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Use of GIS to Find Optimum Locations for Anaerobic Digestion or Composting Facilities in Maine

Usha Humagain
University of Maine, usha.humagain@maine.edu

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USE OF GIS TO FIND OPTIMUM LOCATIONS FOR ANAEROBIC DIGESTION OR COMPOSTING FACILITIES IN MAINE

By
Usha Humagain
B.E. Tribhuvan University, 2016

A THESIS
Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Science
(in Civil Engineering)

The Graduate School
The University of Maine
December 2020

Advisory Committee:

Dr. Jean D. MacRae, Associate Professor of Civil and Environmental Engineering, Advisor

Dr. Kate Beard, Professor in School of Computing and Information Science

Travis Blackmer, Lecturer and Undergraduate Coordinator in School of Economics

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Thesis Advisor: Dr. Jean D. Macrae

An Abstract of the Thesis Presented
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As per US EPA, in 2017, 41 million tons of food waste was generated, but only 6.3% was diverted from landfills (US EPA, 2020). When landfilled or incinerated, organic waste (food waste, sludge, manure, agricultural waste) causes environmental pollution through greenhouse gas emissions, land, water, and air pollution. In contrast, if we compost or digest organic waste, we can generate soil additives and a mixture of methane and carbon dioxide gas to produce electricity or energy. Both digestion and composting reduce greenhouse gas emissions, improve the land through additives, and boost the economy. Many countries are adopting anaerobic digestion and composting to handle organic waste. There are currently 250 anaerobic digesters in the US (Pennington, 2018). There are 1200 wastewater recovery facilities in the US with anaerobic digestion, and approximately 20% of them co-digest sludge with other organic materials (Pennington, 2019).

Meanwhile, the process of anaerobic digestion is chemically and biologically complex. In 2018 alone, as per EPA, eleven anaerobic digesting facilities were shut down (Pennington, 2019). There were various underlying factors such as; lack of feedstock, economic infeasibility, system shock, hampering the sensitive areas like wetlands through

leaching from the storage areas. Thus, while starting a facility, there are many factors to consider for its long-run success. One of the most crucial factors to consider is the site location. Social acceptance, economic viability, job opportunities, and environmental disturbance are all site-dependent. Hence it is critical to optimize the choice.

This study used ArcGIS Pro 2.6 to find the optimum location for organic waste management facilities in Maine. There are three anaerobic digesters in Maine, of which one is currently closed, and approximately 92 composting facilities handle a large amount of yard trimmings and some food waste. Most of the composting facilities are small scale with 4.3% composting food waste and 4.3% composting sewage sludge. In this study, data on food waste, manure, and sludge were gathered from Maine DEP, EPA, US Farms Data, and published reports to estimate the approximate amount of organic waste. A capture rate of 20% was used for food waste to estimate the amount of food waste collected. For the analysis, four scenarios: (1) the largest anaerobic digester (Fiberight) does not resume, or (2) resumes its work, and (3) co-digesting waste with or (4) without sludge were taken into consideration. To be more area-specific, the analysis was done for the Maine Department of Transportation (DOT) regions: Eastern, Northern, Southern, Mid-Coast, and Western Regions. Eight criteria- food waste availability, sludge availability, transportation cost, distance from residential areas, slope, land cover, distance from airports, and environmentally sensitive areas like conserved lands and wetlands were used to find the optimum locations. Analytical Hierarchy Process determined the criteria weights before assigning them in the suitability modeler of ArcGIS Pro to find the optimum locations. By transforming these criteria, the five best locations in Maine and three possible optimum locations in each region for each scenario were identified. Opportunities for the upgrading of existing farms with excess manure, transfer stations, composting facilities, and WRRFs were identified.

The facilities that coincide in all the scenarios are the optimum facilities that work in all scenarios. Hence feasibility study can be started on those facilities. In the Northern region, Caribou WWTF and Pinelands Farms Natural Meats Inc. coincide in all scenarios, making them the best existing facilities that could be upgraded in the future. Similarly, in the Eastern region, the transfer station of the Town of Lincoln, and the Dover Foxcroft WRRF coincide in all scenarios, making them the best existing facilities that could be upgraded in the Eastern region. Four farms and the transfer station of the town of Clinton coincide in all scenarios in Mid-Coast. Out of these four farms, Stedy Rise farms and Caverly Hills LLC are 330 acres and 840 acres and generate excess manure of 4096 tons /year and 4175 tons/year. These farms could be good locations for a new facility using food waste. In the Southern region, no single facility was identified in all the scenarios, but Sanford WRRF and a few farms could be chosen for feasibility analysis. In the Western region, six farms and the transfer station of the town of Turner coincide in all the scenarios. Feasibility analysis can be done in these facilities to determine which can be upgraded as a new waste management facility utilizing food waste.

ACKNOWLEDGMENTS

I want to thank my advisory committee for the regular feedback on my project and for working with me on this. My advisor, Dr. Jean D. MacRae, has continuously supported me and helped me with the new waste-related information. She has always pushed me forward to learning new things and showing my works to the community. I am thankful to her. Being an international student and having English as a second language was pretty tough for me to gain confidence. These two and half years in the University has made me more confident to express myself. I am glad I chose this University for my master's degree. My second family: the Nepalese students of Maine, has never made me feel alone and far away from family and friends. Finally, I want to be thankful to my family and friends back home, who always have believed in me.

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CHAPTER 1

USE OF GIS TO FIND OPTIMUM LOCATION FOR ANAEROBIC DIGESTER OR COMPOSTING FACILITIES

1.1 INTRODUCTION

Globally the Food and Agriculture Organization of the United Nations (FAO) has estimated that one-third of food produced for human consumption is lost or wasted, equivalent to about 1.3 billion tonnes per year, with the highest proportion contributed by household waste (IEA Bioenergy, 2018). In the U.S. in 2017 alone, EPA estimates that almost 41 million tons of food waste was generated, with only 6.3% diverted from landfills and incinerators (US EPA, 2020). Piles of food waste and other organic waste contributed from municipal solid waste, wastewater, and food processing waste fill up the landfills and impact the environment with greenhouse gas emissions, air, water, and land pollution (IEA Bioenergy, 2018). We need a shift towards a renewable and sustainable system to circularize the food system. There are various measures to reduce organic wastes like source reduction, feeding excess food to people and animals, composting, waste-to-energy technologies like anaerobic digestion, and incineration; however, this study focuses only on anaerobic digestion and composting.

1.1.1 ANAEROBIC DIGESTION

Carbon dioxide fixed into organic matter by photosynthesis is regenerated upon the decomposition of organic matter by O_2, requiring (aerobic) organisms in aerated habitats (Wall et al., 2008). Under anaerobic conditions, a complex mixture of symbiotic microorganisms can also decompose organic materials into a mixture of gas called biogas, consisting of methane, carbon dioxide, hydrogen sulfide, and moisture; plus, nutrients and additional cell matter (Wall et al., 2008). This process is commonly known as anaerobic digestion. David Fulford describes anaerobic digestion as the process that uses naturally occurring microorganisms to break down organic materials-food waste, wastewater sludge, agricultural waste, or manure - into methane and carbon dioxide in the absence of oxygen (Fulford, 2015).

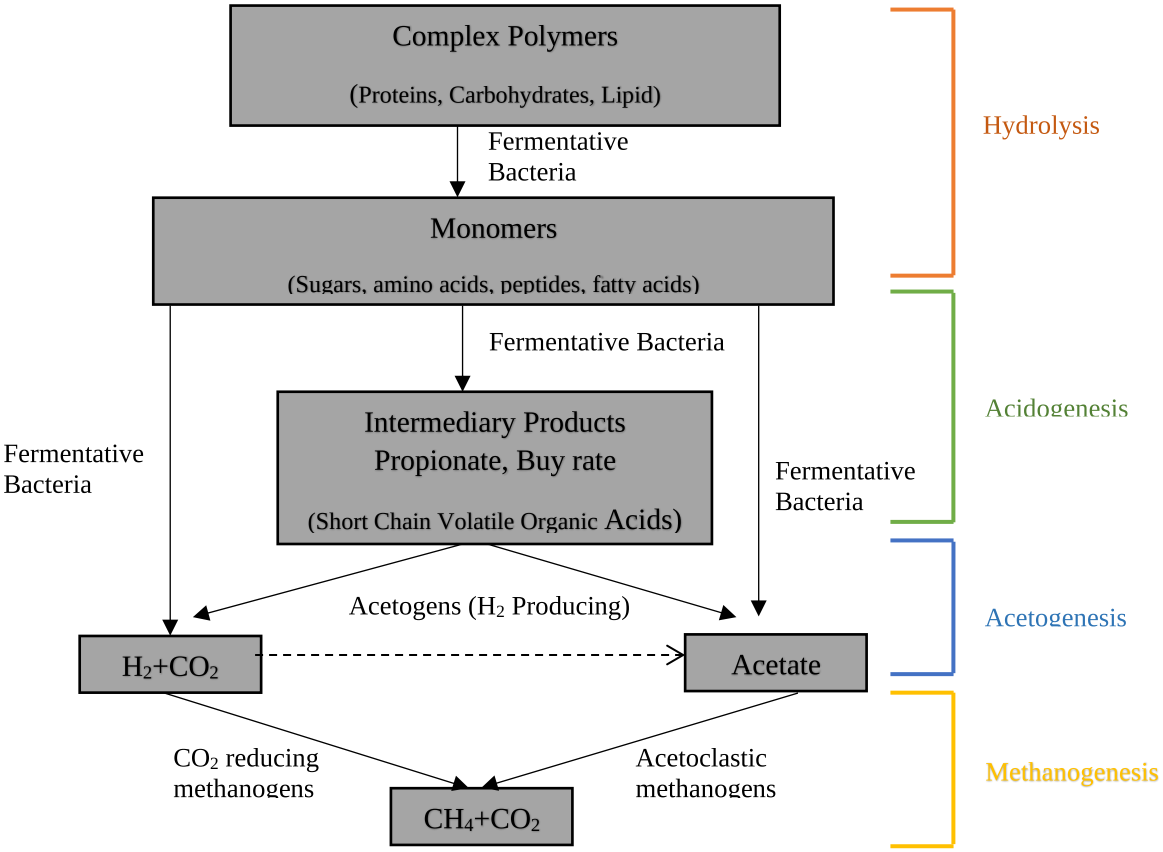


Figure 1-1: Anaerobic digestion process (Leal, 2020)

Anaerobic digestion completes in four biological processes: hydrolysis, acidogenesis, acetogenesis, and methanogenesis.

In the hydrolysis process, microbes break down the chemical bonds by incorporating a water molecule. Complex molecules like carbohydrates, proteins, lipids, and cellulose are broken down into smaller molecules like sugars, amino acids by hydrolytic bacteria with extracellular enzymes like amylase for carbohydrates, cellulase for cellulose, lipase for lipids, and protease for proteins (Kim et al., 2012). This step occurs very slowly; thus, this step can be a rate-limiting step in anaerobic digestion (Kim et al., 2012). The hydrolysis rate depends on the size and type of organic materials, pH, temperature, salt content, metals, and enzymes (Ali Shah et al., 2014). The compounds formed in the hydrolysis stage ferment into alcohols like ethanol and acids like propionic, acetic, valeric, and butyric acids in acidogenesis (Mir et al., 2016). In acetogenesis, the acidogenesis phase products convert to acetate, carbon dioxide, and hydrogen (Mir et al., 2016). Methanogenesis is the final step in the anaerobic digestion of organic matter, where methanogenic archaea are responsible for utilizing acetate, hydrogen, and carbon dioxide to produce methane. There are three types of methanogens: acetoclastic (acetate to methane and carbon dioxide), hydrogenotrophic (hydrogen and carbon dioxide to methane), and methylotrophic (methyl compounds like methanol, methylamines, methyl sulfides to methane) methanogens (Amani et al., 2010). Generally, acetoclastic methanogens make 3/4th of methane production, contributing to the largest amount (Wall et al., 2008). Among all the processes, acidogenesis is generally faster and can lead to the accumulation of volatile fatty acids in the system, making the system acidic and inhibit methanogens responsible for methane production (Wisconsin Department of Natural

Resources, 1992). However, in a well operating system, methanogens keep up, and the pH remains stable. (Wisconsin Department of Natural Resources, 1992).

1.1.2 COMPOSTING

Composting, an aerobic microbial transformation, and stabilization of organic matter is an exergonic process that releases energy, about 50– 60 % of this energy is utilized by microorganisms to synthesize ATP; the remainder loses as heat (Stentiford & de Bertoldi, 2010). In practice, there are four main activities required for efficient composting, namely: shredding, to reduce particle size and increase the surface area to volume ratio; mixing different feedstocks to improve homogeneity and adjust the carbon to nitrogen (C: N) ratio; adding water where mainly dry materials are received; and removing contaminants (Swan et al., 2002). A typical composting process completes in four phases.

1. Mesophilic Phase: A diverse population of mesophilic bacteria and fungi proliferates and degrade readily available organic matter, thereby increasing the temperature to about 45℃.
2. Thermophilic Phase: Temperature increases to 55-65℃ and this heat eliminates pathogenic and helminths eggs.
3. Cooling Phase: Temperature decreases and remains at about 25-30℃, also known as the stabilization or curing phase.
4. Humification Phase: The humic acid content and cation exchange capacity of compost increases.

(Stentiford & de Bertoldi, 2010; Williams et al., 2002).

Anaerobic digestion technology has two significant advantages over composting: firstly, it is cost-effective for use at large scale and with “strong” wastes because it does not require aeration and produces a small amount of excess sludge. Secondly, it recovers some of the energy content of the organic matter as gaseous methane (Narihiro & Sekiguchi, 2007). On the other hand, composting facilities are simpler to operate, easier to expand, require less capital investment, can accept variable input materials (by type and amount) and produce a more stable product (Mohee & Mudhoo, 2012).

1.1.3 WASTE MANAGEMENT IN THE UNITED STATES

As per the EPA's resource recovery hierarchy (EPA, 2019) shown in

Figure 1-2, the least preferred waste management method is landfilling and incineration, followed by composting and anaerobic digestion, industrial uses, feed people and animals and source reduction. There are programs like EPA's Food Too Good To Waste Program, which uses consumer education and awareness through its pilot projects to recover food. Consumers are also provided with shopping bags, measurement tools, and tips for food storage and meal planning as a measure to reduce food waste (Hobson, 2006).

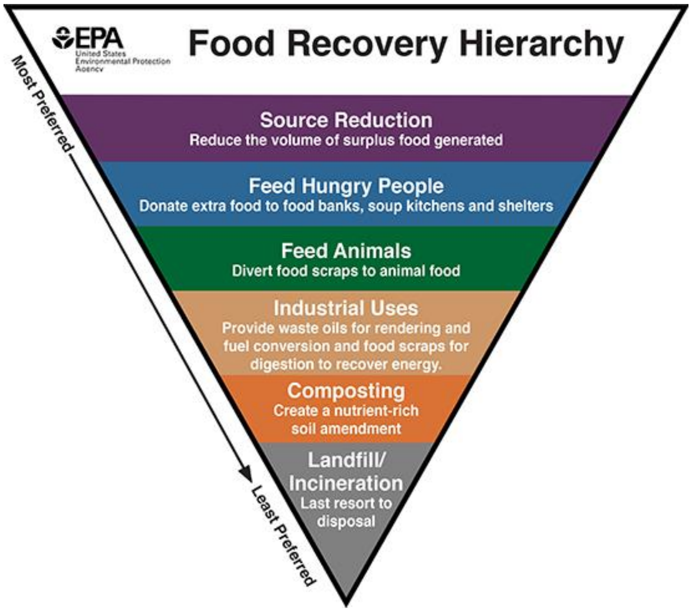


Figure 1-2: Food Recovery Hierarchy by EPA (EPA, 2019)

The total municipal solid waste (MSW) generation in 2017 was 267.8 million tons or 4.5 pounds per person per day. From this MSW, 27 million tons were composted, of which 2.6 million tons was food waste, and the remainder was yard trimmings (OLEM US EPA, n.d.). More than 139 million tons of MSW, out of which 22% was food, were landfilled (OLEM US EPA, n.d.). AgSTAR estimates that biogas recovery is technically feasible at over 8000 large dairy and hog operations that can potentially generate nearly 16 million MWh of energy per year and displace about 2010 MWs of fossil fuel-fired generation (OAR US EPA, n.d.). Meanwhile, as per EPA's AgSTAR program, approximately 250 anaerobic digesters are operating on livestock farms in the USA (Pennington, 2018). Forty-three of these anaerobic digesters co-digest food waste with manure (Pennington, 2018). There are 58 stand-alone anaerobic digesters that are built to digest food waste (Pennington, 2018). The Water Environment Federation and American Biogas Council database identify about 1200 Wastewater Resource Recovery Facilities (WRRFs) in the

U.S. that use anaerobic digestion to manage wastewater sludge. Of these, roughly 20% co-digest food waste received from other sources (Pennington, 2019).

1.1.4 WASTE MANAGEMENT IN MAINE

In Maine, unit-based pricing for waste disposal "pay as you throw" (PAYT) is in place in more than 160 communities (Isenhour et al., 2016). There are currently three anaerobic digesters digesting sludge and food processing waste, manure and FW, soluble organics from MSW and composting facilities that compost FW with other kinds of organic waste. There are transfer stations that collect and transfer the municipal waste to the corresponding site.

1.1.4.1 Anaerobic digesters in Maine

1.1.4.1.1 Exeter Agri-Energy:

Exeter Agri-Energy is a renewable energy company using manure from the Stonyvale farm of Exeter, Maine, and organic waste from Scarborough and different communities around Portland, Hannaford grocery stores around Maine and Walmart (ecomaine, 2017). Agri-Cycle, a food waste collection service, delivers industrial loads of food waste from area supermarkets, restaurants, and food processors in Greater Portland to Exeter Agri-Energy (ecomaine, 2017). Stonyvale farm collects manure from 1000 milking cows. It mixes with the organic waste collected from different areas to produce electricity and heat, organic fertilizer, organic soil additives, healthy and comfortable animal bedding. The system heats the mixture to just over 100 degrees Fahrenheit and agitates it intermittently over a 15-25 days retention period. A 1500 horsepower engine burns the biogas produced, powering the generator that produces enough heat every day to replace 700 gallons of heating oil on average and 22000 KW hours of electricity. On an annual basis, this energy is enough to heat 300 New England homes and enough to power as many as 800 households.

(*How It Works | EAE – Exeter Agri-Energy*, n.d.)

1.1.4.1.2 Fiberight Inc:

Fiberight Inc., a next-generation waste processing facility in Hampden, Maine, processes municipal solid waste for the Municipal Review Committee (MRC) member communities (Fiberight, 2018). The MRC is a group of 115 Maine cities and towns joined together as a nonprofit organization to manage their municipal solid waste (MSW) (MRC Inc., 2018b). All the members have contracted to process their MSW in this facility (MRC Members, n.d.). MRC members are collectively anticipated to deliver 100,000 tons of MSW annually (MRC Inc., 2018b). After delivery of the municipal solid waste to Fiberight, it is sorted, removing the inert materials, bulky items, and recyclables. The rest of the waste is pulped, and the remaining plastics are separated from pulped organic materials. The organic pulp is washed to remove contaminants, and dirty water is sent to an anaerobic digester. Clean pulp is used to make new paper products, biomass fuel, or converted to sugars. Anaerobic digesters process the sugars from the clean pulp.

(MRC Inc., 2018a)

Meanwhile, as per Bangor daily news, Fiberight Inc. is temporarily closed as of June 2020 (Bangor Daily News, 2020) without fully reaching full operation since the planned April 2018 start. This closure has forced 115 communities to divert their municipal waste to landfills (Bangor Daily News, 2020).

1.1.4.1.3 Lewiston Auburn Water Pollution Control Authority (LAWPCA)

LAWPCA provides wastewater treatment services to Lewiston and Auburn. Starting its operation in 1974, the plant was one of the first secondary wastewater treatment plants in the state. The plant has digested wastewater sludge since 2013 and additionally accepts grease and food processing waste to generate additional biogas and electricity. The capacity of the digester is 45000 gallons of waste/day.

(*About Us – LAWPCA*, n.d.)

1.1.4.2 Composting Facilities

Many companies compost waste and provide subscription-based service with the regular pickup of organic materials. There are a mix of household, commercial, and industrial focused companies. These companies include Garbage to Garden, We Compost It!, Mr. Fox Composting, Project Earth (NRCM, 2016a), and Scrapdog Community Composting. These facilities serve greater Portland, Lincoln county, southern Maine (NRCM, 2016b), and the Mid-Coast region.

1.1.5 THE RATIONALE OF THE STUDY

Additional waste management capacity can be obtained by upgrading existing facilities or by constructing new one. However, if we want to build or upgrade any facility, we need to understand the different parameters like availability of feedstock, transportation cost, geographic location, competitors and market availability for the products. Selecting suitable areas among several possible alternatives, is the most crucial step for pollution control and minimizing environmental hazards (Nazari et al., 2012). Hence locating a facility is an essential aspect of the successful operation of a waste management facility.

There are several methods for selecting a site while considering multiple attributes, but we chose the Geographic Information System (GIS) for better visual representation and analysis.

1.1.6 OBJECTIVES OF THE STUDY

With the 712 livestock farms, 155 municipal WRRFs, and 318 pounds of FW generation per person per year, Maine generates a large amount of organic waste. There are only three anaerobic digestion facilities, with one closed at the moment, which leaves a large amount of waste to be managed. The state of Maine has a goal, started in 1994, of diverting 50% of total waste generated away from the landfill by January 1, 2021, and has yet to meet the goal (Public Law Chapter 461, n.d.). The broader availability of organics diversion would help meet this goal while removing a fraction of waste that produces a management problem in landfills and incineration. This study aimed to find the optimum locations to divert more food waste and ensure that all parts of the state have viable FW management options while considering transportation, slope, land cover, FW and sludge availability, environmentally sensitive areas, and distance to airports and residential areas. ArcGIS pro 2.4 and 2.6 versions were used for the analysis.

1.2 METHODOLOGY

1.2.1 ARCGIS PRO ANALYSIS

ArcGIS Pro is the latest professional desktop GIS application from Esri that can explore, visualize, analyze data; create 2D maps and 3D scenes, and share users' work with ArcGIS Online or ArcGIS Enterprise portal (*About ArcGIS Pro—ArcGIS Pro | Documentation*, n.d.). This study used ArcGIS Pro 2.4 for data representation in the map, finding the approximate amount of waste generated and the amount of waste that needs management. ArcGIS 2.6, released in July 2020, contained the suitability modeler in which one could use different criteria of different weights to find a suitable location, precisely what this study aimed for. Thus, for finding appropriate locations in each designated polygonal area, ArcGIS pro 2.6.1 was used. The coordinate system used for the analysis was WGS 1984 UTM zone 19 N. Tools like the clip, intersect, spatial join, join, geocode, feature to raster, and many others were used for the analysis.

1.2.2 WASTE MANAGEMENT SCENARIOS

The biosolids characteristics that affect their suitability for land application and beneficial reuse include organic content, nutrients, pathogens, metals, and toxic organics concentrations (Metcalf & Eddy, 2003). Some chemicals like highly halogenated compounds and heavy metals are not readily amenable to biological degradation and stabilization, and microbial degradation may lead to more toxic or mobile substances than the parent compounds (Mohee & Mudhoo, 2012). There is growing concern about PFAS (Per- and Poly-FluoroAlkyl Substances) as they are persistent in the environment and the human body, and they accumulate (US EPA, 2018). PFAS are found in a wide range of consumer products. Some of these compounds cause low infant birth weights, effects on the immune system, and cancer (US EPA, 2018). Thus, there are concerns that digestion or composting of biosolids with other organic wastes for application to agricultural soils may amplify these bioaccumulative chemicals in the food system (National Sewage Sludge, 2020).

Given the uncertainty around the reopening of Fiberight, two scenarios – Fiberight remaining out-of-operation and resuming operations were considered to observe the impact on the optimum location. Two other conditions, allowing for, or excluding wastewater treatment plant sludge, were also added creating the four scenarios shown in Figure 1-3.Scenario for waste management in Maine

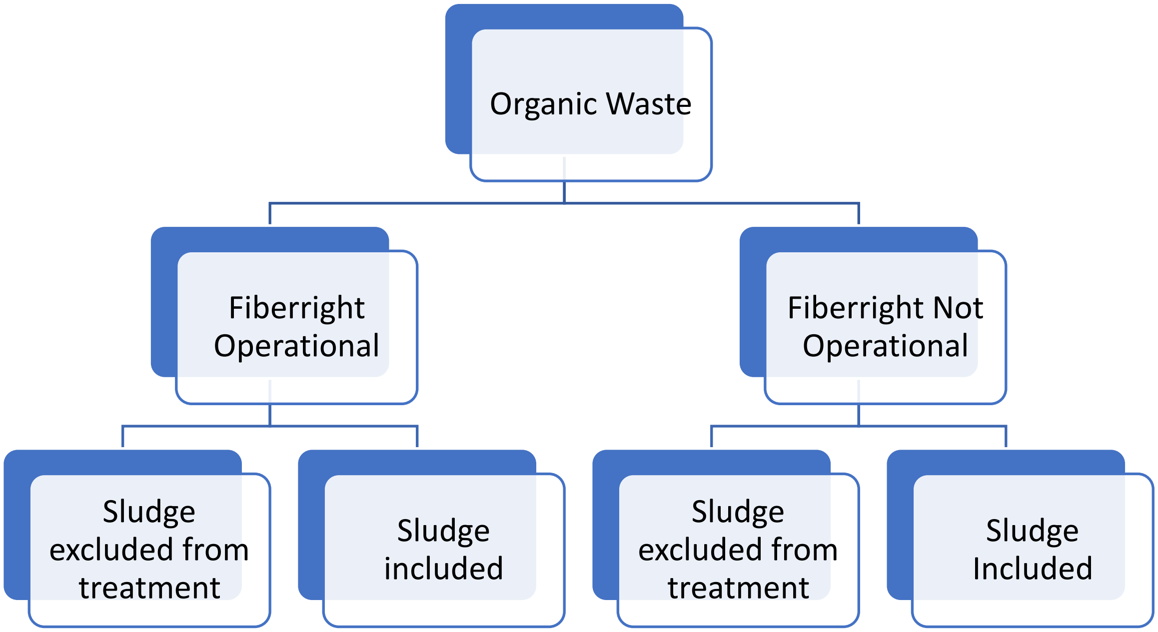


Figure 1-3: Scenario for waste management in Maine

1.2.3 DIVIDING MAINE INTO WASTE MANAGEMENT AREAS

The Department of Transportation (DOT) of Maine has divided Maine into five regions-mid-coast, southern, eastern, northern and western. These regions are presented in Figure 1-4 with their population. The optimum locations were determined for these regions in each scenario. As per Table 1-1, the Southern region has the highest population density of 191 people/square mile, whereas the Northern region has the lowest at 6 people/mi^2.

