizontal Mixed Plug Flow	Vertical Pumped Plug Flow	Garage-Type LBR	Landfill-Cell LBR	Modular LBR	Word Scales	
Operational Requirements								Word	Rating
	Number of Individual Reactors		Good	Very Good	Medium	Very Good	Very Poor	Very Good	5
	Material Handling Requirements		Low	Low	High	Very Low	Medium	Good	4
								Fair	3
								Poor	2
								Very Poor	1
Potential for Hydraulic Failure								Very Small	5
	Hydrolysis Stage Resilience		Poor	Very Poor	Good	Very Poor	Very Good	Small	4
	Flow Regime		Good	Very Good	Fair	Poor	Good	Medium	3
								Large	2
								Very Large	1
								Very Low	5
Capital Requirements								Low	4
	Number of Stages	Min	2	1	1	1	3	Med	3
	Retention Time	Min	28	14	21	365	16	High	2
	Preprocessing Requirements		Very Good	Poor	Very Good	Very Good	Very Good	Very High	1
	Reactor Materials Cost		Fair	Fair	Fair	Very Good	Poor		
Operational Control									
	Customizable Operating Conditions		Fair	Fair	Very Good	Very Poor	Very Good		
	Customizable Retention Time		Poor	Fair	Good	Poor	Very Good		
Feedstock Composition Technology Fit									
	Inerts Handling		Fair	Poor	Very Good	Very Good	Very Good		
	Total Solids Operating Range	Max	30	40	50	60	60		
Process Efficiency									
	Volatile Solids Reduction		Good	Good	Good	Poor	Very Good		
	Biogas Production Stability		Fair	Good	Fair	Very Poor	Very Good		

(Adapted from Fontane and Sharvelle 2014)

APPENDIX B: MCDA ASSUMPTIONS

Operational Requirements

- *Number of Individual Reactors:* assumes that operational complexity will increase with an AD system that has a higher quantity of reactors (Table 3). This is due to the need for increased process monitoring and sequencing of LBRs to provide a consistent stream of leachate for conversion to methane. While leachate storage capacity can alleviate some of the concern over steady leachate production, process control (including pumping and valve control) will remain more complex in a system with a higher number of individual reactors.
- *Material Handling Requirements:* assumes that the Landfill-Cell system will have very low material handling needs because the feedstock remains in place over the course of a long retention time (Table 3). The two plug flow alternatives will have low material handling requirements, since material loading is automated in these continuous systems. Refer to (Table 3).

Hydraulic Failure

- *Hydrolysis Stage Resilience:* assumes that the modular LBR provides a high degree of resilience to a hydraulic failure because of the high number of LBR reactors operating simultaneously; if one LBR fails, it can be taken offline without causing a major disruption in leachate/biogas production (Table 3). This is in diametric opposition to the plug flow reactors and the landfill-cell because they rely on a very small number of reactors for the entire digestion process; in a system with such a low level of redundancy, a hydraulic failure or process upset can lead to significant downtime.

- *Flow Regime (hydraulic performance):* assumes that the vertical pumped plug flow can be rated as very good because the entire feedstock mass is undergoing constant circulation and each portion of the mass will experience multiple exposures to the headspace where gases can escape and additional mixing occurs as the feedstock changes direction and moves back down the reactor column. The modular LBR receives a rating of good because its upflow leachate recirculation may reduce feedstock compaction and clogging (Table 3). The garage-type LBR receives a rating of fair because its downflow leachate recirculation can provide adequate fluid percolation if the feedstock's structure and porosity enable sustained flow. The landfill-cell LBR receives a rating of poor because the high stacking of feedstock can lead to compaction and clogging that cannot be remedied without disruption of the entire digestion process.

Capital Requirements

- *Number of Stages:* is quantified using the actual number of stages in the systems. The modular LBR has 3 stages, which will lead to higher capital requirements compared to the single stage systems (Table 3).
- *Retention Time:* is quantified using the actual retention times used by the systems. The best is the vertical pumped plug flow at 14 days, while the worst is the landfill-cell LBR (Table 3).
- *Preprocessing Requirements:* is quantified based on the nature of preprocessing required by the systems. The vertical pumped plug flow received a rating of poor because it requires particle size reduction to below 40mm, while the other systems received ratings

of very good as they are designed to function without requiring expensive preprocessing (Table 3).