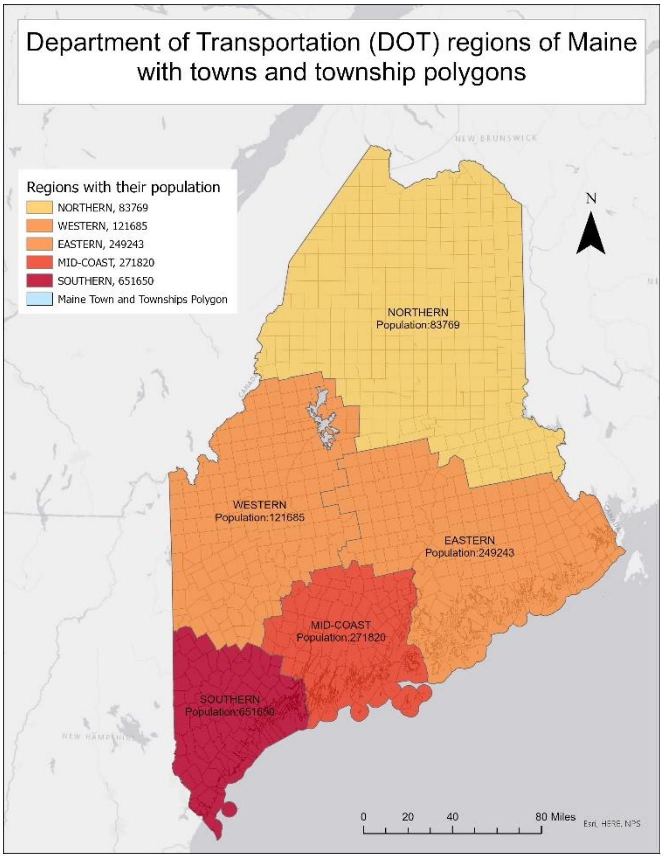


Figure 1-4: Five regions used for site optimization

Table 1-1: Details of Maine DOT Regions

Region	**2020 Total Population**	**Area (sq. miles)**	**Population per square miles**	**Towns and Township polygons**
Eastern	249,243	7,884.022	32	3109
Mid-Coast	271,820	3,835.56	71	2902
Northern	83,769	12,896.28	6	348
Southern	651,650	3,408.6	191	1585
Western	121,685	7,191.54	17	473

1.2.4 DATA COLLECTION AND ASSUMPTIONS

1.2.4.1 Farms of Maine

US Farm Data is a part of the U.S. crop production industry that keeps a database of farmers and ranchers in the US, crop type, livestock type, and operation size (Dun & Bradstreet, 2020). A dataset of livestock farms from US Farm Data depicting the number and type of livestock, farm area, and contact information of Maine's farms was bought (US Farm Data, 2020). Based on that data, there were 772 farms in Maine with livestock-cattle, dairy, pigs, Hogs, Sheep, Goats. Four hundred eighty-two farms of this dataset had their area provided in acres.

1.2.4.1.1 Assumptions to be made on the manure production by each livestock:

Manure production differs based on animal weight and milk production: a 1000 pounds cow produces 82-97 pounds/day manure (Fischer, 1998; USDA & Natural Resource Conservation Service, 1995). As per USDA, under the best conditions, only 90-95% manure can be collected (USDA & Natural Resource Conservation Service, 1995). A manure production rate of 100 pounds/day and 90% collection rate was assumed since the actual weight and breed of cattle, and milk production rate were unknown.

1.2.4.1.2 Excess Manure generation from farms

Hay is an essential source of food for livestock. Alfalfa is the primary hay crop grown in the US since it produces more than 119 million tons of hay every year (EPA, 2015). This study estimates that each livestock farm grows hay (Alfalfa) as feedstock. The manure application rate for Alfalfa hay's growth is seven tons-manure/acre (Undersander et al., 2011). Any farm with more than 7 tons of manure/acre had excess manure. These farms were selected for further analysis. The data obtained from US Farm Data was uploaded and geocoded, and the geocoding resulted in only 765 farms. Figure 1-5 shows the location of farms with excess manure in Maine. It shows that most of the farms are concentrated between Bangor, Augusta, and Portland.

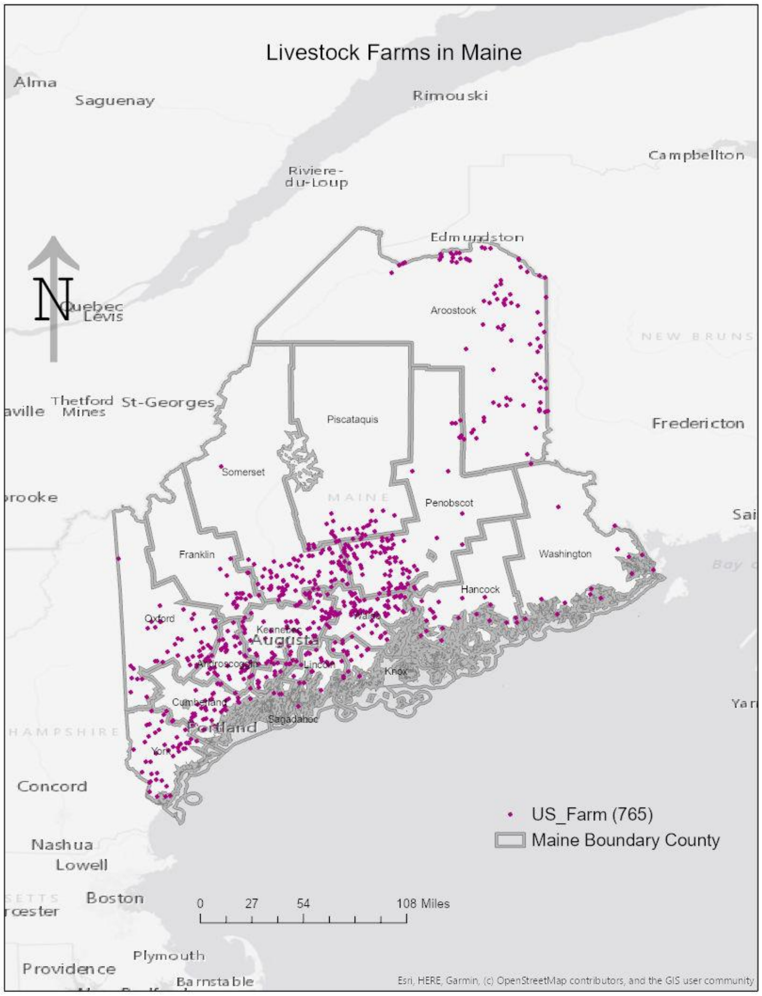


Figure 1-5: Cluster of Livestock Farms in Maine.

1.2.4.2 Wastewater Resource Recovery Facilities

EPA keeps a record of wastewater recovery facilities in the United States. This GIS dataset contains data collected in January 2020 on wastewater recovery facilities, based on EPA's Facility Registry Service (FRS), EPA's Integrated Compliance Information

System (ICIS) (EPA Facility Registry Service, n.d.). The primary facility and location information of wastewater treatment plants was compiled from EPA Facility Registry Service (FRS), and attribute data was collected from ICIS (EPA Facility Registry Service, n.d.). As the study focused only on municipal wastewater treatment plants, industrial, groundwater, and fish treatment plants were filtered from the data. After cleaning the data, there were 155 municipal wastewater treatment plants in Maine. Department of Environmental Protection has a dataset on WRRFs with its licensed flow. The data was downloaded in shapefile from the Maine Office of GIS. The two datasets in GIS were joined together to get the licensed flow of each wastewater recovery facility. The facilities that generated more than 500 tons of sludge annually were selected for further analysis.

(EPA Facility Registry Service, n.d.)

1.2.4.3 Sludge Generation from Wastewater Recovery Facilities

A model from a paper in the Journal of Environmental Management was adopted for calculating the amount of the sludge generated from WRRFs. In this method, the author uses generally accepted literature values to estimate primary, secondary, and total annual sludge production on a dry weight basis at the facility (Seiple et al., 2017).

Table 1-2: Typical national values for municipal wastewater

Variable	**Value**	**Range in Literature**
TSS	260	120 to 400 mg/L
S_o	230	110 to 350 mg/L
F	0.6	0.4 to 0.70
f_v	0.85	0.8 to 0.9
K	0.4	0.4 to 0.6

(Seiple et al., 2017)

The total dry solids generated in the wastewater treatment plant is given by,

$$M_T = M_P + M_S$$ Equation 1

Where M_T is total dry solids in g/d, M_p is total dry solids captured during primary treatment in g/d, and M_s is total dry solids from secondary treatment in g/d.

Primary treatment solids are estimated by

$$M_P = Q * TSS * f$$ Equation 2

Q is the average influent flow rate in m3/d. *TSS* is the average influent total suspended solids concentration in g/m^{3,} and *f* is the fraction of total suspended solids removed in primary settling.

Secondary solids, commonly known as waste activated sludge, is estimated as,

$$M_S = Q\ [(k*S_o) + (((1-f)*TSS)*(1-f_v))]$$ Equation 3

S_o is the average influent BOD$_5$ concentration in g/m^3, k is the fraction of influent BOD$_5$ that becomes excess biomass, and f_v is the ratio of average influent volatile suspended solids to total suspended solids.

Figure 1-6 represents the location of WRRF$_s$ in Maine. After removing the industrial and other treatment systems, there were 155 WRRF$_s$.

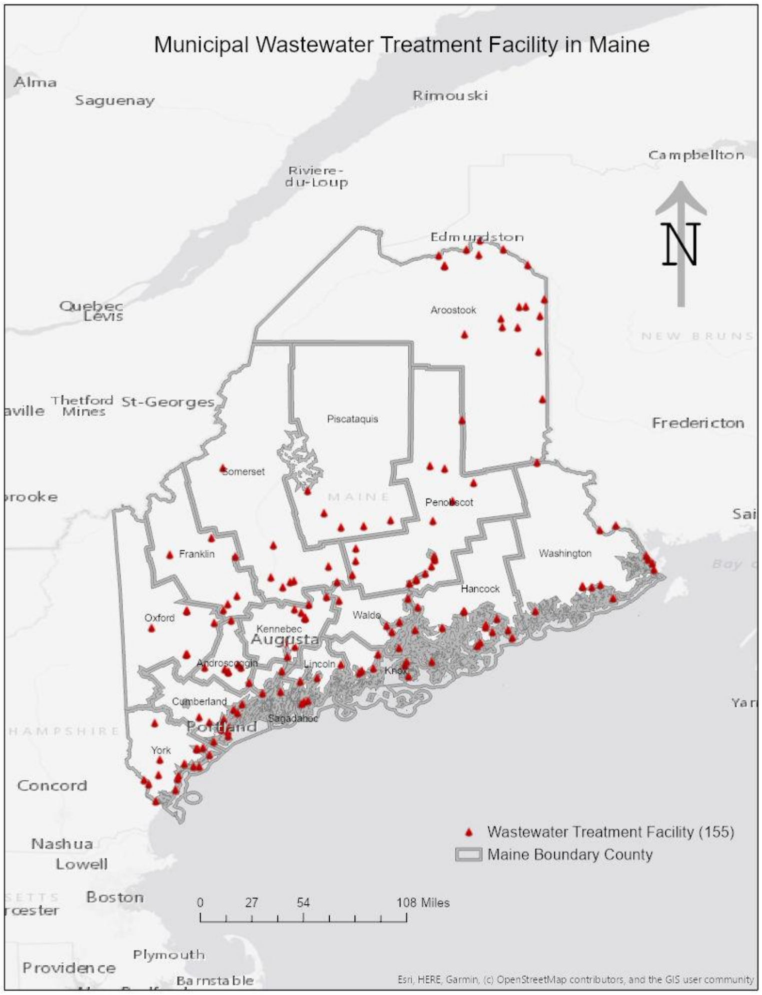


Figure 1-6: Clusters of municipal wastewater recovery facilities in Maine

1.2.4.4 Food waste Generation

The excess food opportunities map of EPA has a dataset for FW generation from restaurants (*Excess Food Opportunities Map*, n.d.). The file was downloaded in .xls format and uploaded in ArcGIS pro. The table in ArcGIS pro was geocoded using multiple numbers of fields. The attribute table had a rough estimate of the lowest and the highest amount of food waste generation. The amount corresponding to the highest food waste was used as the analysis would cover the food waste generation at an extreme level.

The EPA's methodology for the data collection:

Based on the North American Industry Classification System (NAICS), 76 categories of industries and three school types representing nearly 1.2 million establishments in the US were identified as potential excess food sources. These 76 categories were grouped into the following sectors: Food manufacturers and processors (46), food wholesale and retail (17), educational institutions (3), the hospitality industry (3), correctional facilities (1), healthcare facilities (3), and restaurants and food services (6). Commercially and publicly available data were compiled to create a dataset of all identified establishments. Sector-specific methodologies for estimating excess food generation rates were adopted from existing studies conducted by state environmental agencies, published articles, and other sources, such as the Food Waste Reduction Alliance (FWRA). All adopted studies used methodologies based on commonly tracked business statistics to estimate excess food generation rates for several or all the targeted sectors. These business statistics include the number of employees, annual revenue, number of students (for educational institutions), number of inmates (for correctional facilities), and number of beds (for healthcare facilities).

(Excess Food Opportunities- Technical Methodology, 2020)

1.2.4.4.1 Assumptions made on the generation of FW from households:

In 2014, Maine residents disposed and generated 0.570 tons (1140 pounds) of MSW per person (Solid et al., 2016). This rate was held steady in 2015 as per Maine Solid Waste Generation and Disposal Capacity Report (Maine DEP, 2017). A study done at the University of Maine in 2011 shows that Maine food waste comprises 27.86% of the total MSW (Criner & Blackmer, 2011). Based on this data, each person in Maine produces

0.16 tons (318 pounds) of food waste in a year. This rate was used to find the total amount of food waste generated in Maine.

1.2.4.4.2 Capture rate of food waste

Based on the 2007 EPA data, the capture rate of food waste was 2.7% in the U.S at that time (Xu et al., 2016). However, with the establishment of anaerobic digesters and composting facilities, the rate should be higher by 2020. A European Commission DG-ENV study considers a capture rate of 85% with mandatory source separation (COWI, 2004). This study assumed FW's target capture rate of 20% as source separation is not mandatory in Maine. Existing transfer stations were assumed to be operating for transferring the waste to the management facility.

1.2.4.5 Composting Facilities

EPA Excess Food Opportunities map has a dataset on the composting facilities of the US. The data identifies operational composting facilities, and some are currently accepting food as a feedstock (*Excess Food Opportunities Map*, n.d.). EPA compiled this data through a review of state government websites, usually state departments of natural resources or environmental protection, and communication with state government employees (Excess Food Opportunities- Technical Methodology, 2020) in 2018 (*Layer: All Composting Facilities (ID: 22)*, 2018). As per this dataset, there are 92 composting facilities in Maine. Most of these composting facilities compost wood, leaf, and yard waste. Information of the communities served by composting companies in Maine- Garbage to Garden, We Compost It!, Mr. Fox Composting, Project Earth- was not found. The shapefile was uploaded in GIS, and two facilities were removed as they were outside

Maine. Figure 1-7 shows that most of the composting facilities are in the southern and central region of Maine.

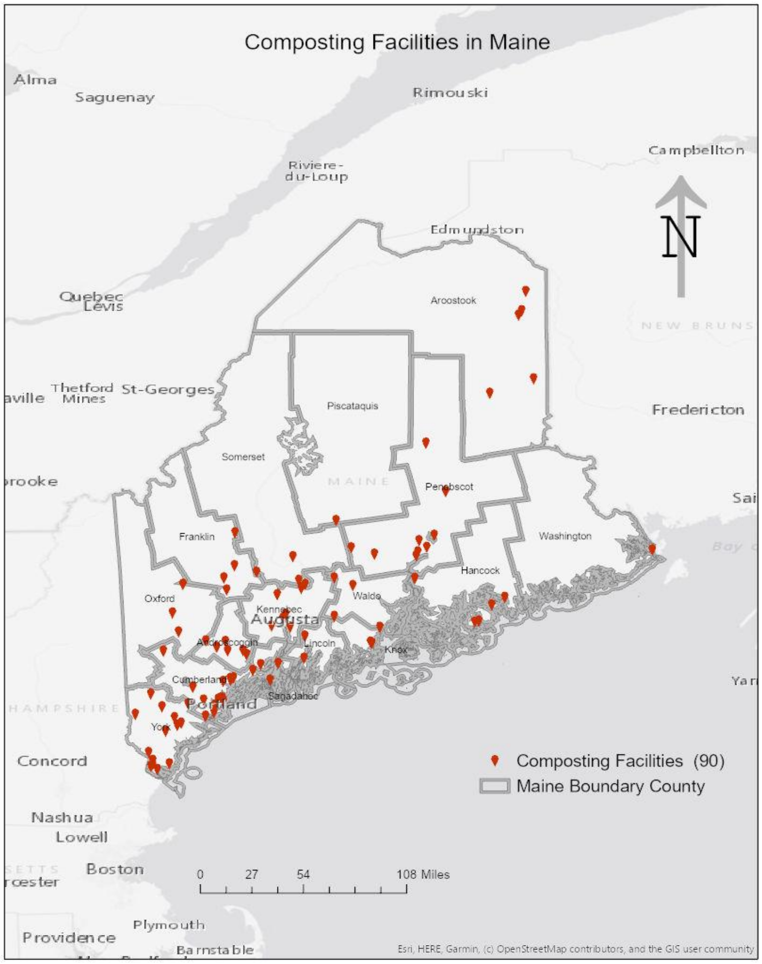


Figure 1-7: Location of composting facilities as per the EPA data (*Excess Food Opportunities Map*, n.d.).

1.2.4.6 Transfer Stations

Maine DEP has a pdf on the existing transfer stations of Maine updated in 2020 (Maine DEP, 2020). This pdf was converted to excel and uploaded in GIS. As per this dataset, there are 251 transfer stations in Maine. The excel data was geocoded using multiple attributes. Only 162 transfer stations geocoded correctly; the remaining transfer stations were filtered out as they were outside Maine.

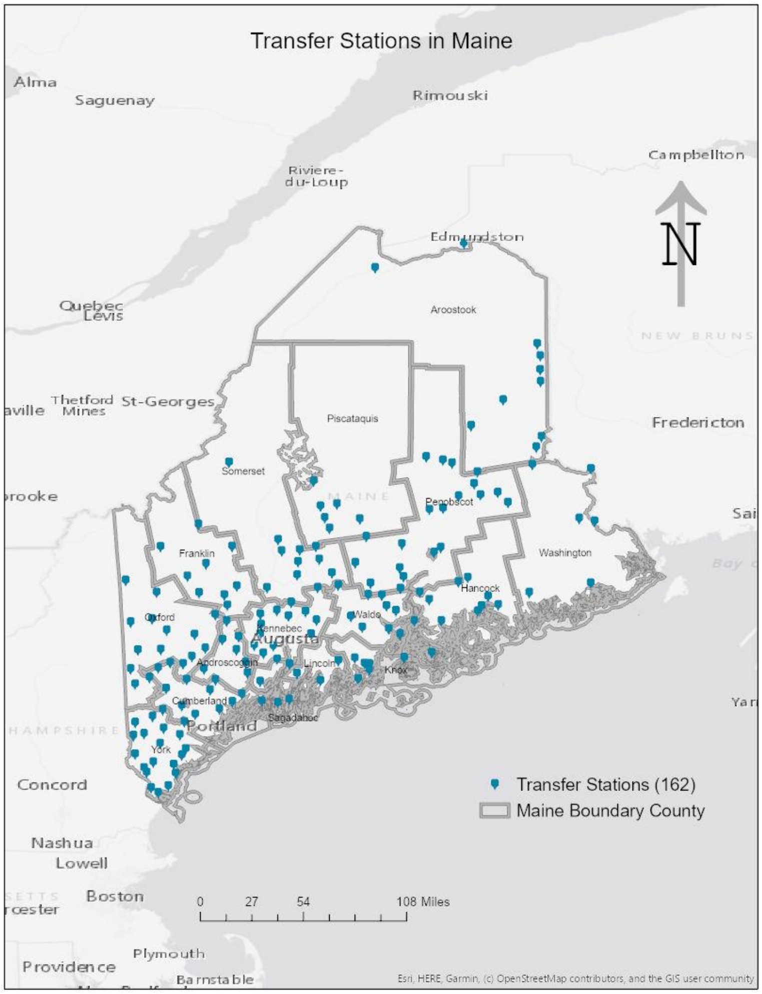


Figure 1-8: Transfer stations in Maine

1.2.4.7 Maine Towns and Townships

The Maine Office of GIS has a shapefile of the towns and townships polygon data in the dataset's boundary catalog (Maine Office of GIS). This dataset was uploaded in GIS, and the analysis was done in the towns and township as this seemed the smallest and reasonable boundary feature to work for population and food waste by towns.

1.2.4.8 Maine Conserved Lands, Wetlands, and Landslide Extent

Conserved lands, Wetlands, and the landslide extent areas are not suitable places to build any structure. These were represented as environmentally sensitive locations and were excluded from the mainland and described the remaining site as possible locations for construction. The shapefile dataset was downloaded from the Maine Office of GIS. Conserved lands represent national parks, state parks, private areas, whereas landslide extent represents Maine's inland landslide extent.

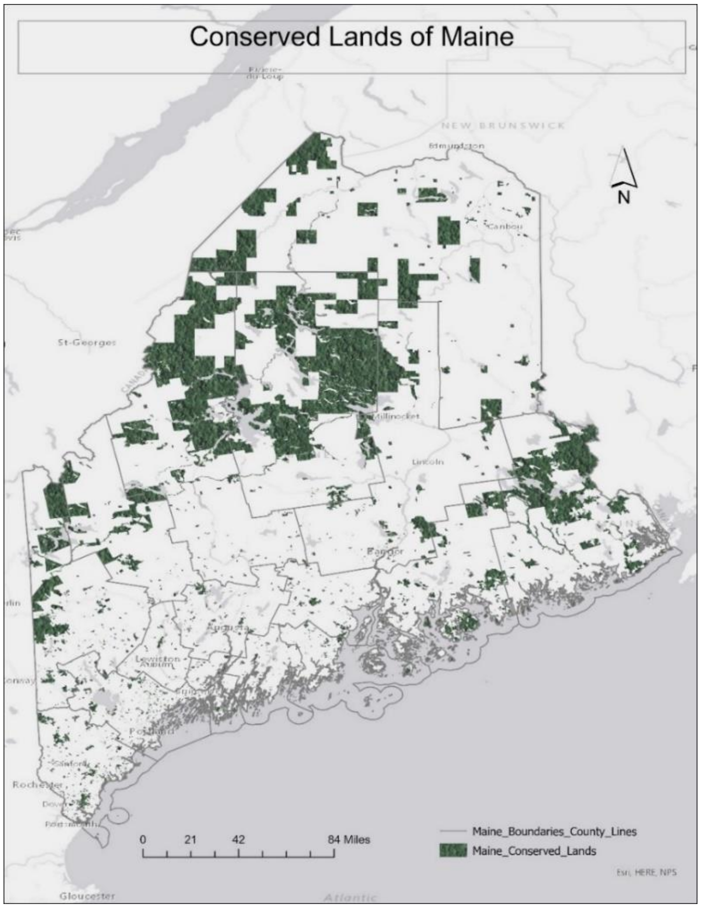


Figure 1-9: Maine conserved lands. These lands include park, forests which are private or public

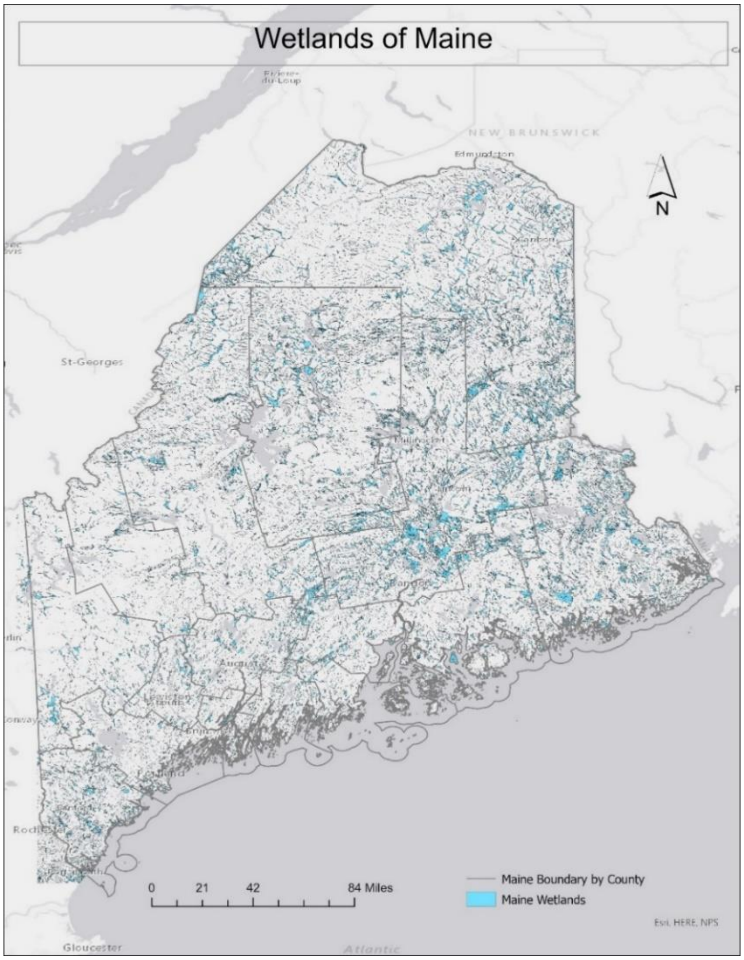


Figure 1-10: Wetlands of Maine

There were only a few areas for the extent of the inland landslide in the south of Maine.

1.2.4.9 Airports of Maine

The point shapefile was downloaded from the Maine Office of GIS. As per the US Department of Transportation Federal Aviation Authority, the composting facilities should not be closer than 1,200 feet to airports. Since the airports' actual area was not known, 2 miles of circular buffer was made at each airport. This buffer was masked from the remaining area of Maine using a symmetric difference tool.

1.2.4.10 Slope of Maine

From the Maine Office of GIS, a shapefile of the contour of 100 feet layers was downloaded. This contour layer was converted to DEM using the topo to raster tool, and the slope tool determined the slope of Maine (Esri, 2020). The slope was represented in terms of percentage.

1.2.4.11 Maine Land Cover

Maine land cover data was gathered from the Office of Coastal Management National Oceanic and Atmospheric Administration. The NOAA Coastal Change Analysis Program (C-CAP) produces national standardized land cover for the US's coastal regions. The maps were developed through the automated classification of high-resolution National Agriculture Imagery Program (NAIP) imagery, available Lidar digital elevation data, and assorted ancillary information. It was a 10 m land cover beta. The attributes represented impervious developed, open space developed, grassland, upland trees, shrub, Wetlands, Bare land, wetlands, and aquatic bed.

(*2015-2017 C-CAP Derived 10 Meter Land Cover - BETA | ID: 57099 | InPort*, 2019)

1.2.4.12 Summary of data use and their sources

Table 1-3: Summary of data and their uses

Type of data	Purpose of the data	Source
Farms Data	data for manure estimate	US Farms Data
Wastewater Treatment Plants	data to develop sludge estimate	http://hub.arcgis.com/datasets/maine::mainedep-pollutant-discharge-elimination-system-facility/data?selectedAttribute=LICENSED_FLOW
Location and Capacity of existing digesters	Existing digestion capacity	Website of the facilities
excess food generation from restaurants, grocery stores, food processing, and manufacturers	Information on non-residential food waste production	https://geopub.epa.gov/ExcessFoodMap/
Composting Facilities	Existing composting capacity	https://geopub.epa.gov/ExcessFoodMap/
Transfer Stations	Probable composting sites Estimate transportation cost by transporting waste from/to these facilities	https://www.maine.gov/dep/maps-data/documents/swactivelict.pdf
Maine Boundary by County	Visualize Maine by its boundary	https://www.maine.gov/geolib/catalog.html
Maine Towns and Township Polygons	Estimate the population, food waste by towns	https://www.maine.gov/geolib/catalog.html
Maine Airports	Information on the location of airports	https://www.maine.gov/geolib/catalog.html
Slope of Maine	Keep the optimum location within 2-5 % slope	https://www.maine.gov/geolib/catalog.html
Maine Land Cover	Keep the optimum location in grassland and bare land	https://coast.noaa.gov/dataviewer/#/landcover/search/

1.2.5 SUITABILITY MODELER

The Suitability Modeler is an interactive, exploratory environment for creating and evaluating a suitability model and is available with an ArcGIS Spatial Analyst extension license (ArcGIS Pro, 2020). This tool was used to find the best location based on food waste generation, sludge availability, residential areas represented by the population, land cover, slope, distance to airports, and environmentally sensitive areas. Excess sludge production was in terms of points; population and FW generation were in terms of towns. Hence, there was no common scale for data representation, making it difficult to use the modeler. All the criteria were represented in terms of towns, and the vector layers were converted into raster using the feature to raster tool. The standard suitability scale of 1-10 was used by multiplicity, one as the least and ten as the most suitable area. The weights for each criterion were assigned, as explained in section 1.2.6. Transformative functions like Gaussian or linear were used as explained in section 1.2.7.

The suitability modeler's locate tool finds the optimum site based on the suitability score (ArcGIS Pro, 2020). For finding the optimum sites in Maine, 500 square miles was divided into five regions. The best locations for constructing the new facility were determined for each region and each of the scenarios. In the case of the five DOT areas, 100 square miles was divided into three regions. Three optimum locations for each area were determined, explained in the section 1.2.2.

1.2.6 ANALYTICAL HIERARCHY PROCESS (AHP)

The analytical hierarchy process (AHP) was proposed by Saaty (1977, 1980) to model subjective decision-making processes based on multiple attributes in a hierarchical system (Leal, 2020). Mainly, the application of AHP allows consideration of socio-cultural and environmental objectives that are recognized to be of the same importance as the economic objectives in selecting the optimal alternative (Tzeng & Huang, 2011). AHP considers all the decision problems as a hierarchy. The first level of hierarchy indicates the goal of the specific situation. The second level represents several criteria, and the lower levels follow this principle to divide into sub-criteria (Song & Kang, 2016). Decision-makers then use AHP in determining the weights of the criteria (Song & Kang, 2016). There are four steps of AHP:

1. set up the hierarchical system by decomposing the problem into a hierarchy of interrelated elements;
2. compare the comparative weight between the attributes of the decision elements to form the reciprocal matrix;
3. synthesize the individual subjective judgments and estimate the relative weights;
4. aggregate the relative weights of the elements to determine the best alternatives/strategies

(Leal, 2020).

If we wish to compare a set of n attributes pairwise according to their relative importance weights, where the attributes are denoted by $a_1, a_2, \ldots, a_n$ and the weights are indicated by $w_1, w_2, \ldots, w_n$, then the pairwise comparisons can be represented by questionnaires with subjective perception as:

$$A= \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \vdots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix}$$

Where $a_{n1}= 1/a_{1n}$ (positive reciprocal)

Considering a given criterion, matrix A is supplemented with values a_{n1}, where n is a base alternative for comparison, corresponding to row n. One is the alternative being compared with n. Suppose the contribution of n to the criterion being considered is of strong importance relative to 1. In that case, a_{n1} assumes the value of 5, which can be regarded as dominance of n over 1 (Tzeng & Huang, 2011).

The consistency index (C.I.) is determined to ensure the consistency of the AHP numbers assigned to the criteria. C.I. is calculated by;

$$C.I. = (\lambda_{max} - n)/(n-1) \qquad \text{Equation 4}$$

λmax is the maximum eigenvalue, and n is the number of criteria

C.I is desired to be less than 0.1 (Urban & Isaac, 2018).

(Urban & Isaac, 2018)

Table 1-4: AHP numbers

Importance	**AHP Numbers**
Equal Importance	1
Moderate Importance	3
Strong Importance	5
Very Strong Importance	7
Extremely Strong Importance	9
Intermediate Importance (equal & moderate)	2
Intermediate Importance (Moderate & Strong)	4
Intermediate Importance (Strong & Very Strong)	6
Intermediate Importance (Very Strong & Extremely Strong)	8

In this study, we considered eight criteria, as shown in Table 1-5. These eight criteria were divided into technical, environmental, and economic factors. The criteria weights (global weights) between environmental, technical, and economic factors were adopted as 0.16, 0.24, and 0.6 indicating the economic factor as the most important. AHP was used to find the local weights for each criterion under their respective factors. Then the local weights were multiplied by the weight of the factor to find the global criteria weight. Seven criteria were used for determining weights in sludge exclusion. In contrast, all eight criteria were used in the sludge inclusion method.

AHP numbers were assigned based on personal judgment. In determining the criteria weights, firstly, AHP numbers were provided, followed by creating a normalized matrix and the criteria weights presented in APPENDIX B: CRITERIA WEIGHTS BY AHP. The consistency index was calculated at the end. The consistency index was desired to be less than 0.1 for the assigned weights to be consistent. The weights obtained from AHP were used in the GIS suitability modeler for finding the optimum locations. In this study, no alternatives were assigned, and the use of AHP was ended after determining weights. To run the suitability modeler, the minimum weight of criteria in the suitability modeler should be 1; all the criteria weights were transformed by keeping the minimum weight as one.

Criteria used in the analysis and their symbols are in Table 1-5. Food waste and sludge availability, and transportation cost were represented as economic factors, whereas environmentally sensitive areas and distance to residential areas were represented as the environmental factors. Technical factors included airports, landcover, and slope.

Table 1-5: Criteria for AHP and Suitability modeler

Attributes	**Criteria**	**Symbols**
Economical	Transportation Cost	A_1
	Food Waste Availability	A_2
	Sludge Availability	A_3
Technical	Airports	B_1
	Land Cover	B_2
	Slope	B_3
Environmental	Environmentally Sensitive Areas	C_1
	Distance to Residential Areas	C_2

In comparing transportation cost with food waste availability, transportation was given twice the importance. Maintaining the waste management facility should be economical in the long run. Though food waste availability seems a critical factor, food waste transportation should be economical all around the year. The same reason applied when sludge availability was compared against transportation.

While comparing airports with land cover, airports were given strong importance (5). Airports are associated with people's safety, and constructing a waste management facility near airports would compromise safety. At the same time, the slope and the airports were given moderately importance (AHP number of 3) to each other.

Environmentally sensitive areas and residential areas have intermediate importance to each other. It is essential not to construct any facility in sensitive areas and be away from the residential areas because of the odor issues.

The AHP numbers assigned, normalized matrix, criteria weights, and consistency index are presented in APPENDIX B: CRITERIA WEIGHTS BY AHP.

1.2.6.1 AHP for sludge exclusion

Seven criteria were considered when sludge was excluded from co-digesting or co-composting. The Table 1-6 represents the criteria weight. Transformed weights were used in the modeler.

Table 1-6: Criteria weights for sludge exclusion method

Attributes	**Global Weight**	**Criteria**	**Symbol**	**Sludge Exclusion**		**Transformed weights**
				Local Weights	**Global Weights**	
Economical	0.6	Transportation Cost	A1	0.67	0.400	13.64
		Food Waste Availability	A2	0.33	0.200	6.82
		Sludge Availability	A3	-	-	-
Technical	0.24	Airports	B1	0.65	0.156	5.3
		Land Cover	B2	0.12	0.029	1
		Slope	B3	0.23	0.055	1.88
Environmental	0.16	Sensitive Areas	C1	0.67	0.107	3.64
		Residential Areas	C2	0.33	0.053	1.82
Sum	1			3	1	34.10

1.2.6.2 AHP for sludge inclusion

While including the sludge for co-digesting or co-composting, eight criteria were used.

Table 1-7: Criteria weights for sludge inclusion method

				Sludge Inclusion		
Attributes	**Global Weight**	**Criteria**	**Symbol**	**Local Weights**	**Global Weights**	**Transformed Weights**
Economical	0.6	Transportation Cost	A1	0.49	0.294	10.04
		Food Waste Availability	A2	0.31	0.187	6.38
		Sludge Availability	A3	0.20	0.119	4.04
Technical	0.24	Airports	B1	0.65	0.156	5.30
		Land Cover	B2	0.12	0.029	1.00
		Slope	B3	0.23	0.055	1.88
Environmental	0.16	Sensitive Areas	C1	0.67	0.107	3.64
		Residential Areas	C2	0.33	0.053	1.82
Sum	1			3	1	34.10

1.2.7 USE OF THE MODELER AND THE TRANSFORMATION TO THE CRITERIA

We selected transportation cost, FW availability, sludge availability, environmentally sensitive areas, distance from residential areas, land cover, slope, airports as the criteria.

1.2.7.1 Transportation Cost

A network analysis solver called Origin Destination cost matrix was used to determine the transportation cost. The solver finds and measures the least-cost paths along the network from multiple origins to multiple destinations (ArcGIS pro, n.d.), making a matrix of the origins and destinations. After the analysis, only straight lines were visible in the map, rather than the network. Considering a truck would be used as the means of transportation of waste, the total truck travel time was determined in minutes. The line's attribute table recorded the total truck travel time; this time was reflected in the transportation cost. If the truck travel time were high, the cost would be high. Composting facilities, transfer stations, and WWRFs represented origin and destination points, as any of these facilities can be upgraded as a digester or composting site, and the waste would be transported from these sites to the management facility. For sludge exclusion, origin and destination points were composting facilities and transfer stations. WRRFs were added to the list for sludge inclusion. The sludge inclusion and exclusion strategy made two different feature layers for transportation cost, one for each condition.

It was assumed that food waste would be transported to the transfer stations, but the study did not consider its cost. Transportation cost represented transportation of waste from the transfer stations to the new facility. Total truck travel time was summarized for each point and joined to the destination attribute table by the destination ID. Travel time for each point represented the total time to reach all the destinations from that point. The feature layers of destination and towns were spatially joined using one to many join operation and intersect match option. A total truck travel time field was used to convert the final feature layer to the raster. Two feature layers of transportation-sludge exclusion and the inclusion- resulted in two raster layers. This raster was used in the suitability modeler with a suitability scale of 1-10. Sludge exclusion transportation cost had a criteria weight of 13.64, whereas sludge inclusion transportation cost had 10.04 based on Table 1-6 and Table 1-7. The Gaussian model was used as the transformative function as we want to cover many areas for waste management; simultaneously, we do not want cost to be very high while transporting waste. Lower transportation cost, in this study, represented the transportation of food waste only from nearby regions. As food waste is transported from farther regions, the cost increases. As the facility is desired to manage food waste for larger region as compared to the smaller region, the Gaussian model showed the peak point in the middle; hence the best suitable location would have a medium transportation cost-covering a significant number of the areas.

1.2.7.2 Food Waste

The enrich tool was used to get the 2020 total population data by the towns feature layer. The field calculator calculated the amount of food waste in a new field by multiplying the 2020 total population with 318 pounds/year and dividing by 2000 to get the food waste data in US tons/year. We used a spatial join tool with one to many join operations and intersect match options to join this layer with the restaurants' food waste generation.

Fiberight Inc. website has the list of members of MRC in pdf format. This pdf was converted to excel and geocoded in GIS. The towns were joined with the feature layer of FW. In the towns where Fiberight works, it was assumed it manages all the food waste of that town. Two new fields were added to the attribute table of the layer. These fields were food waste quantity if Fiberight shuts down, food waste quantity if Fiberight resumes. Feature to raster layer converted each field to raster resulting in two raster layers. Each raster was uploaded in a suitability modeler based on the scenario explained in section 1.2.2 with a suitability scale of 1-10. As per section 1.2.6, the weight of FW availability for sludge exclusion was 6.82 and 6.38 for sludge inclusion. These weights were assigned in the modeler and transformed using the MS Large function. Areas that generate a large amount of food waste require the attention of waste management. MS Large function gives higher suitability to the areas that generate a larger amount of food waste. We were concerned about managing a more considerable amount of waste; hence it was more suitable to locate the facility nearby a high FW generation area.

1.2.7.3 Environmentally Sensitive Areas

The shapefiles of conserved lands, wetlands, and inland landslide extent of Maine were intersected with the polygonal area to get these features, only for that area. These three feature layers were combined using the union tool. The spatial join tool was used to join the polygon and environmentally sensitive areas. The area which was not environmentally sensitive in the polygon was referred to as the normal land. The normal land was selected in the attribute table and was converted to a raster layer. The suitability scale for this land was 10, as the data excluded the sensitive areas from the whole area, and the remaining area was very suitable for an infrastructure. No transformative function was used for this in modeler as it only had normal land of high suitability. The weight of the environmentally sensitive areas was 3.64 for sludge exclusion and sludge inclusion.

1.2.7.4 WRRFs

Each polygonal area intersected the layer of WRRFs through an intersect tool that gave the WRRFs only in that area. The intersected layer was joined spatially with the town and township polygons. The polygons that do not have any sludge production were assigned the value of 0 before converting this layer into raster by sludge generation and analyzing in the suitability modeler. Higher sludge generation area demands higher management than lower sludge generation areas; based on this; high sludge generation areas were prioritized. The MS Large transformation function was used to show higher suitability in high sludge areas. This function gave higher suitability to the areas that generate a larger amount of sludge.

1.2.7.5 Distance to residential areas

The population was used as an indicator for the residential areas. People do not want waste management facilities in very crowded areas. Hence placing a facility in an area that has a very high population is not desired. The town polygonal layer was enriched with the 2020 total population. This layer was converted to the raster and uploaded in the modeler on the suitability scale of 1-10. The criteria weight of 1.82 for the sludge inclusion and sludge exclusion was used. The linear transformative function was used. This function gave higher suitability to the areas with a lower population. Since it is not desired to construct a waste management facility near residential areas, a linear function was used.

1.2.7.6 Airports

The point feature layer of airports was buffered by two miles, and the shape was dissolved. To find the areas excluding this buffer zone, the symmetric difference tool was used between the total area of Maine and the buffered layer of airports. The resulting feature layer was converted to a raster and uploaded in the suitability modeler. No transformative function was used, as the raster represented the area of highest suitability. For sludge exclusion, the airport's criteria weight was 5.3. Similarly, for the sludge inclusion, the criteria weight was 5.3.

1.2.7.7 Land Cover

The raster layer of the land cover data was uploaded in the suitability modeler. Grasslands and bare land were given the highest suitability, whereas wetlands, developed areas, trees were given zero suitability. This resulted in suitable locations only where there was grassland and the bare land. For each polygonal area, land cover for that area was determined using extract by mask tool. No transformative function was used as the highest suitability value was given to grassland and bare land.

1.2.7.8 Slope

The slope of Maine was uploaded in the suitability modeler, and a symmetric linear function was used. This function was constrained between 0% and 2% slope. This function gave higher suitability for the slope between 0-2% and gave no suitability to the slope outside this range.

1.3 DATA ANALYSIS AND INTERPRETATION

1.3.1 ORGANIC WASTE IN MAINE

1.3.1.1 Sludge from Wastewater Recovery Facilities

After calculating the sludge from each facility, the data was visualized using proportional symbols, as shown in Figure 1-11. WRRFs in Portland, Bangor, and Lewiston-Auburn generate a large amount of sludge as they treat a large amount of wastewater each day. The treatment facility in Lewiston-Auburn is digesting its sludge, whereas the sludge in other WRRFs is either composted, placed in a covered lagoon, or sent to the landfill.

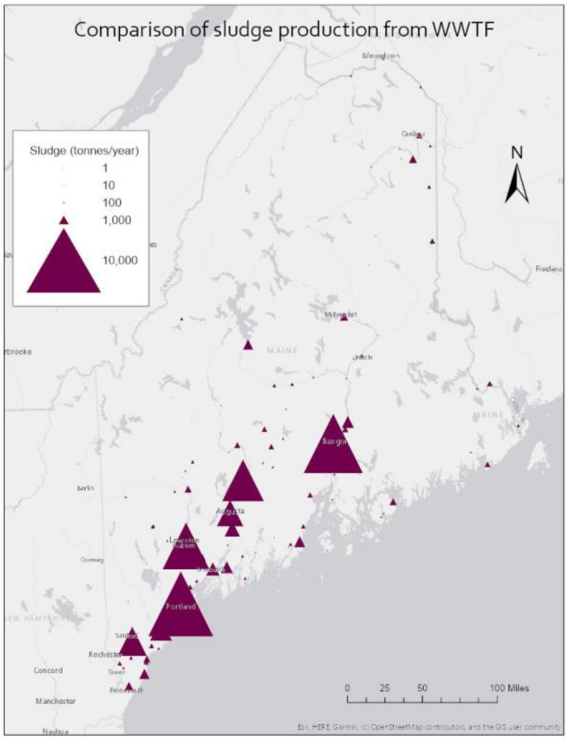


Figure 1-11: Sludge generation in Maine by wastewater recovery facilities. The proportional symbol represents a higher sludge generation with a larger symbol.

1.3.1.2 Food Waste Generation from households

Each person generating 318 pounds FW per year, and Portland, having a population of 66,417 (2018), generates a large amount of FW. Figure 1-12 represents the food waste generation in Maine. Southern regions produce a large amount of food waste.

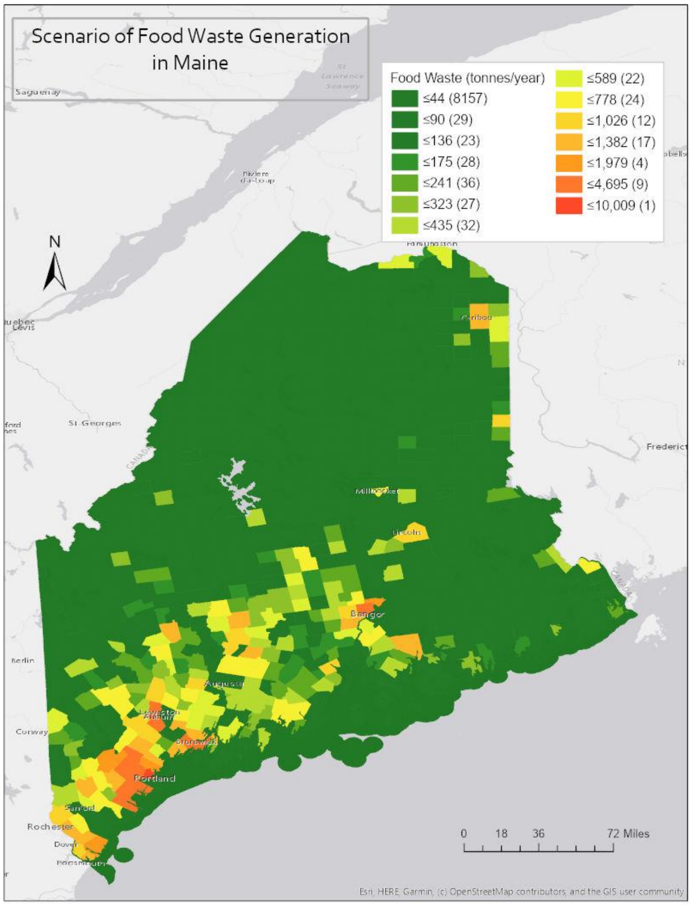


Figure 1-12: Food waste generation in Maine by towns and township polygons. There are 14 categories divided by Natural Jenks. The color map ranges from green to red, where red rephresents the highest food waste generated area.

1.3.1.3 Excess Manure generation from farms

Farms having an application rate greater than 7 tons/acre (considered for hay) produce excess manure. Figure 1-13 shows a heatmap to represent the areas that generate excess manure. There is excess manure between Augusta and Bangor, followed by Lewiston-Auburn and Portland. The northern region also shows sparsely located excess manure generating areas. Currently, since there is only one AD that digests manure, there is an opportunity to co-digest food waste with manure, as excessive manure is generated.