- *Reactor Materials Costs:* is based on the resources required to construct the reactors. The landfill-cell LBR received a rating of very good due to its use of low-cost geosynthetic materials and established landfill construction techniques. The modular LBR received a rating of poor because it requires relatively elaborate material selection and fabrication; however this rating may improve if a mature mass-production system can be established. The other reactors receive a rating of fair, as they use standard construction methods and materials (Table 3).

Operational Control

- *Customizable Operating Conditions:* assessed the systems' abilities to tailor reactor conditions to a feedstock. The modular LBR received a rating of very good because its large number of LBRs and multiple stages allow customization based on feedstock characteristics and the overall needs of the system. The plug flow reactors both received a rating of fair because the process conditions can be slowly changed, but not to the degree of the modular LBR system (Table 3). The landfill-cell LBR received a rating of very poor, as the system offers very little control over process conditions. Some operational parameters that may be changed include Leachate: Flow Direction, Flow Rate, Continuous vs. Discontinuous Recirculation, Dilution, Injection Pressure, as well as Temperature, Waste Bed Depth, Inoculum, and Bulking Agent.
- *Customizable Retention Time:* is quantified by evaluating how well each system can tailor the time needed to achieve adequate treatment levels given variation in the characteristics of each load of feedstock. The modular LBR was rated very good due to

the high number of LBR units and multiple stages (Table 3). The landfill-cell LBR was rated very poor due to its monolithic nature.

Feedstock Composition Fit

- *Inerts Handling:* The garage-type LBR, the landfill-cell LBR, and the modular LBR all received ratings of very good for this sub-criteria because they are operated in batch mode and can be regularly emptied of any inert materials. The horizontal mixed plug flow received a rating of fair because its mechanical mixing should help move difficult feedstocks through the process, but small amounts of inerts may accumulate (Table 3). The vertical pumped plug flow received a rating of poor because under certain conditions (especially at low solid contents) sand and rocks can settle to the bottom of the reactor and clog pump inlets.
- *Total Solids (TS) Operating Range:* the LBR systems can handle higher total solids compared to the plug flow systems (Table 3).