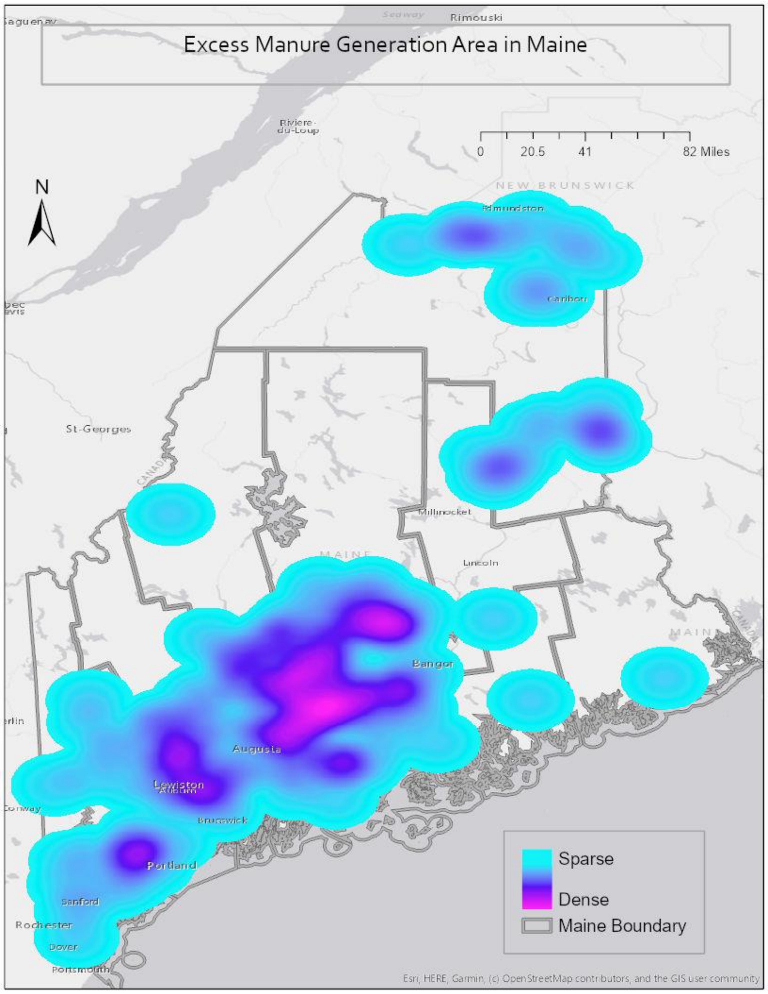
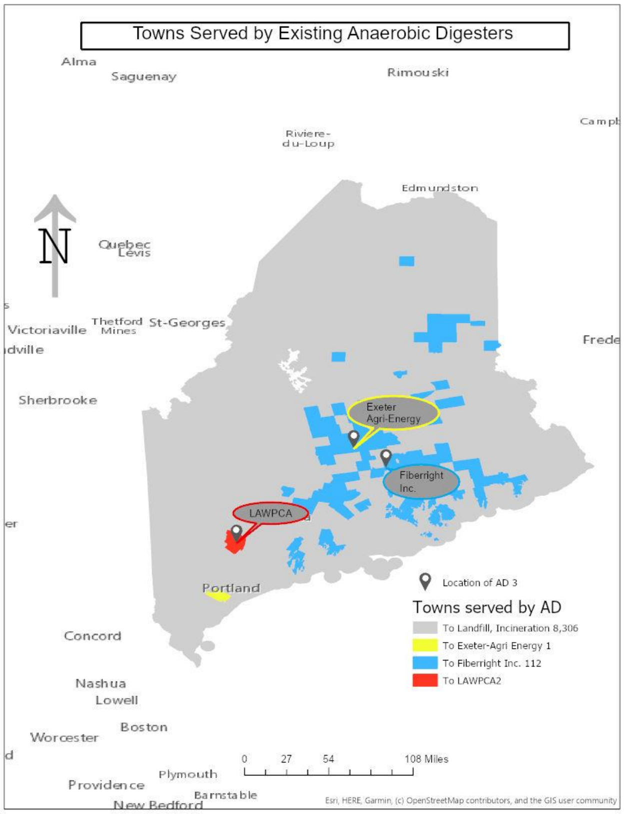


Figure 1-13: Heatmap to show excess manure generation in Maine.

1.3.1.4 Existing Waste Management in Maine

There are three digesting facilities in Maine. Exeter Agri-Energy digests FW of Scarborough and some areas of Portland with the manure of Stonyvale farm. LAWPCA digests wastewater sludge from Lewiston and Auburn with food processing waste. Fiberight Inc. manages the municipal solid waste of 115 municipalities. However, Fiberight shut down in June 2020 due to financial issues, and its future is uncertain. An alternative management option for FW may be required. Figure 1-14 presents the towns served by these facilities. Fiberight Inc. serves a large number of towns, hence plays a crucial role in managing the FW.

Meanwhile, the existing management system still leaves behind organic waste from many towns. If Fiberight and Exeter run like this without adding additional food waste in the future, the additional facilities would be for the remaining organic waste. This remaining waste was determined by deducting existing management from the total organic waste.



Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

Figure 1-14: Towns served by existing anaerobic digesters. Blue color represents towns served by Fiberight Inc; Yellow represents towns served by Exeter Agri-Energy. Red represents Lewiston and Auburn served by LAWPCA; it serves only sludge generation in that area.

The visual representation of the organic waste in Maine shows densely populated areas generate large amounts of waste-sludge and food waste. There is a large amount of waste in Maine's southern regions, as these regions are highly populated. The availability of a significant amount of waste in these areas demands waste management facilities in the southern region; however, all the present anaerobic digesters and most composting facilities are in the southern and central regions. Other regions of Maine are also generating a fair amount of FW, sludge, and manure. This study looked into all the regions through the polygonal areas.

1.3.2 OPTIMUM LOCATIONS FOR ADDITIONAL FACILITIES

The suitable locations for each scenario were determined. Appendix 1 contains the suitability maps used to determine suitable locations of Maine and each region. For Maine, there are five optimal locations whose total area is 500 square miles. There are three optimal areas for each region, whose total area is 100 square miles.

1.3.2.1 Fiberight Operational and sludge is co-digested

1.3.2.1.1 Maine

When Fiberight is operational, and sludge is treated with food waste, the optimum locations are Clinton, Washburn, Limestone, Bowdoinham, and Ellsworth, as shown in Figure 1-15.

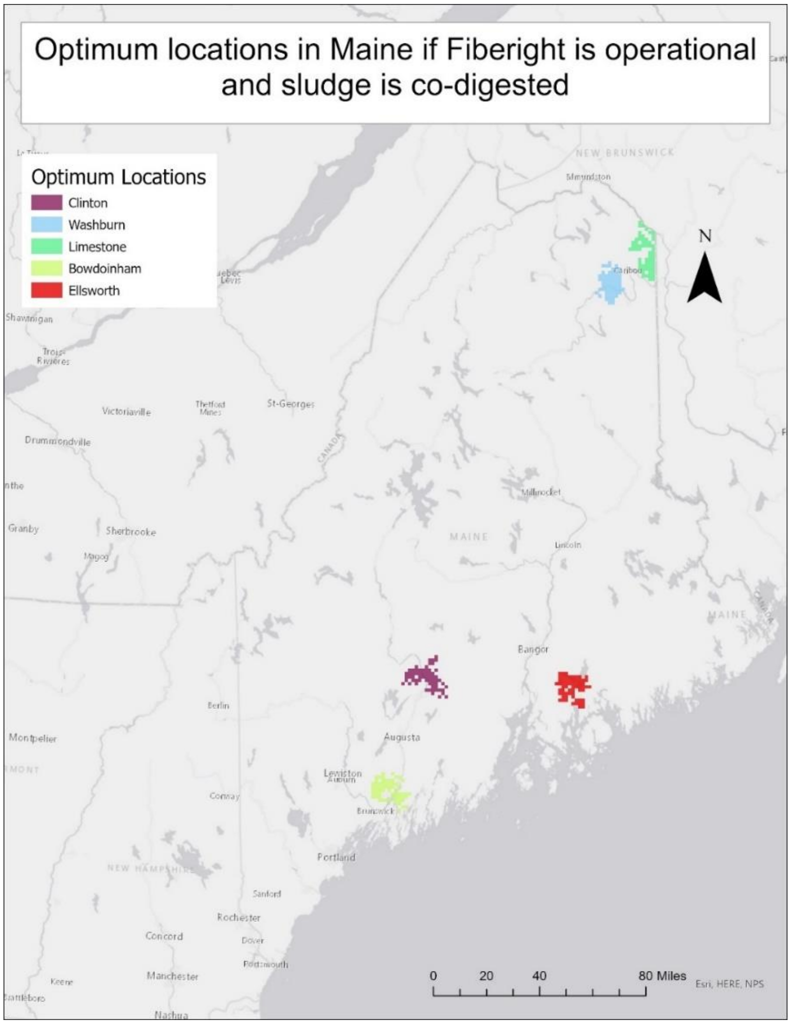


Figure 1-15: Optimum locations in Maine if Fiberight is operational and sludge is treated with food waste

Maine DOT Regions

Figure 1-16 shows the optimal regions when Fiberight is operational, and sludge is treated with food waste. For the Eastern region, areas around Dover Foxcroft, Lincoln, and Gouldsboro are optimum for new additional facilities. Similarly, Monroe, Clinton, and the area around Augusta are optimum locations in the Mid-Coast region. In the Northern region, Caribou and Presque Isle are optimum locations, whereas, in the

Southern region, the optimum locations are Lewiston, Saco, Biddeford, and Sanford. For the Western region, the best locations are Turner, Skowhegan, and Hanover.

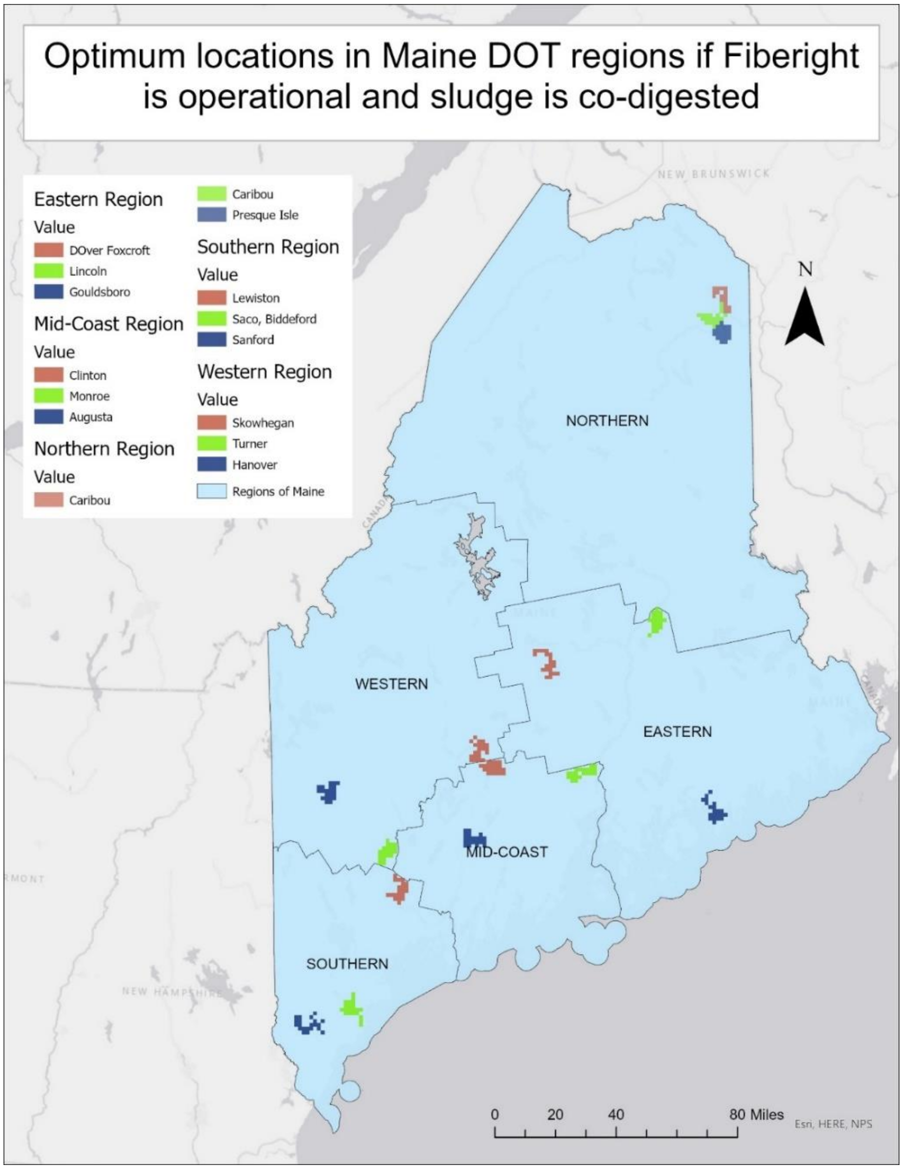


Figure 1-16: Optimum locations in Maine DOT regions if Fiberight is operational and sludge is treated with food waste

1.3.2.2 Fiberight operational and sludge is excluded

1.3.2.2.1 Maine

When Fiberight is operational, and sludge is excluded from co-digesting with food waste, Maine's optimum locations are shown in

Figure 1-17. Ellsworth, Lewiston, Maddison, Norridgewock, and Saco are the optimum locations.

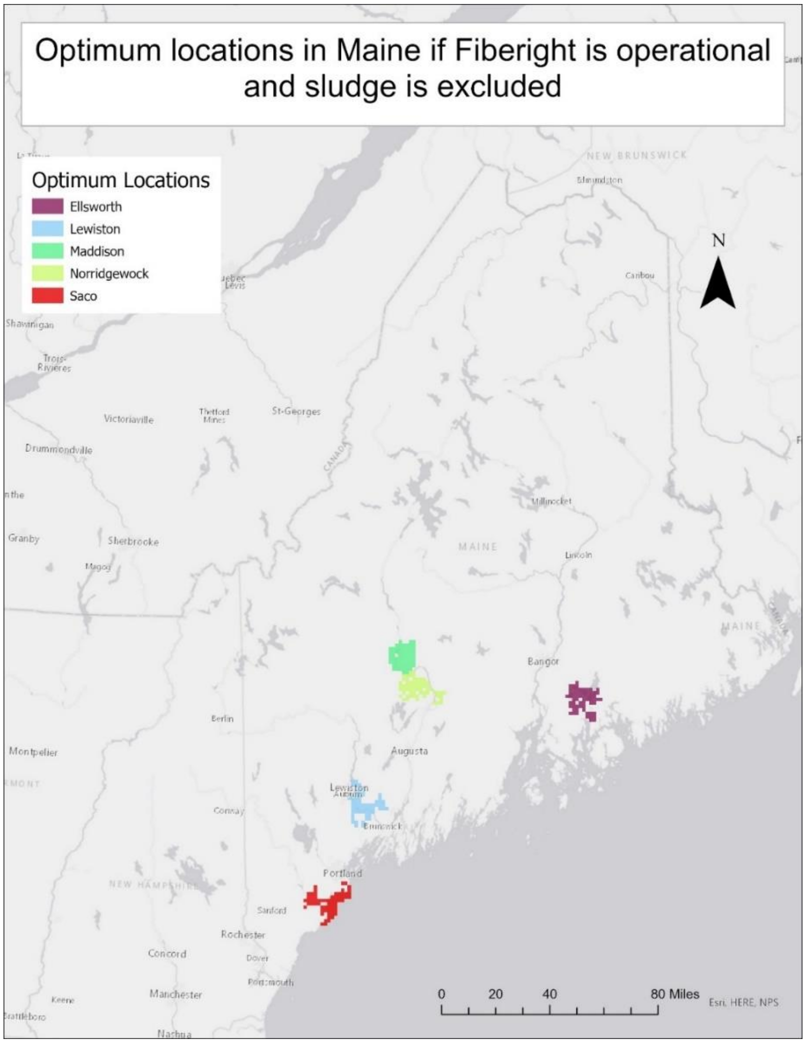


Figure 1-17: Optimum locations in Maine if Fiberight is operational and sludge is excluded from treatment

1.3.2.2.2 Maine DOT Regions

Optimum locations for Maine DOT regions when Fiberight is operational and sludge is excluded from treatment are shown in Figure 1-18. For the Western region, Turner, Skowhegan, and Hanover are optimum locations, whereas, for the Southern region, the locations are Standish, Wells, Sanford, and Springvale. The optimum locations for the Northern region are Caribou and Springfield area. Similarly, for the Mid-Coast region, the areas are Clinton, Warren, Rockland, and Monroe, while for the Eastern region, Dover Foxcroft and the area around Lincoln are optimal.

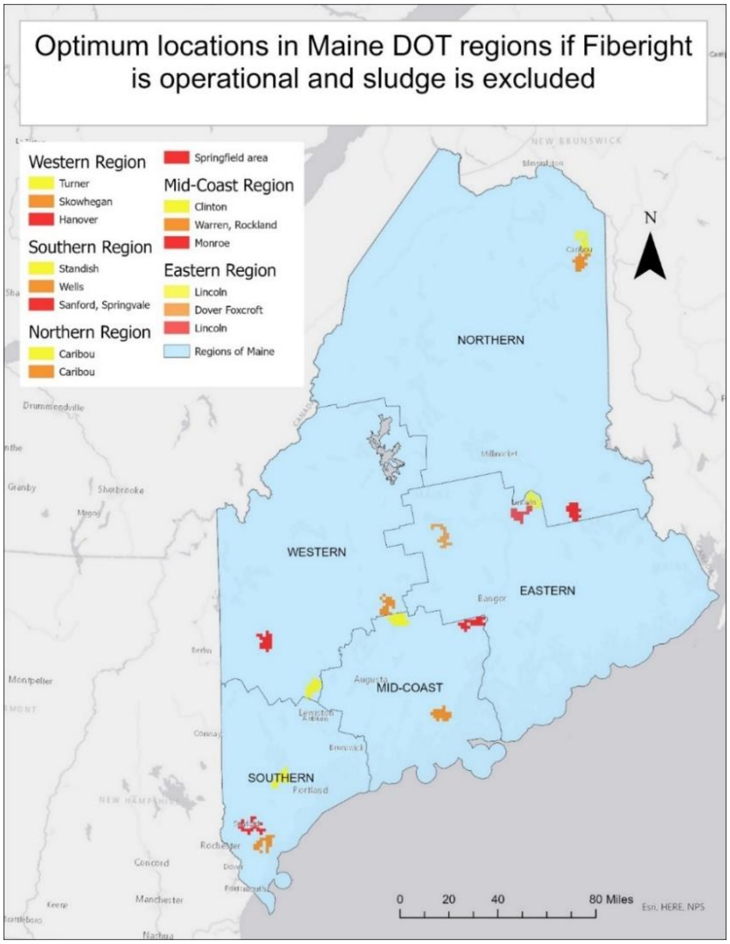


Figure 1-18: Optimum locations in Maine DOT region if Fiberight is operational and the sludge is excluded from treatment

1.3.2.3 Fiberight not operational and sludge is treated with food waste

Maine

Figure 1-19 shows the optimal locations when Fiberight is not operational, and sludge is treated with food waste. In Maine, the optimum areas are Surry, Norridgewock, Levant, Corinna, and Bowdoinham.

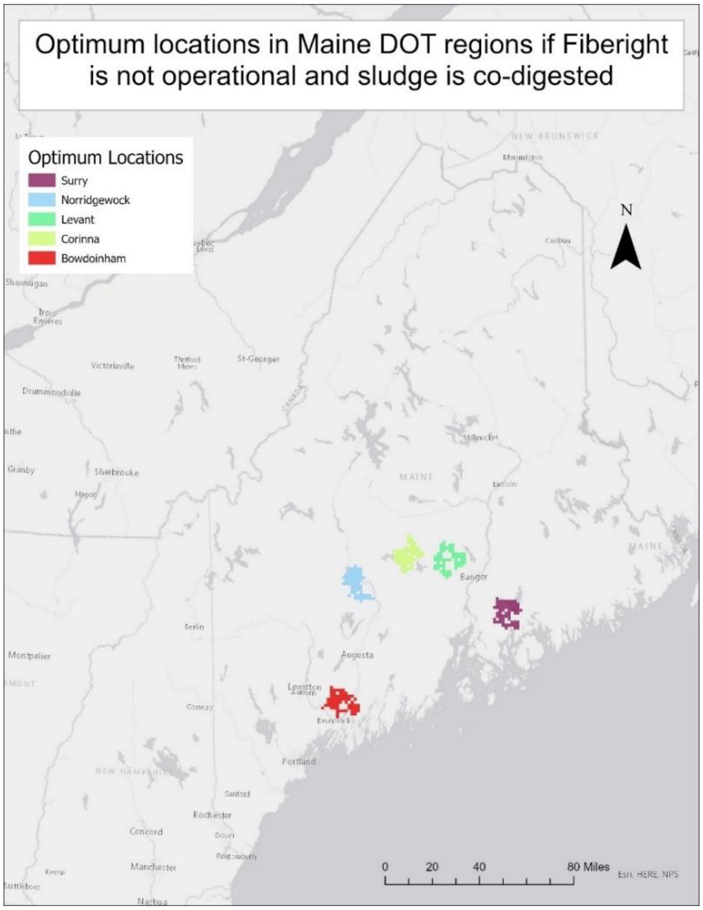


Figure 1-19: Optimum Locations in Maine if Fiberight is not operational and sludge is treated with food waste

1.3.2.3.1 Maine DOT Regions

The optimum regions in Maine DOT regions when Fiberight is not operational, and the sludge is treated with food waste are shown in

Figure 1-20. In the Western region, the best locations for additional waste management facilities are Turner, Skowhegan, and Athens. Lewiston, Saco, and Sanford are optimal locations for constructing or upgrading additional waste management facilities in the Southern region. Similarly, in the Northern region Caribou and Presque Isle are the best locations, while in the Mid-Coast region, Clinton, Oakland, and Belfast are the optimum regions. Dover Foxcroft, Orono, and areas around Lincoln are optimal in the Eastern region.

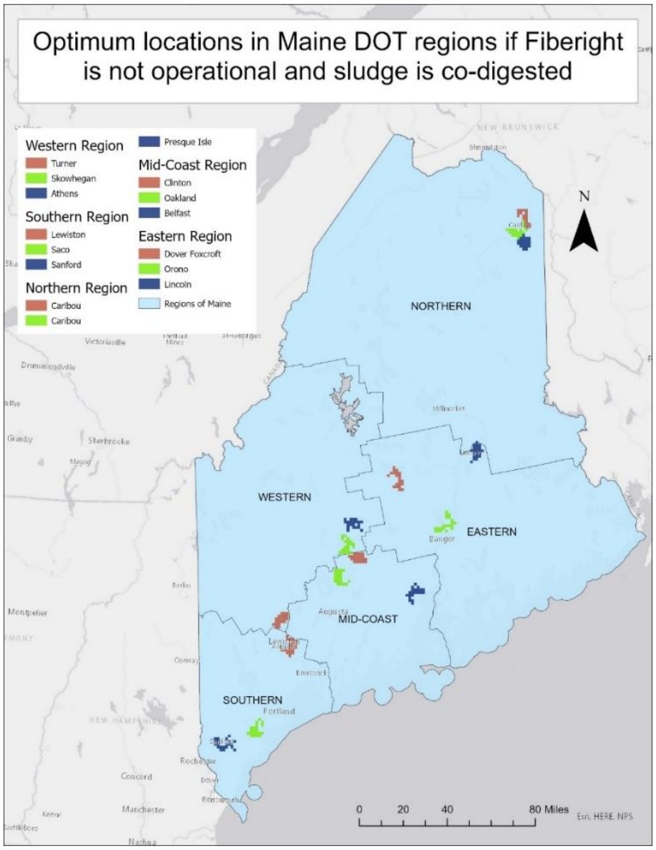


Figure 1-20: Optimum locations in Maine DOT regions if the Fiberight is not operational and the sludge is treated with food waste

1.3.2.4 Fiberight not operational, and sludge is excluded

1.3.2.4.1 Maine

When Fiberight is not operational and sludge is excluded from treatment, the optimum locations in Maine are East Machias, Addison, Jonesboro, Brooksville, Pembroke, as shown in

Figure 1-21.

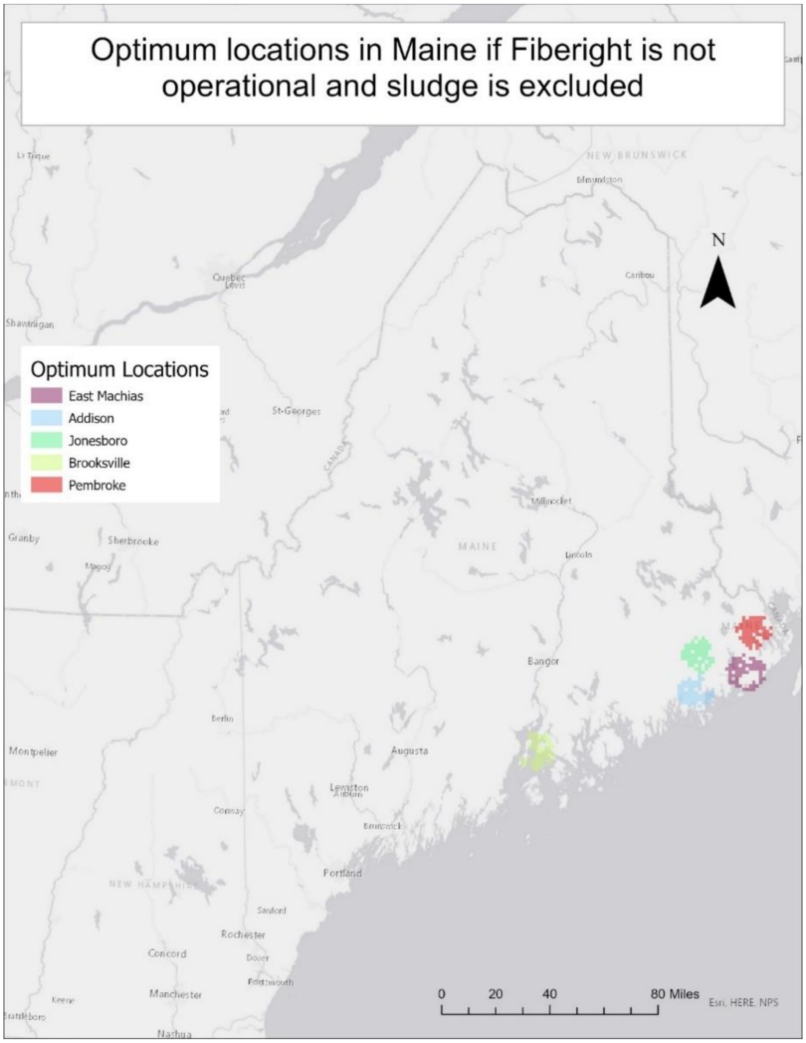


Figure 1-21: Optimum Locations in Maine if Fiberight is not operational and sludge is excluded

1.3.2.4.2 Maine DOT Regions

In the Eastern region, the optimum locations are Lincoln, Dover Foxcroft when Fiberight is not operational, and sludge is excluded from co-digestion shown in

Figure 1-22. Similarly, Caribou and Springfield are the optimal area in the Northern region for additional waste management facilities. In the Mid-Coast region, Clinton, Warren, Rockland, and Monroe are optimal areas, whereas, in the Southern region, Scarborough, Standish, and Wells are the best locations. Meanwhile, in the Western region, Turner, Skowhegan, and Hanover are the optimum locations.

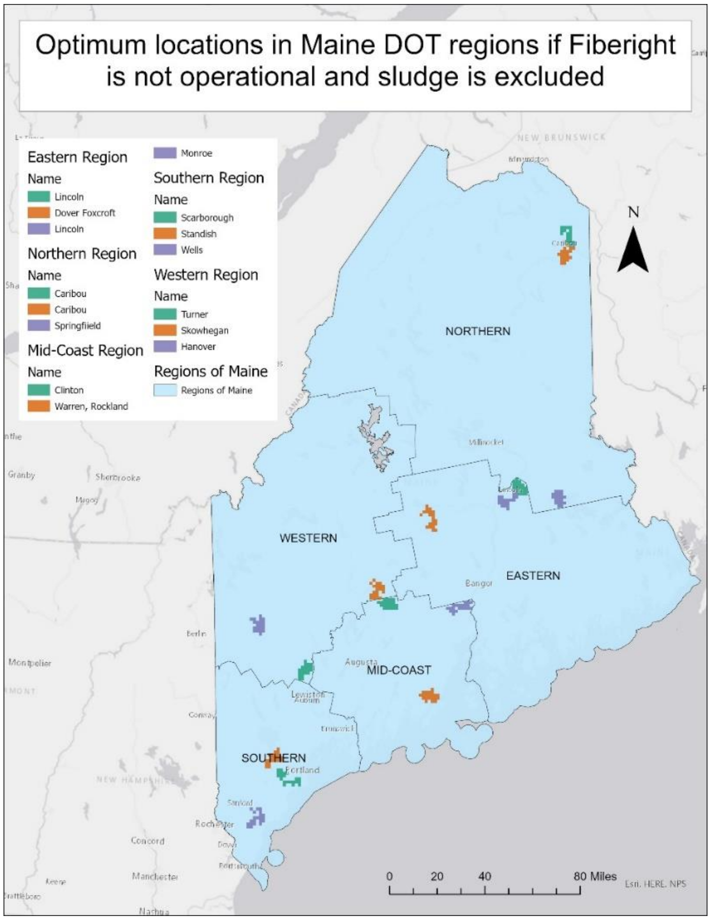


Figure 1-22: Optimum Locations in Maine DOT regions when Fiberight is not operational, and sludge is excluded from treatment

In the Northern region, the Caribou area coincides in all the scenarios. Similarly, Dover Foxcroft and Lincoln is the optimum area for all scenarios in the Eastern region. Clinton is the best area in the Mid-Coast area. In the Southern region, Sanford area coincides in three scenarios, while Turner, Skowhegan and Hanover area is the best location in the Western region.

The summary of the locations for each scenario in each region is given in the following table:

Table 1-8: Summary of the optimum locations in each region

Region	**Fiberight Operational**		**Fiberight not Operational**	
	Sludge treated	**Sludge excluded**	**Sludge treated**	**Sludge excluded**
Maine	• Clinton • Washburn • Limestone • Bowdoinham • Ellsworth	• Ellsworth • Lewiston • Maddison • Norridgewock • Saco	• Surry • Norridgewock • Levant • Corinna • Bowdoinham	• East Machias • Addison • Jonesboro • Brooksville • Pembroke
Northern Region	• Caribou • Presque Isle	• Caribou • Springfield	• Caribou • Presque Isle	• Caribou • Springfield
Eastern Region	• Dover Foxcroft • Lincoln • Gouldsboro	• Lincoln • Dover Foxcroft	• Dover Foxcroft • Orono • Lincoln	• Lincoln • Dover Foxcroft
Mid-Coast Region	• Clinton • Monroe • Augusta	• Clinton • Warren • Monroe	• Clinton • Oakland • Belfast	• Clinton • Warren • Monroe
Southern Region	• Lewiston • Saco • Sanford	• Standish • Wells • Sanford, Springvale	• Lewiston • Saco • Sanford	• Scarborough • Standish • Wells
Western Region	• Skowhegan • Turner • Hanover	• Turner • Skowhegan • Hanover	• Turner • Skowhegan • Athens	• Turner • Skowhegan • Hanover

1.3.3 UPGRADING OF FACILITIES

Existing wastewater recovery facilities, transfer stations, composting facilities, and farms that intersect in the optimum regions can be upgraded to the new waste management facilities. The opportunities for the upgrading of existing facilities are determined for Maine DOT regions.

Fiberight Operational and sludge is treated with food waste

Figure 1-23 shows the opportunities for upgrading existing facilities in Maine DOT regions when the Fiberight is operational, and sludge is treated with food waste. In the Northern region, one wastewater recovery facility and two composting facilities can be upgraded. Similarly, one composting facility in the Eastern region, one transfer station, and two wastewater recovery facilities can be upgraded. Seven farms and two transfer stations can be upgraded in Mid-Coast, while two farms, three WRRFs can be upgraded in the Southern region. Six farms and a transfer station can be upgraded in the Western region. The details of these facilities are presented in Table 1-9.

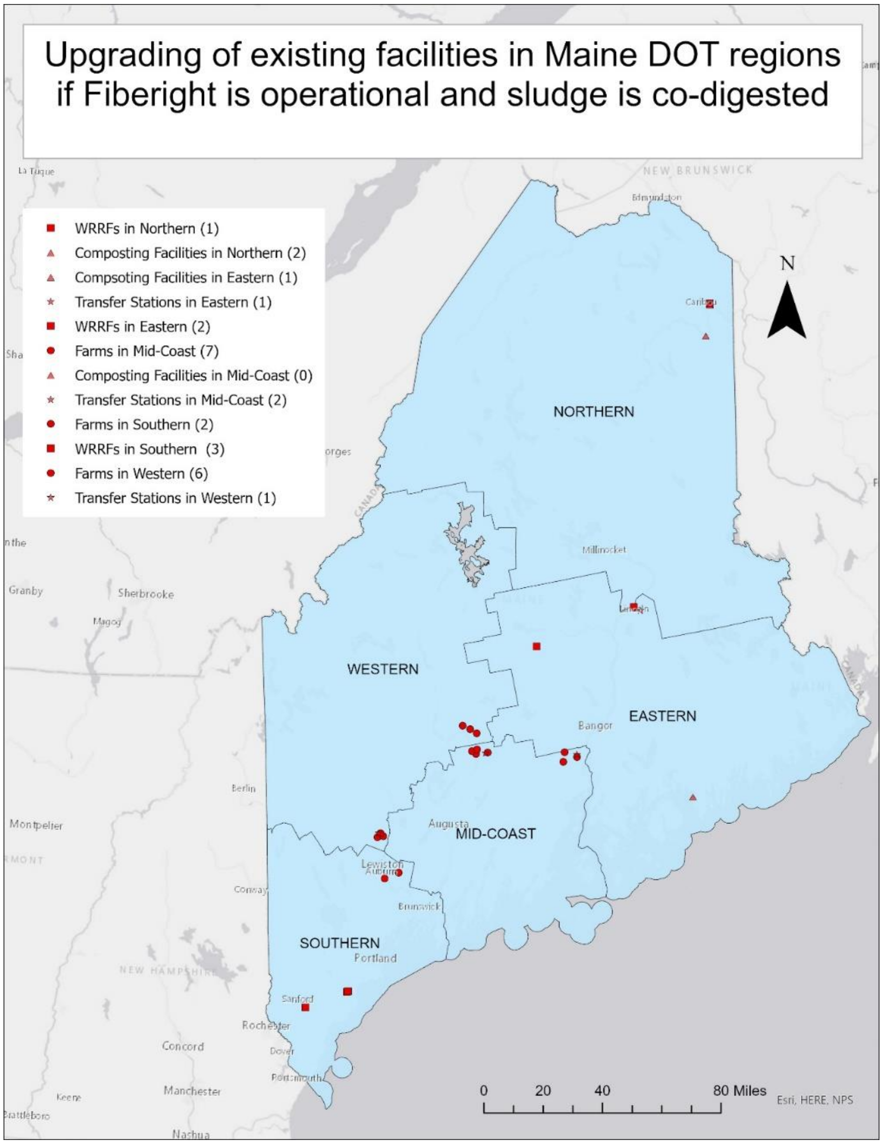


Figure 1-23: Upgrading of existing facilities in Maine DOT regions if Fiberight is operational and sludge is treated with food waste

1.3.3.1 Fiberight Operational and sludge is excluded

When Fiberight is operational, and sludge is excluded from treatment, the facilities that can be upgraded in different regions are shown in

Figure 1-24. In the Northern region, a composting facility, a transfer station, and a WRRF can be upgraded as new additional waste management facilities using food waste. One composting facility, two transfer stations, and a WRRF can be upgraded in Maine's Eastern region. In Mid-Coast, seven farms, five transfer stations, and three composting facilities can be upgraded. Four farms, a WRRF, a transfer station, and two composting facilities can be upgraded in the Southern region, whereas in the Western region, six farms and a transfer station can be upgraded. The details of these facilities are presented in Table 1-9.

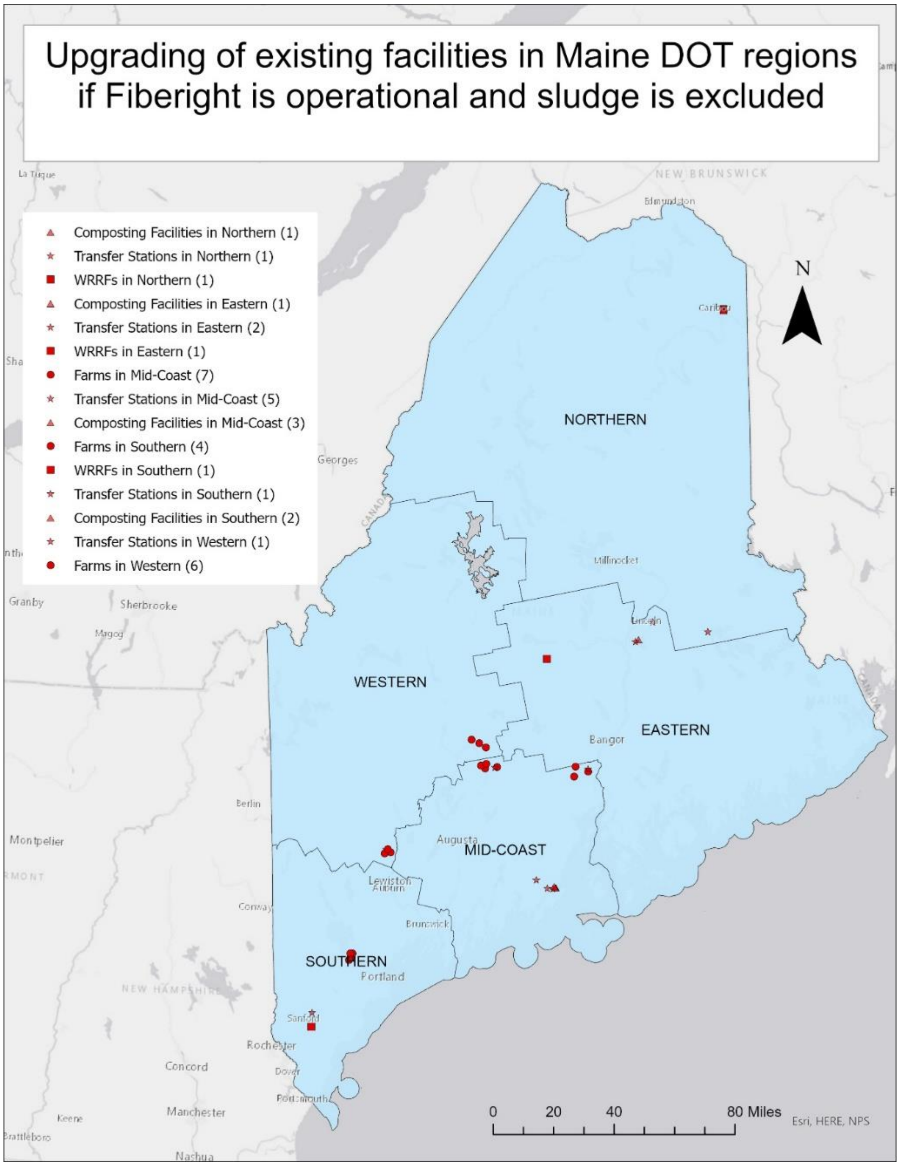


Figure 1-24: Upgrading of existing facilities in Maine DOT regions if Fiberight is operational and sludge is excluded from treatment

Fiberight not Operational and sludge is treated with food waste

Figure 1-25 represents the existing facilities that can be upgraded in Maine DOT regions if Fiberight is not operational and sludge is treated with food waste. Two composting facilities and a WRRF can be upgraded in the Northern region, while a composting facility, a transfer station, and two WRRFs can be upgraded in the Eastern region. In Mid-Coast, five farms, two transfer stations, and a composting facility can be upgraded to new additional waste management facilities using food waste. Five farms, a WRRF, and two composting facilities can be upgraded in the Southern region, whereas in the Western region, seven farms and a transfer station can be upgraded. Table 1-9 contains the details of these existing facilities.

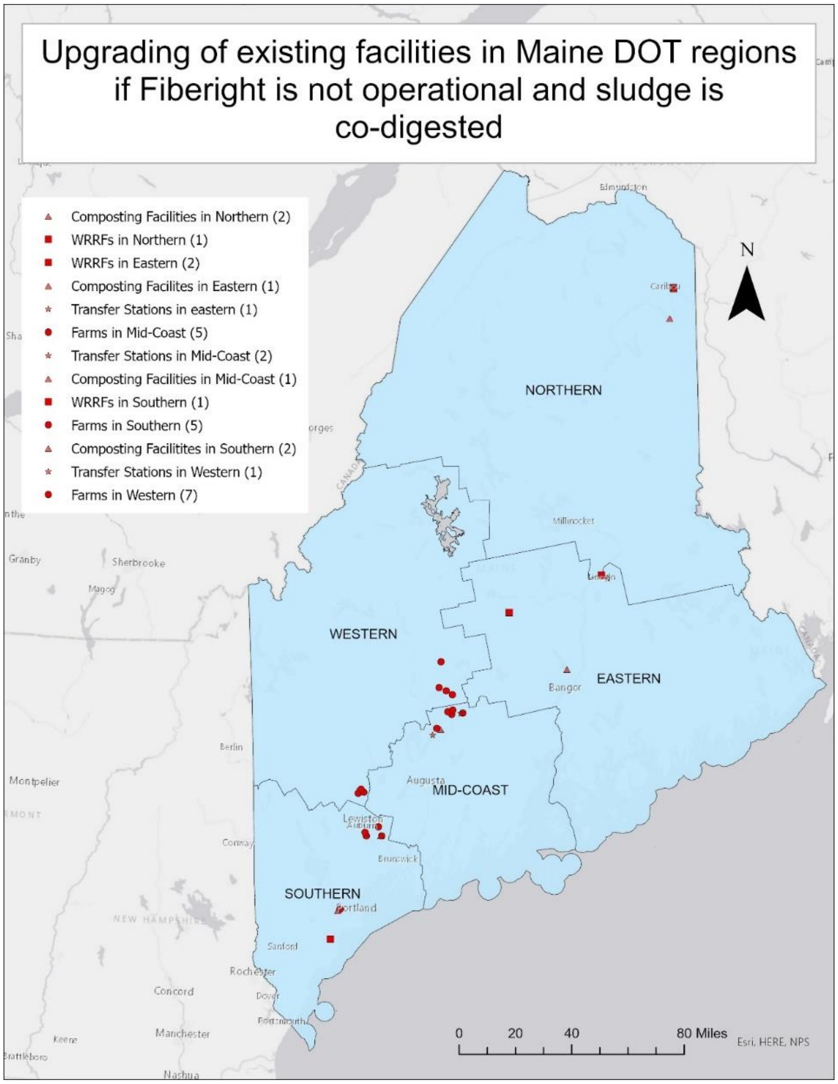


Figure 1-25: Upgrading of existing facilities in the Maine DOT regions if Fiberight is not operational and sludge is treated with food waste

1.3.3.2 Fiberight not Operational, and sludge is excluded

When the Fiberight is not operational, and sludge is excluded from treatment, the existing facilities that can be upgraded in different regions are shown in Figure 1-26. In the Northern region, a transfer station, a composting facility, and a WRRF can be upgraded, whereas, in the Eastern region, two transfer stations, a composting facility, and a WRRF can be upgraded. Seven farms, three composting facilities, and five transfer stations can be upgraded in the Mid-Coast. In the Southern region, five farms and four composting facilities can be upgraded, while in the Western region, six farms and a transfer station can be upgraded.

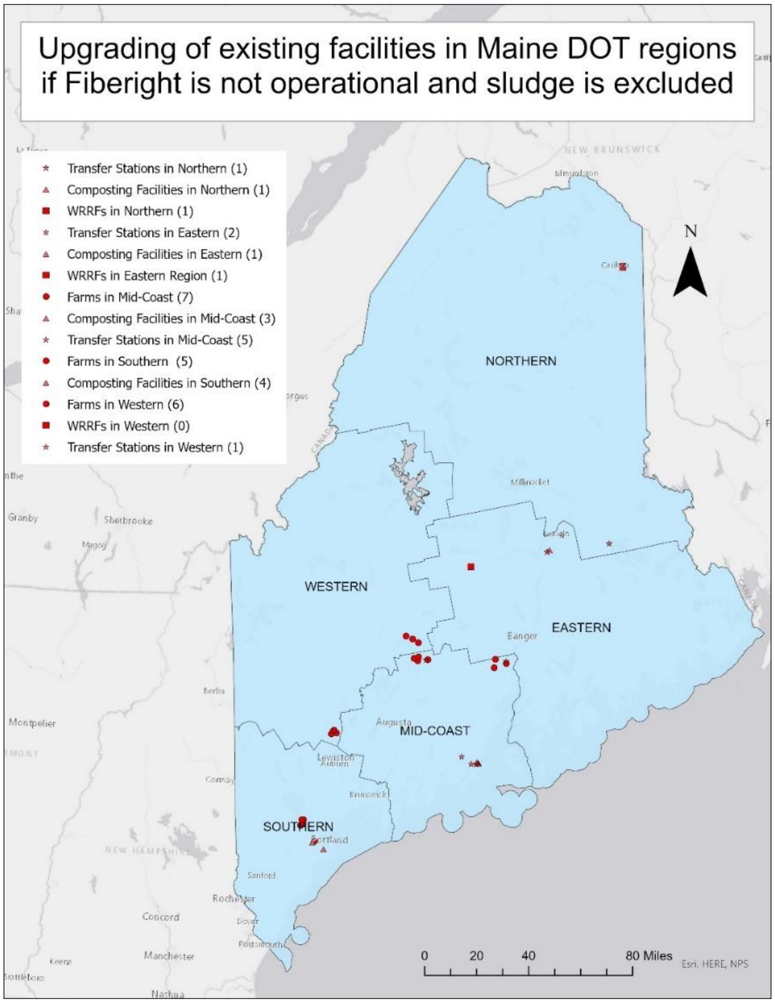


Figure 1-26: Upgrading of facilities in Maine DOT regions if Fiberight is not operational and sludge is excluded from treatment

Table 1-9: Facilities that can be upgraded in Maine DOT regions in different scenario

Area	Scenario		Facilities that can be upgraded					
			Farms			WRRFs	Transfer Stations	Composting Facilities
			Name of the Owner/ Company Name	Area (acre)	Excess Manure (tons/yr.)			
Northern Region	Fiberight not Operational	With Sludge	-	-	-	Caribou UD WWTF	-	H Smith Packing Corporation Pineland Farms Natural Meat Inc. (residual processing at Loring Comme)
		Without Sludge	-	-	-	Caribou UD WWTF	Town of Lakeville	Pineland Farms Natural Meat Inc. (residual processing at Loring Comme)
	Fiberight Operational	With Sludge	-	-	-	Caribou UD WWTF	-	H Smith Packing Corporation Pineland Farms Natural Meat Inc. (residual processing at Loring Comme)
		Without Sludge	-	-	-	Caribou UD WWTF	Town of Lakeville	Pineland Farms Natural Meat Inc. (residual processing at Loring Comme)
Eastern Region	Fiberight not Operational	With Sludge	-	-	-	Dover Foxcroft WWTF Lincoln WWTF	Town of Lincoln	University of Maine Orono
		Without Sludge	-	-	-	Dover Foxcroft WWTF	Town of Lincoln Town of Enfield	Lincoln Sanitary District-Windrow

	Fiberight Operational	With Sludge	-	-	-	Dover Foxcroft WWTF	Town of Lincoln	White Buffalo Forest
						Lincoln WWTF		
		Without Sludge	-	-	-	Dover Foxcroft WWTF	Town of Enfield	Lincoln Sanitary District-Windrow type
							Town of Lincoln	
Mid-Coast Region	Fiberight not Operational	With Sludge	Donald Shores	228	339	-	Town of Oakland	Town of Oakland
			Stedy-Rise Farm	330	4096			
			Kenneth Irving	4	72		Town of Clinton	
			Caverly Farms LLC	840	4175			
			Richard Lary	5	1443			
		Without Sludge	John Hill	237	275	-	Owls Head	Interstate Septic Systems Inc
			Arabest Farms Inc	609	318		Town of Thomaston	Town of Thomaston
			Stedy-Rise Farm	330	4096		Town of Warren	
			Kenneth Irving	4	72		Town of Winterport	City of Rockland
			Glendon Ward	4	2727		Town of Clinton	
			Caverly Farms LLC	840	4175			
			Richard Lary	5	1443			
	Fiberight Operational	With Sludge	John Hill	237	275	-	Town of Clinton	-
			Arabest Farms Inc	609	318			
			Stedy-Rise Farm	330	4096			
			Kenneth Irving	4	72		Town of Winterport	
			Glendon Ward	4	2727			
			Caverly Farms LLC	840	4175			
			Richard Lary	5	1443			
		Without Sludge	John Hill	237	275	-	Owls Head	Interstate Septic Systems Inc
			Arabest Farms Inc	609	318		Town of Thomaston	Town of Thomaston
			Stedy-Rise Farm	330	4096		Town of Warren	
			Kenneth Irving	4	72			
			Glendon Ward	4	2727		Town of Winterport	City of Rockland
			Caverly Farms LLC	840	4175			
			Richard Lary	5	1443		Town of Clinton	
Southern Region	Fiberight not Operational	With Sludge	L Farm Inc	83	532	Saco WWTF	-	We Compost It
			Charles Bosworth	87	869			

			Botma Farm	57	4203			
			Roger Gauthier	4	2728			Ricker Farm
			M Jerome Davis	253	985			
		Without Sludge	L Farm Inc	83	532	-	-	Commercial Recycling Systems
			Find View Farm	192	590			We Compost It
			Bensons Kay Ben Farm	4	2728			Benson farm
			Scott Balcomb	2	187			Kay-Ben Farm
			Jocelia Hartwell	81	90			
	Fiberight Operational	With Sludge	Roger Gauthier	4	2728	Sanford WWTF	-	-
			M Jerome Davis	253	985	Biddeford WWTF Saco WWTF		
		Without Sludge	Find View Farm	192	590	Sanford WWTF	Town of Alfred	Benson farm
			Bensons Kay Ben Farm	4	2728			
			Scott Balcomb	2	187			
			Jocelia Hartwell	81	90			Kay-Ben Farm
Western Region	Fiberight not Operational	With Sludge	Goodnow Jersey Farms Inc	3	1071	-	Town of Kittery	Town of Kittery (Windrow: Leaf & Yard Waste)
			Jay Roebuck	220	5869		Town of Turner	-
			Nezinscot Farm	279	2628			
			Pamela Clark	215	429			
			Geraldine Saunders	3	2735			
			Singing Falls Farm	6	1071			
			Sherry Cress	47	228			
		Without Sludge	Goodnow Jersey Farms Inc	3	1071	-	Town of Turner	-
			Pamela Clark	215	429			
			Singing Falls Farm	6	1071			
			Geraldine Saunders	3	2735			
			Nezinscot Farm	279	2628			
			Jay Roebuck	220	5869			
	Fiberight Operational	With Sludge	Goodnow Jersey Farms Inc	3	1071		Town of Turner	-
			Jay Roebuck	220	5869			
			Nezinscot Farm	279	2628			

			Pamela Clark	215	429			
			Geraldine Saunders	3	2735			
			Singing Falls Farm	6	1071			
		Without Sludge	Goodnow Jersey Farms Inc	3	1071		Town of Turner	-
			Jay Roebuck	220	5869			
			Nezinscot Farm	279	2628			
			Pamela Clark	215	429			
			Geraldine Saunders	3	2735			
			Singing Falls Farm	6	1071			

Table 1-9 represents the detailed lists of the facilities that can be upgraded in Maine DOT regions. The facilities that coincide in all the scenarios are the optimum facilities that work in all scenarios. Hence feasibility study can be started on those facilities. In the Northern region, Caribou WWTF and Pinelands Farms Natural Meats Inc. coincide in all scenarios, making it the best existing facilities that can be upgraded in the future. Similarly, in the Eastern region, the transfer station of the Town of Lincoln and Dover Foxcroft WWTF coincide in all scenarios, making it the best existing facilities that can be upgraded in the Eastern region. Four farms and transfer station of the town of Clinton coincide in all scenarios in Mid-Coast. Out of these four farms, Stedy Rise farms and Caverly Hills LLC are 330 acres and 840 acres and generate excess manure of 4096 tons /year and 4175 tons/year. These farms can be good locations for a new facility using food waste. In the Southern region, not a single facility coincides in all the scenarios, but Sanford WWTF and few farms can be upgraded after doing feasibility analysis. In the Western region, six farms and the transfer station of the town of Turner coincide in all the scenarios. Feasibility analysis can be done in these facilities to determine which can be upgraded as a new waste management facility utilizing food waste.