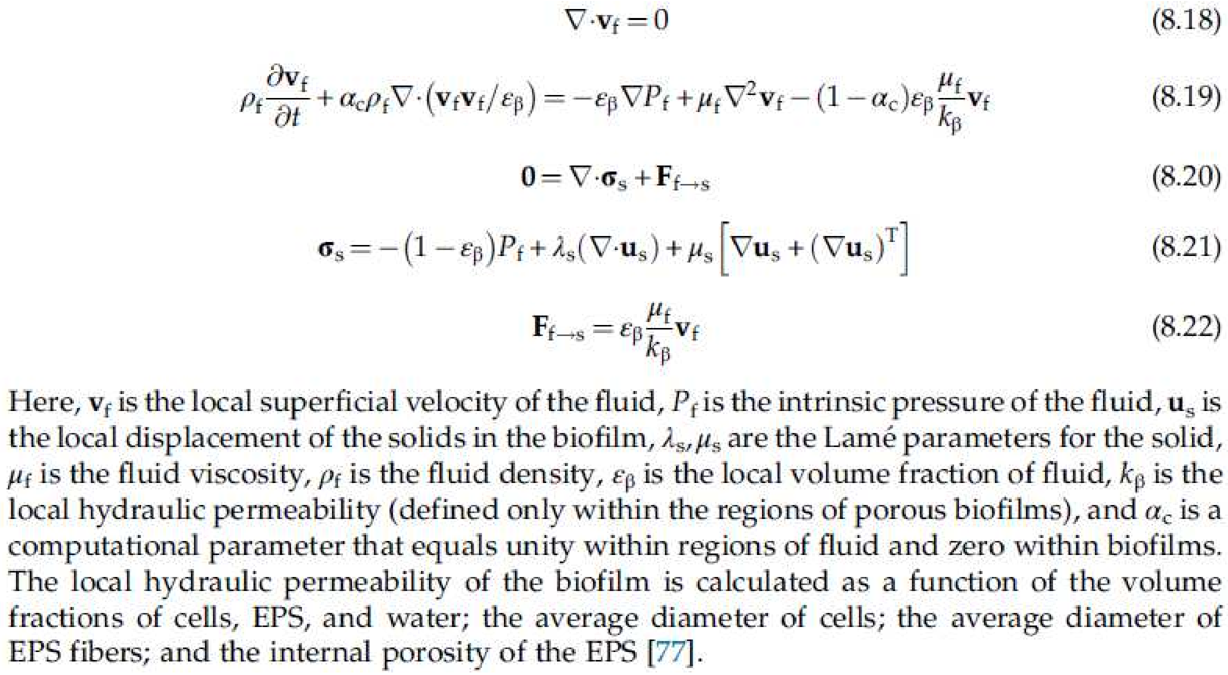
Treatment Efficiency

- *Volatile Solids (VS) Reduction:* is quantified by the reactors' abilities to destroy volatile solids in the feedstock. The modular LBR received a rating of very good, as its high level of operational control allows it to achieve a high level of VS reduction (Table 3). The landfill-cell LBR received a rating of very poor due to its low level of process control. The rest of the reactors received ratings of good as they should all generally provide a sufficient level of VS reduction.
- *Customizable Retention Time:* is quantified by evaluating how well each system can tailor the time needed to achieve adequate treatment levels given variation in the

characteristics of each load of feedstock. The modular LBR was rated very good due to the high number of LBR units and multiple stages (Table 3). The landfill-cell LBR was rated very poor due to its monolithic nature.

- *Biogas Production Stability:* gave the modular LBR system a rating of very good because of its hydrolysis stage redundancy and leachate storage capability. The landfill-cell LBR received a rating of very poor because of its lack of general process control and it is the only system that cannot effectively control reactor temperature, which has a profound effect on biogas production (Table 3).

APPENDIX C: BRINKMAN'S EXTENSION TO DARCY'S LAW



$$\nabla\cdot\mathbf{v}_f = 0 \tag{8.18}$$

$$\rho_f\frac{\partial \mathbf{v}_f}{\partial t} + \alpha_c\rho_f\nabla\cdot\left(\mathbf{v}_f\mathbf{v}_f/\varepsilon_\beta\right) = -\varepsilon_\beta\nabla P_f + \mu_f\nabla^2\mathbf{v}_f - (1-\alpha_c)\varepsilon_\beta\frac{\mu_f}{k_\beta}\mathbf{v}_f \tag{8.19}$$

$$\mathbf{0} = \nabla\cdot\boldsymbol{\sigma}_s + \mathbf{F}_{f\to s} \tag{8.20}$$

$$\boldsymbol{\sigma}_s = -\left(1-\varepsilon_\beta\right)P_f + \lambda_s(\nabla\cdot\mathbf{u}_s) + \mu_s\left[\nabla\mathbf{u}_s + (\nabla\mathbf{u}_s)^{\mathrm{T}}\right] \tag{8.21}$$

$$\mathbf{F}_{f\to s} = \varepsilon_\beta\frac{\mu_f}{k_\beta}\mathbf{v}_f \tag{8.22}$$

Here, $\mathbf{v}_f$ is the local superficial velocity of the fluid, P_f is the intrinsic pressure of the fluid, $\mathbf{u}_s$ is the local displacement of the solids in the biofilm, λ_s, μ_s are the Lamé parameters for the solid, μ_f is the fluid viscosity, ρ_f is the fluid density, ε_β is the local volume fraction of fluid, k_β is the local hydraulic permeability (defined only within the regions of porous biofilms), and α_c is a computational parameter that equals unity within regions of fluid and zero within biofilms. The local hydraulic permeability of the biofilm is calculated as a function of the volume fractions of cells, EPS, and water; the average diameter of cells; the average diameter of EPS fibers; and the internal porosity of the EPS [77].

(Kapellos et al. 2015)