1.4 CONCLUSIONS

This study aimed to find the optimum locations for establishing new additional facilities in Maine. FW availability, sludge availability, conserved lands, wetlands, inland landslide extent, population, airports, land cover, sludge, and transportation cost were chosen for the analysis. Opportunities for the upgrading of existing farms with excess manure, composting facilities, transfer stations, and WRRFs was determined. Four scenarios Fiberight operational/not operational with treatment with/without sludge. Five optimum regions and three optimum regions were determined for Maine and Maine DOT regions. The areas that coincided in all scenario was regarded as an area for further study. In the Northern region Caribou, in Eastern region, Dover Foxcroft and Lincoln, in Mid-Coast region, Clinton, in Southern region, Sanford and in the Western region Turner, Skowhegan are the areas that coincide in all scenario. The details of the existing farms, WRRFs., transfer stations and the composting facilities that can be upgraded in different regions were determined. In the Northern region, Caribou WWTF and Pinelands Farms Natural Meats Inc. coincide in all scenarios, making it the best existing facilities that can be upgraded in the future.

Similarly, in the Eastern region, the transfer station of the Town of Lincoln and Dover Foxcroft WWTF coincide in all scenarios, making it the best existing facilities that can be upgraded in the Eastern region. Four farms and transfer stations of the town of Clinton coincide in all scenarios in Mid-Coast. Out of these four farms, Stedy Rise farms and Caverly Hills LLC are 330 acres and 840 acres and generate excess manure of 4096 tons /year and 4175 tons/year. These farms can be good locations for a new facility using food waste. In the Southern region, not a single facility coincides in all the scenarios, but Sanford WWTF and few farms can be upgraded after doing feasibility analysis. In the Western region, six farms and the transfer station of the town of

Turner coincide in all the scenarios. Feasibility analysis can be done in these facilities to determine which can be upgraded as a new waste management facility utilizing food waste.

1.5 THE SENSITIVITY OF THE METHODOLOGY

The sensitivity of the method was checked by adding different global criteria weighting in AHP. In one case, the technical aspect (slope and proximity to airports and residential areas) was prioritized more, whereas the economic aspect (travel time and waste availability) was given more importance in the next case. In case 1, the weightage for economic, technical and environmental aspects were 0.24, 0.6 and 0.16 which showed technical aspect was more important than others. Weights for each criteria in case 1 are shown in Table 3-13 and Table 3-14 and AHP numbers used for each criteria are described in 1.2.6. Meanwhile, for case 2, the weights of economic, technical and environmental were assigned as 0.6, 0.24, and 0.16 showing economic aspect was more important than others. The weights for each criteria in case 2 is shown in Table 1-6 and Table 1-7, and AHP numbers assigned to each criteria is described in 1.2.6. Optimum locations in both cases were determined, as shown in Table 1-10. With the change in the weighting of the criteria, at least one optimum location out of three remained the same. There were changes in the optimum locations in each scenario. Hence the methodology is sensitive to the weighting of the criteria.

Table 1-10: Comparison of optimum locations determined using different global weighting schemes

Region	Case 1 (Technical aspect more important)				Case 2 (Economic aspect more important)			
	Fiberight Operational		Fiberight not Operational		Fiberight Operational		Fiberight not Operational	
	Sludge treated	Sludge excluded	Sludge treated	Sludge excluded	Sludge treated	Sludge excluded	Sludge treated	Sludge excluded
Northern Region	Presque Isle Caribou Ashland	Presque Isle Caribou	Presque Isle Caribou Ashland	Presque Isle Caribou	Caribou Presque Isle	Caribou Springfield	Caribou Presque Isle	Caribou Springfield
Eastern Region	Gouldsboro Cherryfield Dover Foxcroft	Cherry Field Dover Foxcroft Lincoln	Gouldsboro Cherryfield Dover Foxcroft	Cherry Field Dover Foxcroft Lincoln	Dover Foxcroft Lincoln Gouldsboro	Lincoln Dover Foxcroft	Dover Foxcroft Orono Lincoln	Lincoln Dover Foxcroft
Mid-Coast Region	Litchfield Readfield Clinton	Warren Monmouth Litchfield	Litchfield Oakland Clinton	Warren Litchfield Clinton	Clinton Monroe Augusta	Clinton Warren Monroe	Clinton Oakland Belfast	Clinton Warren Monroe
Southern Region	Saco Brunswick Lewiston	Yarmouth Brunswick Sanford	Saco Brunswick Lewiston	Sanford Scarborough Brunswick	Lewiston Saco Sanford	Standish Wells Sanford, Springvale	Lewiston Saco Sanford	Scarborough Standish Wells
Western Region	Turner Athens Skowhegan	Turner Skowhegan Athens	Turner Skowhegan Athens	Turner Skowhegan Athens	Skowhegan Turner Hanover	Turner Skowhegan Hanover	Turner Skowhegan Athens	Turner Skowhegan Hanover

1.6 FUTURE AREAS FOR RESEARCH

Only eight criteria were used in the analysis. While constructing a new waste management facility, there are various factors to consider. Parameters like the type of facility- anaerobic digester or composting facility- and the facility's size were not considered. In the Northern region of Maine, since there is less population, small scale composting facility would likely be more suitable for waste management. In contrast, in the Southern region, a new anaerobic digester might be required based on population. Feasibility analysis needs to be conducted for deciding the type of waste management facility. Multiple origins and destinations of composting facilities, transfer stations, and wastewater recovery facilities were used to determine the transportation cost assuming the waste will be transported from these facilities to the new waste management facility.

Meanwhile, the transportation cost associated with the transportation of food waste to transfer stations was not considered. Many hauling companies collect food waste and transport it to transfer stations. Incorporating this information into the analysis will make the results more accurate.

Similarly, the DEP dataset for composting facilities where most of the facilities compost yard trimmings was used. However, there are many private companies that compost food waste. Adding this information to the analysis can be an approach for future studies. The analytical hierarchy process was used to determine the weights of each criterion. AHP numbers were assigned on personal judgment and are highly biased. An AHP questionnaire could be sent to experts in different aspects of waste management to arrive at AHP weightings in a more systematic and less biased manner.

CHAPTER 2

LAB TECHNIQUE TO OBSERVE SALT AND AMMONIA TOXICITY

2.1 INTRODUCTION

In 2018 EPA confirmed that 11 anaerobic digesters have ceased working (three stand-alone facilities, three farm co-digestion systems, and five co-digestion systems at WRRFs) (Pennington, 2019). There can be various underlying reasons for closing down an anaerobic digester as the AD process is intrinsically a sequential complex chemical and biochemical function. Many factors (microbiological, operational, and chemical) can affect its performance (Amani et al., 2010). Among various environmental conditions, pH is the most sensitive parameter. The digester's pH indicates the system's stability, and its variation depends on the system's buffering capacity (Mata-Alvarez et al., 2000). Mixing, temperature, heavy metals, sulfide, salts, and organic loading also play an essential role in microorganisms' well-being in an anaerobic digester (Campbell & Mougeot, 2000; Conti et al., 2018; Nghiem et al., 2014; Regueiro et al., 2015).

The metal ions of sodium, magnesium, potassium, calcium, and aluminum are present in anaerobic digesters' feedstock. They may release during the breakdown of organic matter or while adjusting pH (de Baere et al., 1984). These ions are required for microbial growth and consequently affect the specific growth rate like any other nutrient. While moderate concentrations stimulate microbial growth, excessive amounts slow down growth, but higher concentrations can cause severe inhibition or toxicity (de Baere et al., 1984). High salt levels cause cells to dehydrate (plasmolysis) and cause cell death due to the dramatic increase in osmotic pressure in the cell (de Baere et al., 1984; Gagliano et al., 2017). For methanogens, sodium concentration above eight g/L is toxic (Anwar, 2016).

Similarly, high nitrogen content in organic waste poses significant drawbacks to the AD process as nitrogen in biopolymers (i.e., proteins, nucleic acids) will primarily be converted into ammonia in the AD process (Ruiz-Sánchez et al., 2018). In the ammonium/ammonia chemical equilibrium, the second species has a significant negative effect on microorganisms due to its ability to cross the plasma membrane. Once in the cytoplasm, it causes pH shifts that inhibit enzymes involved in fundamental biochemical reactions (Fotidis et al., 2014). Various studies show that ammonia concentrations above five g/L are toxic to methanogens (Raju et al., 2012). This negative effect is particularly marked for the acetotrophic methanogenic archaea (AMA) (Fotidis et al., 2014). Hence, feeding the digester with nitrogen-rich organic materials, such as animal dejections, slaughterhouse wastes, and residues from the food industry, often results in unstable reactor performance and operational failure(Ruiz-Sánchez et al., 2018).

2.2 METHODS AND MATERIALS

2.2.1 SEED DIGESTER

We set up a digester in the fume hood of Room 29, Boardman Hall. The digester was a 4 L Pyrex glass jar fitted with a size eight rubber cork in which we drilled two holes to insert Tygon tubes. One of the Tygon tubes ran to the jar's bottom, while a couple of inches of the other tube was inside the jar. We fed the digester through the tube that ran to the jar's base and collected gas through other tubes. The feeding tube was clamped at the top to maintain anaerobic conditions and prevent airflow into the system. The water displacement method was used to measure gas volume where gas from the Tygon tube goes through another Pyrex glass jar filled with water and displaces water. The jar filled with water was clamped at the top with a cork to prevent gas loss. We used a graduated cylinder to measure the volume of displaced water that equivalents the gas volume produced in the system.

After the instruments' setup, we flushed nitrogen gas from the Matheson Tri-gas Nitrogen cylinder into the jar for full five minutes. We had a total of 1900 ml seed inoculum from three small scale food waste and sludge fed anaerobic digesters operating on Orbital shaker of Room 29 Boardman Hall. We used the *Sous vide Cooker* Immersion heater that we bought from amazon to maintain the constant temperature in the system. After adding the sludge to the new digester, we placed it in the water bath at 35ºC. The digester was left for a single day without feeding so the microorganisms could adjust to the new environment. The feed ratio was mostly 50-50% by volatile solids maintaining the organic loading rate less than 2 kg VSS/m^3-day. A retention time of 20 days was adopted with feeding and taking out 95ml of waste daily. Figure 2-1 shows the layout of the seed digester.

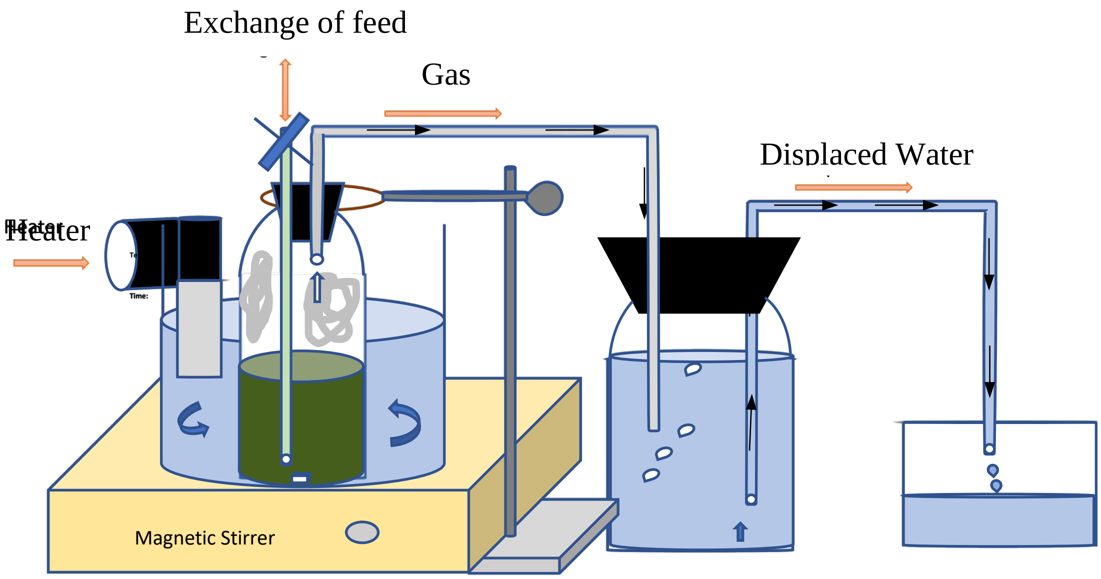


Figure 2-1: Mechanism of the new digester. Digestate is mixed by using a magnetic stirrer and heated in a water bath through a heater. The volume of gas is measured through the water displacement method.

We operated this digester without any issues for 48 days and performed two experiments Sodium Toxicity Experiment and Ammonium Toxicity. Because of COVID 19, the University shut down, and we had to discard the digester.

2.2.2 COLLECTION AND PROCESSING OF THE SUBSTRATE

Food waste was collected from home that mostly contained kale, potatoes, peppers, tomatoes, fruits, bread. It was preprocessed by blending in an Oster blender and sieving through 4.699 mm, 2.36 mm, and 2 mm opening sieves. The resulting slurry would be about 700-800 ml every time. The wastewater sludge, about 1000ml from the secondary clarifier, was collected from the Orono Wastewater Treatment Plant weekly. We stored the feed (100ml of each) in seven different plastic bottles, each for food waste and sludge, in the Fisher Scientific, Model 425F freezer. Since it takes almost two days to measure the VS (Volatile Solids explains the method), we placed it in the different containers to prevent the feed from degrading. After measuring VS, we would determine each feed's volume to meet the feed rate of less than two kg VSS/day for that batch of feed. We thawed two bottles on the feeding day by keeping it in hot water. A 60ml wide-mouthed syringe did the feeding.

2.2.3 SODIUM TOXICITY EXPERIMENT

This experiment was conducted on 2nd February 2020 to observe sodium ion's effect in an anaerobic digester. Twelve pre-autoclaved serum bottles of 130 ml volume were prepared. Each serum bottle had a unique name in the upper half. We measured initial pH, sodium concentration, VS, as described in Chemistry Methods for food waste, biosolids, and seed digester inoculum. The organic solids of food waste and sludge were 160 g/L and 17 g/L. To maintain the organic loading rate (OLR) at 1.9 kg-VSS/m^3-day, we added 0.5 ml FW and 1.5 ml sludge through autoclaved 1ml pipette tips into the serum bottles.

Different volumes of the stock 100 g Na^+/L were added using a sterilized 1ml pipette to obtain the final sodium salt concentration. Final sodium salt concentration was maintained as control, 5 g Na^+/L, 8 g Na^+/L, and 10 g Na^+/L with each batch in triplicates. The serum bottles were flushed with Nitrogen gas for 3 minutes before adding 50ml of fresh seed from the Seed Digester into each bottle. We kept the total volume of the batch as 56 ml by adding additional DI water. Table 2-1 details the amount of DI water added in each batch. The bottles were stoppered and crimp sealed and mixed at 100 rpm in Thermolyne Big Bill SE shaker at 35 ̊C in a Fisher Scientific low-temperature incubator for 85 hours (3.54 days). On the last day, we took the serum bottles out of the incubator, measured gas composition and volume of gas; pH; salt; alkalinity; VS; and prepared the HPLC test samples. We kept the HPLC samples in the refrigerator and examined for fatty acids in a couple of days. Appendix 3: Sodium Experiment contains the pictures of the salt experiment.

Table 2-1: Detail of the batches for salt toxicity experiment

S.N.	Batch	Stock (gNa+/L)	Volume of stock added (ml)	Final (g Na+/L)	DI water (ml)	Inoculum added (ml)	Food(ml)	Biosolids (ml)	Total Substrate Volume (ml)	Total Volume of digester (ml)
1	Blank1	100	0.0	3.26	4.1	50	0.5	1.5	52	56.0
2	Blank2	100	0.0	3.26	4.1	50	0.5	1.5	52	56.0
3	Blank3	100	0.0	3.26	4.1	50	0.5	1.5	52	56.0
4	5.1	100	1.2	5	2.9	50	0.5	1.5	52	56.0
5	5.2	100	1.2	5	2.9	50	0.5	1.5	52	56.0
6	5.3	100	1.2	5	2.9	50	0.5	1.5	52	56.0
7	8.1	100	3.0	8	1.1	50	0.5	1.5	52	56.0
8	8.2	100	3.0	8	1.1	50	0.5	1.5	52	56.0
9	8.3	100	3.0	8	1.1	50	0.5	1.5	52	56.0
10	10.1	100	3.9	10	0.2	50	0.5	1.5	52	56.0
11	10.2	100	3.9	10	0.2	50	0.5	1.5	52	56.0
12	10.3	100	3.9	10	0.2	50	0.5	1.5	52	56.0

2.2.4 AMMONIUM TOXICITY

This experiment was conducted on March 9, 2020, to observe the ammonium ion effect in an anaerobic digester. Twelve pre-autoclaved serum bottles of 130 ml volume were prepared. Each serum bottle had a unique name in the upper half of the bottle. Like the sodium experiment, we measured pH, VS, ammonium for food waste, biosolids, and the inoculum of seed digester. The organic content of food waste, biosolids, and inoculum was 130 g/L,9.3 g/L, and 23.8 g/L. To maintain the organic loading rate of 1.79 Kg VSS/m^3-day, we added 0.65 ml of food waste and 1.85 ml of biosolids. 50ml seed from the Seed Digester was added to each serum bottle. We added different volumes of the stock 90 g NH_4^+-N /L, as shown in the Table 2-2, to make four types of the batch - Blank batch without extra ammonium (control), 3 g/L of ammonium nitrogen, 5 g/L of ammonium nitrogen, and 7 g/L of ammonium nitrogen. The digester's final volume was 57ml by adding additional DI water, as table 2 illustrates.

Table 2-2: Details of the batches for ammonium toxicity

Batch bottles	**Stock concentration (g NH4+-N/L)**	**Volume of stock added (ml)**	**Initial NH4+ (g NH4+-N/L)**	**Final NH4+ (g NH4+-N/L)**	**DI water added (ml)**	**Inoculum added (ml)**	**Food (ml)**	**Biosolids (ml)**	**Total Substrate Volume (ml)**	**Total Volume of digester (ml)**	**Final Volume**
Blank1	90	0.0	0.29	0.29	4.5	50	0.65	1.85	52.5	56.8	57
Blank2	90	0.0	0.29	0.29	4.5	50	0.65	1.85	52.5	56.8	57
Blank3	90	0.0	0.29	0.29	4.5	50	0.65	1.85	52.5	56.8	57
3.1	90	1.7	0.29	3.00	2.8	50	0.65	1.85	52.5	56.8	57
3.2	90	1.7	0.29	3.00	2.8	50	0.65	1.85	52.5	56.8	57
3.3	90	1.7	0.29	3.00	2.8	50	0.65	1.85	52.5	56.8	57
5.1	90	3.0	0.29	5.00	1.5	50	0.65	1.85	52.5	56.8	57
5.2	90	3.0	0.29	5.00	1.5	50	0.65	1.85	52.5	56.8	57
5.3	90	3.0	0.29	5.00	1.5	50	0.65	1.85	52.5	56.8	57
7.1	90	4.3	0.29	7.00	0.2	50	0.65	1.85	52.5	56.8	57
7.2	90	4.3	0.29	7.00	0.2	50	0.65	1.85	52.5	56.8	57
7.3	90	4.3	0.29	7.00	0.2	50	0.65	1.85	52.5	56.8	57

The serum bottles were incubated in a Fisher Scientific low-temperature incubator at 35 ℃ at 100 rpm in Thermolyne Big Bill SE shaker for three days. On the third day, we took the batch out and measured gas composition and volume, pH, ammonium, salt, alkalinity, VS, and prepared HPLC samples, using the methods explained in Chemistry Methods.

The images associated with the ammonia toxicity experiment are in Appendix 4: Ammonia Experiment.

2.2.5 CHEMISTRY METHODS

2.2.6 pH

Corning pH meter 430 was used to measure pH by calibrating two buffers pH 4 & 7. A Thermo Electron Corporation (Orion 910500) pH probe was rinsed with DI water and wiped with Kim wipes before and after each measurement. We measured pH at the beginning and the end for batch experiments, and for the seed digester, we measured it daily. The probe was stored in 1M KCl solution after the measurement to prevent it from drying.

2.2.7 VOLATILE SOLIDS

We poured 10 ml of sample into a 10 ml graduated cylinder and then into a pre-weighed aluminum dish. The cylinder was rinsed with some DI water to remove the solids stuck on the wall and poured back to the aluminum dish. The dish was placed in a Fisher Isotemp Oven (senior model) at 115℃ overnight. Samples were cooled in a Boekel Fisher Scientific desiccator for approximately 30 minutes before weighing on a Mettler AE 50 balance to obtain the dry weight. The samples were then placed in a Thermolyne 4800 furnace at 550℃ for one hour after ramping up at 40℃ per minute. They were left inside the furnace for an additional hour to cool down. We weighed the samples to find the furnace weight after cooling in a desiccator for approximately 30 minutes.

We calculated the volatile solids according to the following equation.

$$VS(\%) = \frac{Dry\ Weight - Furnace\ Weight}{Dry\ Weight - Tare\ Weight}$$ Equation 5

For the new feedstock, we measured VS once every week and for the inoculum each alternate day. Volatile solids for inoculum were measured to observe anaerobic digester through the percentage of VS destroyed. VS was also calculated for feedstock to maintain the organic loading rate below 2 kg VSS/m^3-day.

2.2.8 ALKALINITY

APHA standard method of titration was used (APHA, 2017). 0.1 N H_2SO_4 was used to titrate a known volume of sample to an endpoint pH of 4.5. Using the volume of the sample used, the volume of sulfuric acid consumed to reduce the sample pH to 4.5, and the concentration of acid, we calculated alkalinity using the following equation.

$$\text{Alkalinity, mg CaCO}_3\text{/L} = \frac{A * N * 50{,}000}{ml\ Sample}$$ Equation 6

Where,

$A = ml\ standard\ acid\ used$

$N = normality\ of\ standard\ acid$

We monitored the ratio of volatile fatty acids to alkalinity for the performance of the digester. The Wisconsin department of natural resources says that observing this ratio is better than monitoring pH for the system's performance; the ratio greater than 0.25

indicates the accumulation of acids in the system (Wisconsin Department of Natural Resources, 1992).

2.2.9 VOLATILE FATTY ACIDS (VFAS)

HPLC-RID (Shimadzu) with an Aminex HPX-87H column measured the fatty acids in the system. Throughout the run, the oven temperature was 60℃. Ten ml of sample was prepared using 1N sulfuric acid (1:1) to maintain pH at 1-2. Eppendorf centrifuge centrifuged 4ml of this sample in thermo scientific 2 ml tubes at 14000 rpm for ten minutes. The centrifuged solution was filtered using Thermo Scientific ™ 17mm Nylon syringe filters (0.45 µm) to pour around 1.5 ml clear solution in HPLC vial. These vials were taken to Jennes Hall from Boardman for HPLC measurement. We placed the samples in the autosampler and recorded the information in EZStart software. Each sample ran for 55 minutes by pumping the mobile phase (0.005 M H_2SO_4) at 0.6 ml/min. In each run, the device used 15 µL of the sample as injection volume. Standard acetic acid with concentration of 2, 4, 6, 8 &10 g/L, propionic acid (2, 4, 6, 8 &10 g/L), butyric acid (0.5, 2, 4, 6, 8 g/L) and valeric acid (0.5, 2, 4, 6, 8 g/L) were used for the calibration. In the end, the software gave the retention time and concentration of acids in the form of peaks. For the seed digester, we measured fatty acids almost daily. For the batch experiments, we measured acids at the end of the batch experiments.

2.2.10 GAS COMPOSITION

The volume of gas was measured by the water displacement method. Every time the gas composition needs to be measured, we attached the gas collecting Tygon tube to the Tedlar bags for around 12 hours. Gas chromatography (SRI 8610C gas chromatograph multiple gas analyzer #2) examined the gas composition through two carrier gases-hydrogen and helium- and two columns-molecular sieve 13X and Hayesep-D. Molecular sieve 13X separated oxygen, nitrogen, carbon monoxide, and methane with hydrogen as a carrier gas (carrier 1). In contrast, the Hayesep-D column separated carbon dioxide and methane with helium (carrier 2). In every run, after 8.5 minutes, carrier one turned off, and carrier two started working. Peak Simple software regulated gas flow and equipment. Two standard gas of 34 L and 17 L cylinder capacity from GASCO (60% CH_4, 40% CO_2 and 5% CH_4, 5% CO_2, 90% N_2) and air were used for calibration. We injected 10ml of standard gases through a ten ml syringe and calibrated the instrument. Each sample ran for 12 minutes. At the end of each run, there were peaks in the computer screen with retention time and peak area. The retention time of CH_4 was around 4 minutes and CO_2 at about 11 minutes. Using the peak area, the concentration of calibrated standard gases, the device calculated the percentage composition of the gas.

2.2.11 CONDUCTIVITY

A YSI Multilab meter with the YSI IDS 4310 conductivity probe measured the conductivity. For calibration, we used YSI 3160 conductivity calibrator (1413 µS/cm). A standard solution of 100 g Na^+/L was prepared and autoclaved before making standard solutions with varying concentrations ranging from 1-11 g Na^+/L. A calibration curve was made by plotting concentration vs. conductivity, as shown in Appendix 2: Calibration charts. While measuring conductivity for the sample, we used the meter to measure the conductivity and calculated the corresponding concentration from the calibration curve. We maintained a daily record of sodium concentration for the seed digester.

2.2.12 AMMONIUM

We measured ammonium ion concentration in logger lite 1.9.4 software. The software was installed on a computer and then connected to the probe using a USB port before calibrating with the standard solution of 1 ppm and 100 ppm NH_4^+-N. As our desired concentration was around 5000 ppm, a stock solution of 8000 ppm NH_4^+-N was prepared in the lab using NH_4Cl, and we calibrated the instrument with 100ppm and 8000 ppm. The probe was placed in a high standard solution for 30 minutes before calibration. After calibrating the software, we measured the ammonium ion concentration for each sample. The probe was rinsed with DI water and wiped with Kim wipes every time the sample changed. In the end, we kept the probe in a moist tube to prevent it from drying. We measured the ammonium concentration for the seed digester on alternate days. A separate calibration graph was prepared by measuring the known concentration of ammonium-nitrogen, as shown in Appendix 2: Calibration charts. We used this graph to find the actual ammonium concentration in the solution.

2.3 RESULTS AND DISCUSSION

2.3.1 PERFORMANCE OF THE SEED DIGESTER

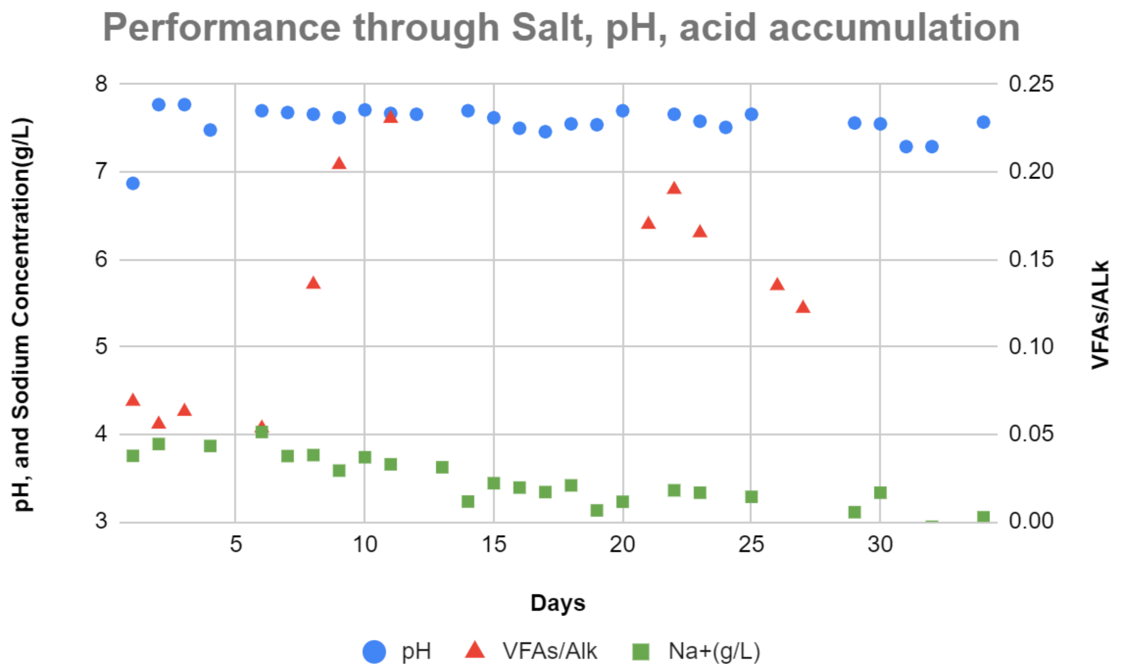


Figure 2-2: Monitoring the pH, sodium ion concentration, the acid accumulation in the system. If the ratio of fatty acids and alkalinity is high it means, there is more acid in the system

pH was between 7 and 8 most of the time, and the acid accumulation was also low in the system as the ratio of fatty acids and alkalinity is lower than 0.25, as shown in Figure 2-2. Sodium salt concentration was less than 4 g/L most of the time. The results of HPLC showed that there was not a higher chain of fatty acids like propionic acid, butyric acid, and valeric acid in the seed digester.

2.3.2 EFFECT OF SODIUM ION IN ANAEROBIC DIGESTERS

The pH of the digester at the beginning of the experiment was 6.97. The range of pH of the batches at the end of the experiment ranged from 7.22-7.55. The paired two-tailed T-test conducted between the 12 batches of the beginning and 12 batches of the end of the experiment showed that the final batches were significantly different (p-value 0.018) from the initial batch salt concentration. The average volatile solids destroyed, shown in Figure 2-3, at 8 g/L and 10 g/L of sodium addition was 29% and 22%, respectively, significantly lower than the average VS destroyed in control (45%) (p-value 0.017,0.001 respectively). In contrast, the volatile solids destroyed at 5 g/L was not statistically significant with the control. Figure 2-4 shows that methane yield is highest in the blank sample with a methane production rate of 149.38 ml CH4/g-VS, whereas it is lowest (80.34 ml CH4/g-VS) in the sample having 10 g/L sodium. When we conducted t-tests with methane yield, the methane generation at 8 g/L was not statistically significant. In contrast, the methane yield at 10 g/L was significantly lower than the control (p= 0.023).

Acid analysis by HPLC showed that higher chain fatty acids accumulated at higher sodium concentration. Only acetic acid was present at the lower sodium salt concentration, whereas as salt increases, there were propionic acid and butyric acid. Traces of butyric acid were seen starting from the concentration of 8 g/L. Naveed Anwar found in his study that with an increase in the sodium salt concentration, the accumulation of higher chain fatty acids increases, and the removal of volatile solids decreases (Anwar, 2016)

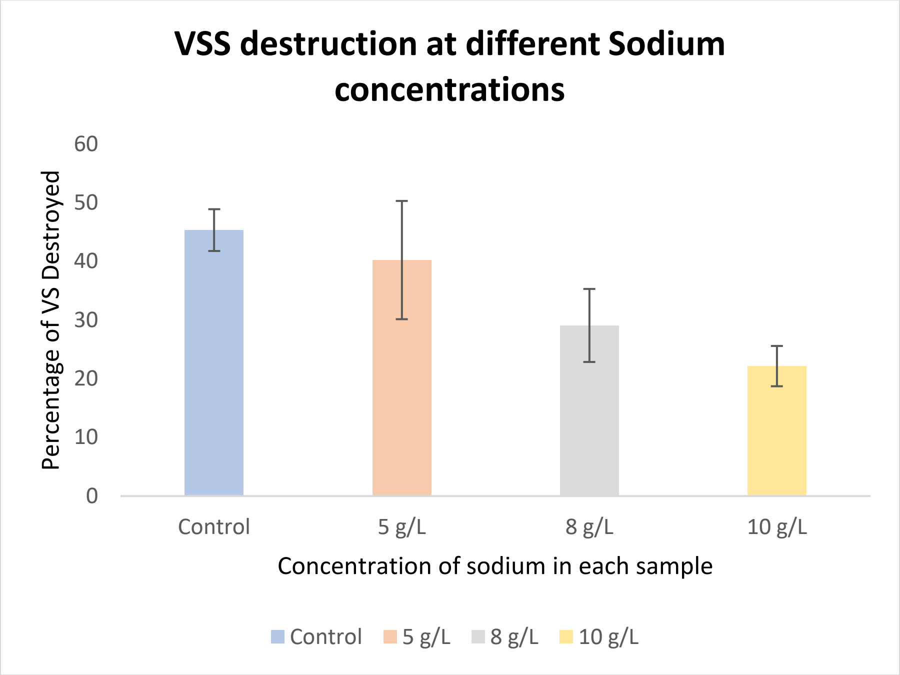


Figure 2-3: VSS destruction at different sodium concentration Four different colors are used to present four batches with different concentration

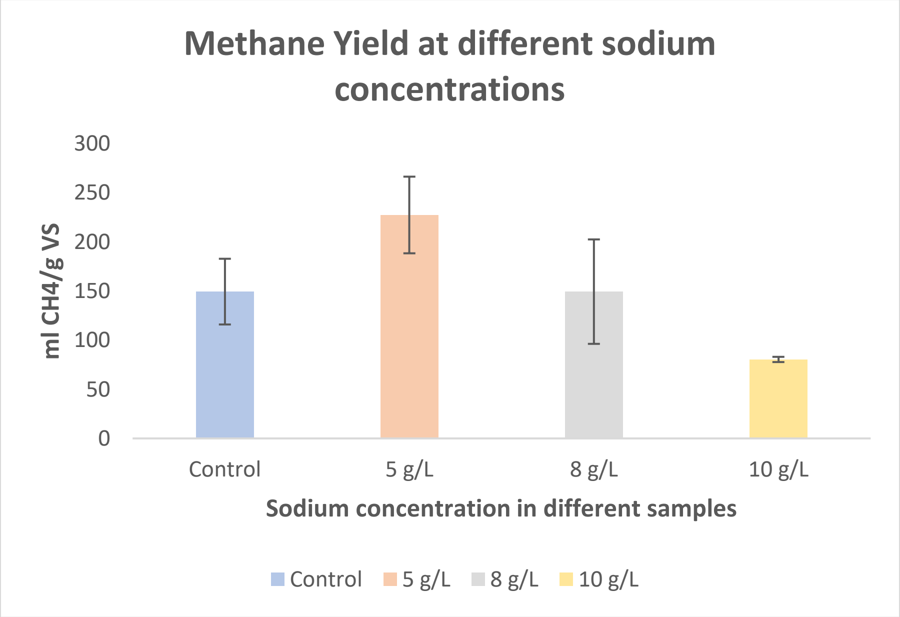


Figure 2-4: Methane yield at different concentration of sodium ion

2.3.3 EFFECT OF AMMONIUM ION IN ANAEROBIC DIGESTERS

The pH of the digester at the beginning of the experiment was 7.36. The range of pH at the end of the experiment is 7.36-7.57. The initial ammonium-nitrogen concentration was 0.29 g NH_4^+-N/L in control. We maintained the ammonium-nitrogen concentration as control 3 g/L, 5 g/L, and 7 g/L NH_4^+-N at the beginning of the experiment. However, the ammonium concentration at the end was dramatically higher at all concentrations, as shown in. The T-test (two-tailed, paired) conducted within the initial and the final concentration of ammonium nitrogen showed that these results are statistically significant. Though ammonia is derived from the added ammonia and the breakdown of proteins, nucleic acids, and urea in the feedstock materials, (Dai et al., 2016) this dramatic increase needs justification. Though the measurements were done twice, it can also be from the error of the instrument or human error.

Figure 2-5, VS destruction graph, shows that more than 80% of volatile solids were destroyed in all reactors, though methane generation rate lowered with higher ammonium concentrations. According to the two-tailed homoscedastic T-test, VS destroyed at 5 g/L and 7 g/L is statistically significant (p-value =0.008, 0.0002) than the unamended controls. From Figure 2-6, Methane production was also lower at 5 g/L and 7 g/L of ammonia-N addition (p-value=0.001, 0.0005, respectively). Propionic acid was detectable at ammonia concentrations of 5 g/L NH_4^+-N and above. Butyric acid was not observed in any treatment.

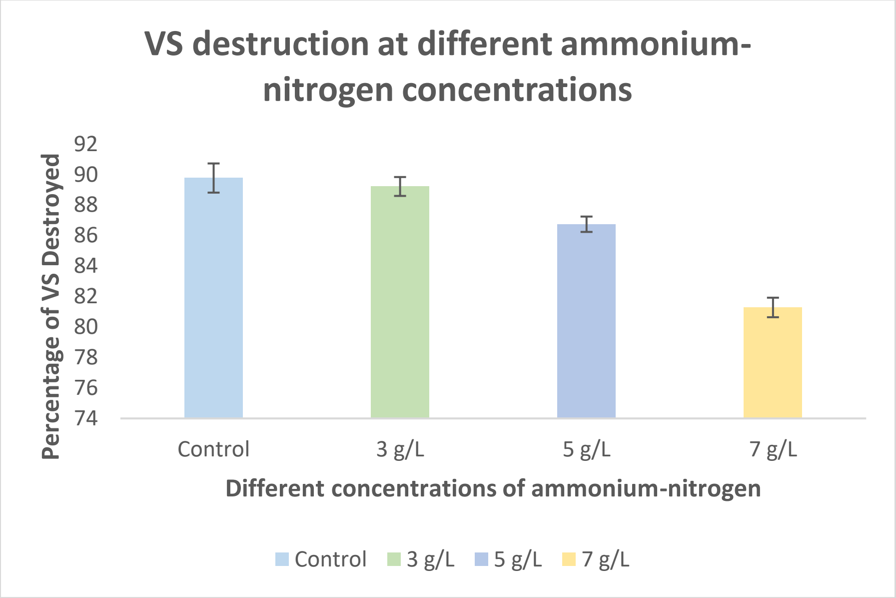


Figure 2-5: VS destruction at different ammonium nitrogen concentrations in the sample

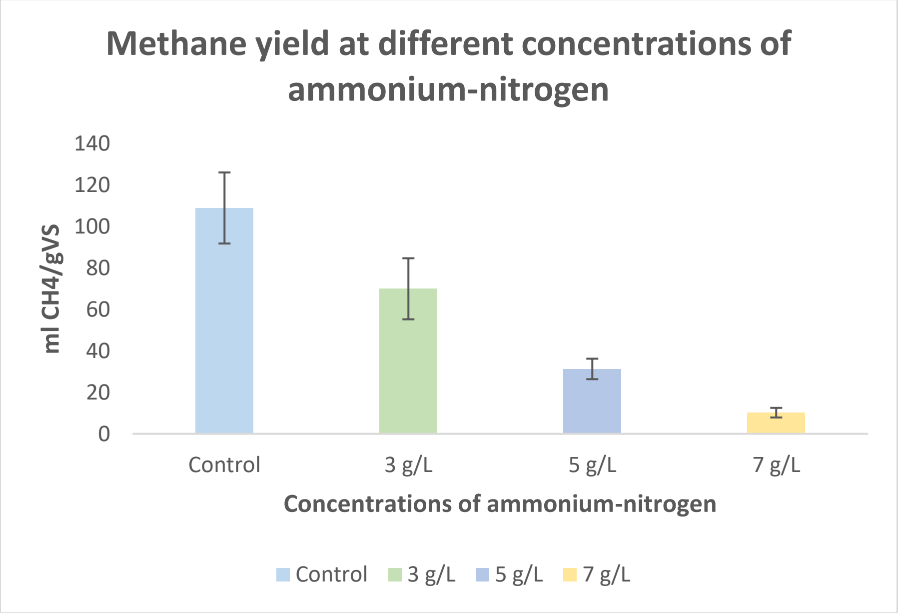


Figure 2-6: Methane yield at different concentrations of ammonium-nitrogen

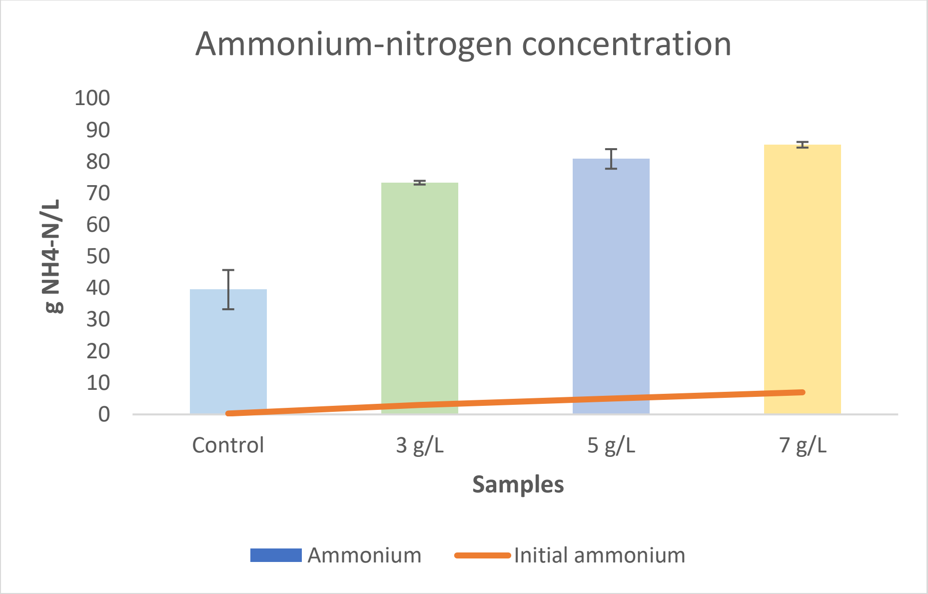


Figure 2-7: Ammonium concentration at the beginning and the end of the experiment.

2.3.4 VARIABILITY OF THE RESULTS

The temperature of the feedstock was not increased to 35℃ after thawing them. They were directly added into the digester after thawing, which would have slightly decreased the temperature of the system and impacted the microorganisms in the system. The feedstock was in their separate containers. They were not mixed homogeneously before feeding in the seed digester and the batch experiments. As the batch experiments were conducted from the seed of a lab-scale digester, the well-being of the seed digester should have high influence on the experiments.

2.4 CONCLUSIONS

Batch experiments were conducted using seed from existing steady state lab scale digester at different concentrations of sodium, and ammonium nitrogen to determine their effects on VSS destruction, VFA production and methane generation. The results show that sodium concentration at and above 8 g Na^+/L decreased VSS destruction by more than 35% than control. Methane production reduced by 46% when the sodium concentration was 10 g/L. NH_4^+-N concentrations of 5 g/L and above reduced methane production by 71%, and VSS destruction by 3%, as compared to control batch. This shows the salt and ammonia are toxic to the methanogens that are responsible for producing methane from anaerobic digestion of organic waste.

BIBLIOGRAPHY

2015-2017 C-CAP Derived 10-meter Land Cover - BETA | ID: 57099 | InPort. (2019). Office for Coastal Management. https://www.fisheries.noaa.gov/inport/item/57099

About ArcGIS Pro—ArcGIS Pro | Documentation. (n.d.). Retrieved October 19, 2020, from https://pro.arcgis.com/en/pro-app/get-started/get-started.htm

About Us – LAWPCA. (n.d.). Retrieved July 25, 2020, from http://www.lawpca.org/?page_id=237

Ali Shah, F., Mahmood, Q., Maroof Shah, M., Pervez, A., & Ahmad Asad, S. (2014). Microbial ecology of anaerobic digesters: The key players of anaerobiosis. In *The Scientific World Journal* (Vol. 2014). Hindawi Limited. https://doi.org/10.1155/2014/183752

Amani, T., Nosrati, M., & Sreekrishnan, T. R. (2010). Anaerobic digestion from the viewpoint of microbiological, chemical, and operational aspects - A review. *Environmental Reviews*, *18*(1), 255–278. https://doi.org/10.1139/A10-011

Anwar. (2016). *Effect of sodium salt on anaerobic digestion of kitchen waste Naveed Anwar , Wen Wang , Jie Zhang , Yeqing Li , Chang Chen ,*. 1865–1872. https://doi.org/10.2166/wst.2016.035

APHA. (2017). *Standard Methods for the Examination of Water and Wastewater*. https://doi.org/10.2105/SMWW.2882.216

ArcGIS pro. (n.d.). *Calculate the travel time between origins and destinations with OD Cost Matrix—ArcGIS Pro | Documentation*. Retrieved October 11, 2020, from https://pro.arcgis.com/en/pro-app/help/analysis/networks/od-cost-matrix-tutorial.htm

ArcGIS Pro. (2020). *What is the Suitability Modeler?—ArcGIS Pro | Documentation*. https://pro.arcgis.com/en/pro-app/help/analysis/spatial-analyst/suitability-modeler/what-is-the-suitability-modeler.htm

Bangor Daily News. (2020). *Hampden waste plant puts operations on hold as it struggles to pay bills*. https://bangordailynews.com/2020/06/10/news/bangor/hampden-waste-plant-puts-operations-on-hold-as-it-struggles-to-pay-bills/

COWI. (2004). *Preliminary Impact Assessment for an Initiative on the Biological Treatment of Biodegradable Waste Final Study Report*.

Criner, K. G., & Blackmer, L. T. (2011). *2011-Maine-Residential-Waste-Characterization-Study*.

Dun & bradstreet. (2020). *US Farm Data, Inc. Company Profile | Omaha, NE | Competitors, Financials & Contacts - Dun & Bradstreet*. https://www.dnb.com/business-directory/company-profiles.us_farm_data_inc.c717d28716249bcf20e5fccebb5cd3f3.html

ecomaine. (2017). *food waste Goes Back to the Farm in FY 2017*.

EPA. (2015). *Ag 101 | Agriculture | US EPA*. http://www.epa.gov/agriculture/ag101/index.html[7http://www.epa.gov/agriculture/ag101/index.html

EPA. (2019). *Food Recovery Hierarchy | Sustainable Management of Food | US EPA*. https://www.epa.gov/sustainable-management-food/food-recovery-hierarchy

EPA Facility Registry Service. (n.d.). *EPA Facility Registry Service (FRS): Wastewater Treatment Plants*. 2020. Retrieved September 18, 2020, from https://edg.epa.gov/metadata/catalog/search/resource/details.page?uuid=%7B86C00471-0D39-4352-B629-14E3C0E2D042%7D

Esri. (2020). *How To: Create a slope map from contour lines in ArcGIS Pro*. https://support.esri.com/en/technical-article/000023285

Excess Food Opportunities Map. (n.d.). Retrieved July 11, 2020, from https://geopub.epa.gov/ExcessFoodMap/

Excess Food Opportunities- Technical Methodology. (2020). *Excess Food Opportunities Map, Version 2.1 - Technical Methodology*. https://www.epa.gov/sustainable-management-food

Fiberight. (2018). *Fiberight Maine – Fiberight, LLC – Leading the Way Forward*. https://fiberight.com/fiberight-maine/

Fulford, D. (2015). *Small-scale rural biogas programmes : a handbook*.

How It Works | EAE – Exeter Agri-Energy. (n.d.). Retrieved July 25, 2020, from http://www.exeteragrienergy.com/how-it-works/

Isenhour, C., Blackmer, T., Wagner, T., Silka, L., & Peckenham, J. (2016). *Moving up the Waste Hierarchy in Maine: Learning from "Best Practice" State-Level Policy for Waste Reduction and Recovery Part of the Environmental Policy Commons, and the Natural Resources Management and Policy Commons Repository Citation*. https://digitalcommons.library.umaine.edu/mitchellcenter_pubs

Karimini, A. R., Mehrdadi, N., Hashemian, S. J., Nabi Bidhendi, G. R., & Tavakkoli Moghaddam, R. (2011). *Selection of wastewater treatment process based on the analytical hierarchy process and fuzzy analytical hierarchy process methods*.

Kim, H. W., Nam, J. Y., Kang, S. T., Kim, D. H., Jung, K. W., & Shin, H. S. (2012). Hydrolytic activities of extracellular enzymes in thermophilic and mesophilic anaerobic sequencing-batch reactors treating organic fractions of municipal solid wastes. *Bioresource Technology, 110*, 130–134. https://doi.org/10.1016/j.biortech.2012.01.146

Layer: All Composting Facilities (ID: 22). (2018). https://gispub.epa.gov/arcgis/rest/services/Region9/LND2003987_ExcessFoodRecipient/MapServer/22

Leal, J. E. (2020). AHP-express: A simplified version of the analytical hierarchy process method. *MethodsX, 7*. https://doi.org/10.1016/j.mex.2019.11.021

Maine DEP. (2017). *Report to the Joint Standing Committee on the Environment and Natural Resources 128 th Legislature, First Session MAINE DEPARTMENT OF ENVIRONMENTAL PROTECTION Maine Solid Waste Generation and Disposal Capacity Report: Calendar Year 2015 Contents*. www.maine.gov/dep

Maine DEP. (2020). *ACTIVE/LICENSED TRANSFER STATIONS Maine Department of Environmental Protection*.

Metcalf & Eddy. (2003). *Wastewater Engineering Treatment and Reuse* (H. D. S. George Tchobanoglous, Franklin L. Burton, Ed.; 4th ed.). McGraw-Hill.

Mir, M. A., Hussain, A., & Verma, C. (2016). Design considerations and operational performance of anaerobic digester: A review. *Cogent Engineering*, *3*(1), 1–20. https://doi.org/10.1080/23311916.2016.1181696

Mohee, R., & Mudhoo, A. (2012). *Bioremediation and Sustainability : Research and Applications*. John Wiley & Sons, Incorporated. http://ebookcentral.proquest.com/lib/umaine/detail.action?docID=861796

MRC Inc. (2018a). *Facility | Municipal Review Committee*. https://www.mrcmaine.org/fiberight/

MRC Inc. (2018b). *MRC Members | Municipal Review Committee*. https://www.mrcmaine.org/municipalities/

Narihiro, T., & Sekiguchi, Y. (2007). Microbial communities in anaerobic digestion processes for waste and wastewater treatment: a microbiological update. *Current Opinion in Biotechnology*, *18*(3), 273–278. https://doi.org/10.1016/j.copbio.2007.04.003

National Sewage Sludge. (2020). *PFASinBiosolidsdocx-formatted*.

Nazari, A., Salarirad, M. M., & Bazzazi, A. A. (2012). Landfill site selection by decision-making tools based on fuzzy multi-attribute decision-making method. *Environmental Earth Sciences*, *65*(6), 1631–1642. https://doi.org/10.1007/s12665-011-1137-2

NRCM. (2016a). *Maine Composting Companies - Natural Resources Council of Maine*. https://www.nrcm.org/sustainability/maine-composting-companies/

NRCM. (2016b). *Maine Composting Companies - Natural Resources Council of Maine*. https://www.nrcm.org/sustainability/maine-composting-companies/

Pennington. (2018). *Anaerobic Digestion Facilities Processing Food Waste in the United States in 2015*.

Pennington. (2019). *Anaerobic Digestion Facilities Processing Food Waste in the United States in 2016*.

Public Law Chapter 461. (n.d.). *PUBLIC Law, Chapter 461, An Act To Create a Sustainable Solution to the Handling, Management and Disposal of Solid Waste in the State*. Retrieved November 13, 2020, from https://www.mainelegislature.org/legis/bills/bills_127th/chapters/PUBLIC461.asp

Raju, C. S., Løkke, M. M., Sutaryo, S., Ward, A. J., & Møller, H. B. (2012). NIR monitoring of ammonia in anaerobic digesters using a diffuse reflectance probe. *Sensors*, *12*(2), 2340–2350. https://doi.org/10.3390/s120202340

Seiple, T. E., Coleman, A. M., & Skaggs, R. L. (2017). Municipal wastewater sludge as a sustainable bioresource in the United States. *Journal of Environmental Management*, *197*, 673–680. https://doi.org/10.1016/j.jenvman.2017.04.032

Solid, M., Anderson, L., & Bergeron, M. (2016). *Report to the Joint Standing Committee on the Environment and Natural Resources 127 th Legislature, Second Session MAINE DEPARTMENT OF ENVIRONMENTAL PROTECTION Contents*. www.maine.gov/dep

Song, B., & Kang, S. (2016). A Method of Assigning Weights Using a Ranking and Nonhierarchy Comparison. *Advances in Decision Sciences, 2016*. https://doi.org/10.1155/2016/8963214

Stentiford, E., & de Bertoldi, M. (2010). *Composting: Process*. http://ebookcentral.proquest.com','_blank'

Swan, R. M., Crook, B., & Gilbert, J. (2002). *Microbial Emissions from Composting Sites*. http://ebookcentral.proquest.com','_blank'

Tzeng, G.-H., & Huang, J.-J. (2011). *Multiple Attribute Decision Making : Methods and Applications*. CRC Press LLC. http://ebookcentral.proquest.com/lib/umaine/detail.action?docID=762529

Undersander, D., Cosgrove, D., Cullen, E., Grau, C., Rice, M. E., Renz, M., Sheaffer, C., Shewmaker, G., & Sulc, M. (2011). *Alfalfa Management Guide ii Alfalfa Management Guide*. www.soils.org

Urban, R. C., & Isaac, R. de L. (2018). WTP and WWTP sludge management: a case study in the metropolitan area of Campinas, southeastern Brazil. *Environmental Monitoring and Assessment*, *190*(10), 584. https://doi.org/10.1007/s10661-018-6972-0

US EPA. (2018). *Basic Information on PFAS*. https://www.epa.gov/pfas/basic-information-pfas

US EPA. (2020). *Sustainable Management of Food Basics | Sustainable Management of Food | US EPA*. https://www.epa.gov/sustainable-management-food/sustainable-management-food-basics

US EPA, OAR. (n.d.). *AgSTAR Data and Trends*. Retrieved October 2, 2020, from https://www.epa.gov/agstar/agstar-data-and-trends

US EPA, OLEM. (n.d.). *National Overview: Facts and Figures on Materials, Wastes and Recycling*. Retrieved October 2, 2020, from https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials

US Farm Data. (2020). *United States Farmers, Ranchers | Farm Mailing Lists, Ag Business Leads - US Farm Data*. https://www.usfarmdata.com/

USDA, & Natural Resource Conservation Service. (1995). *Animal Manure Management*. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/null/?cid=nrcs143_014211

Wall, J. D., Harwood, C. S., & Demain, A. L. (Arnold L.). (2008). *Bioenergy*. ASM Press.

Williams, P. T., Roberts, R. D., Strange, K., Gladding, T. L., Gilbert, E. J., Crook, B., Redfearn, A., Rabl, A., Spadaro, J. v, & Dolk, H. (2002). *Environmental and Health Impact of Solid Waste Management Activities*. Royal Society of Chemistry. http://ebookcentral.proquest.com/lib/umaine/detail.action?docID=1185486

Wisconsin Department of Natural Resources. (1992). *Introduction to Anaerobic Digestion Study Guide Wisconsin Department of Natural Resources Introduction to Anaerobic Digestion Study Guide-June 1992 Edition*. http://dnr.wi.gov

Xu, D. Y., Lin, Z. Y., Gordon, M. P. R., Robinson, N. K. L., & Harder, M. K. (2016). Perceived key elements of a successful residential food waste sorting program in urban apartments: stakeholder views. *Journal of Cleaner Production, 134*(Part A), 362–370. https://doi.org/10.1016/j.jclepro.2015.12.107

CHAPTER 3 APPENDICES

3.1 APPENDIX A: SUITABILITY MAPS

3.1.1 MAINE

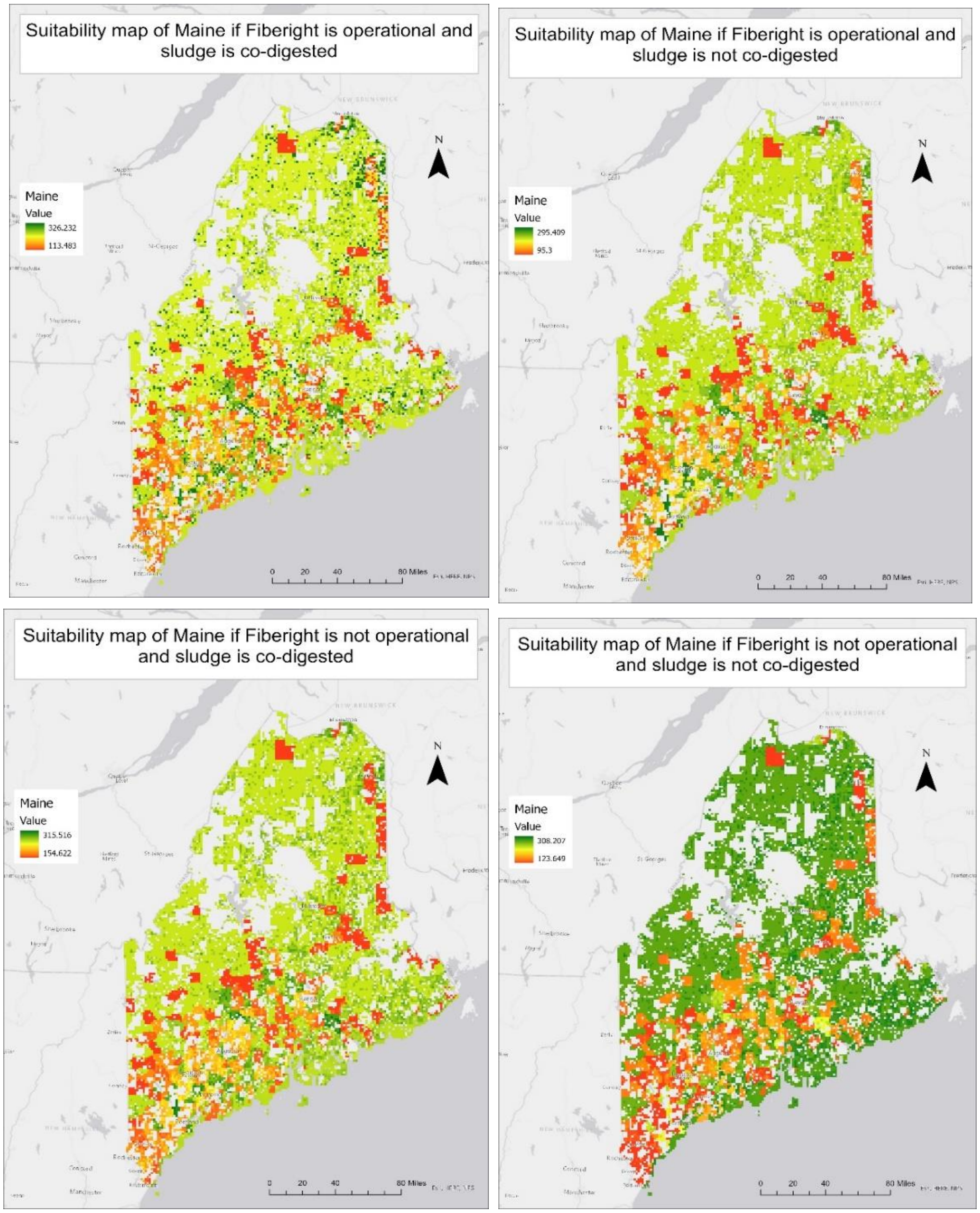


Figure 3-1: Suitability map of Maine.

3.1.2 NORTHERN REGION

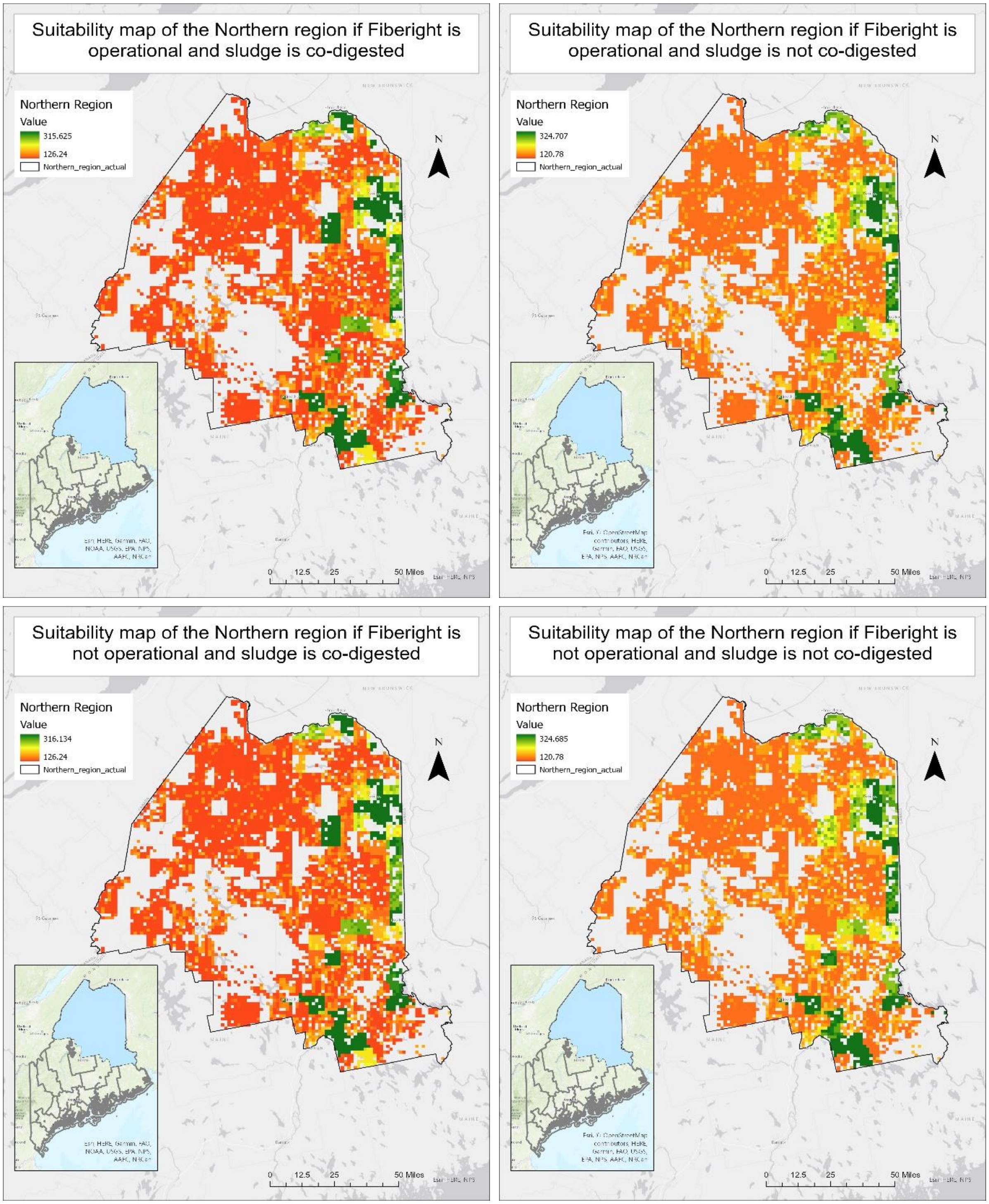


Figure 3-2: Suitability map of Northern region.

3.1.3 EASTERN REGION

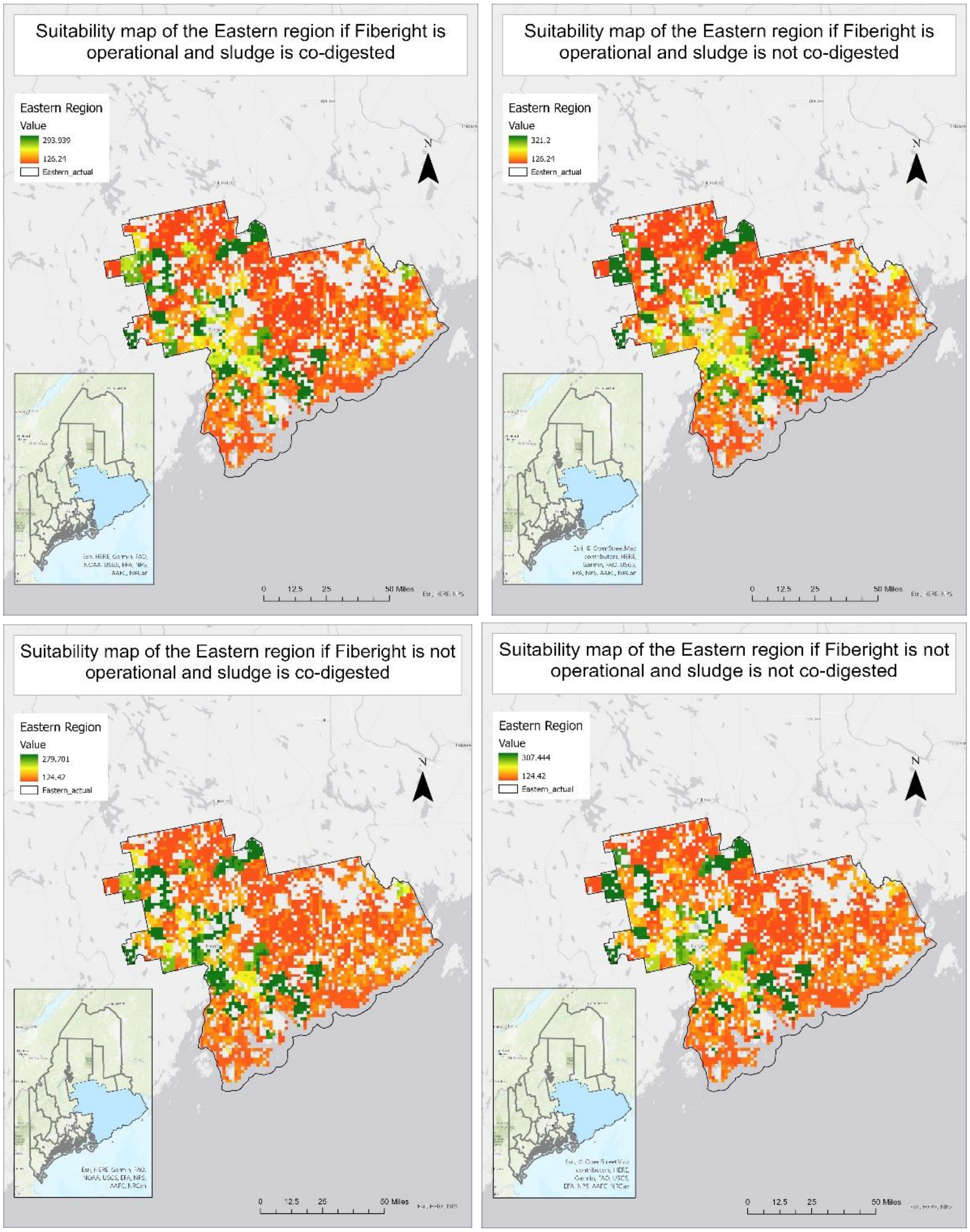
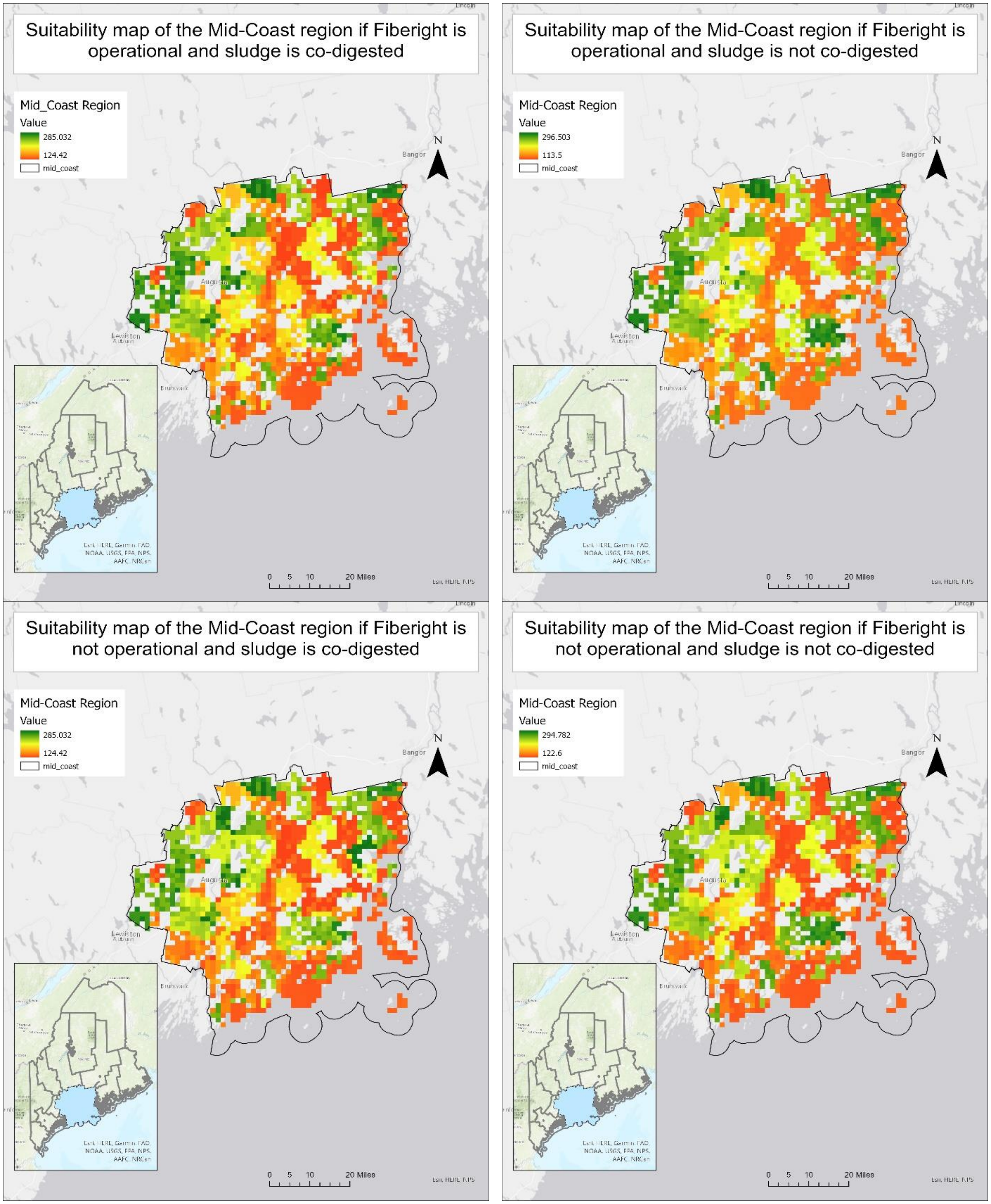


Figure 3-3 Suitability map of Eastern region

3.1.4 MID-COAST REGION



Suitability map of the Mid-Coast region if Fiberight is operational and sludge is co-digested

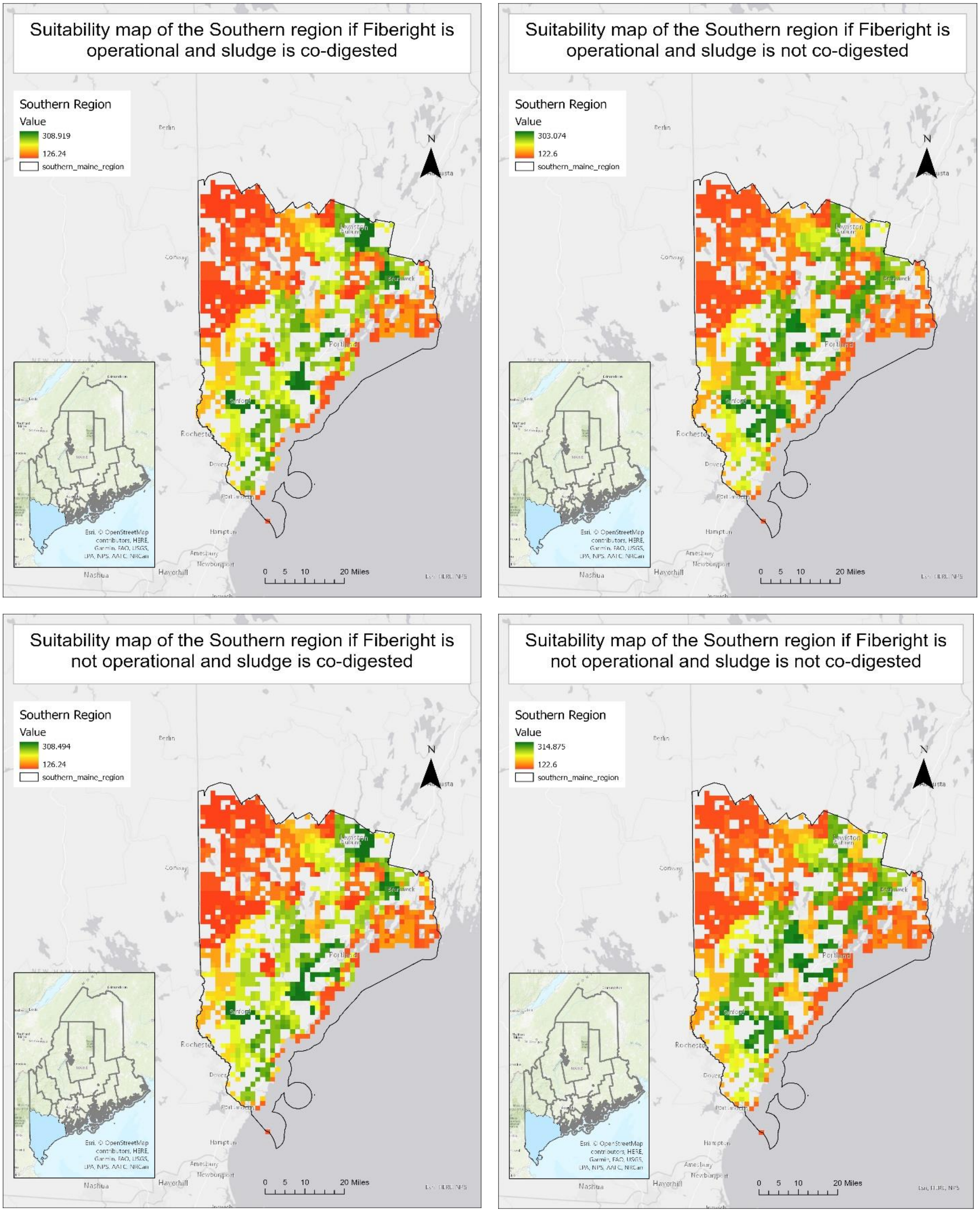
Suitability map of the Mid-Coast region if Fiberight is operational and sludge is not co-digested

Suitability map of the Mid-Coast region if Fiberight is not operational and sludge is co-digested

Suitability map of the Mid-Coast region if Fiberight is not operational and sludge is not co-digested

Figure 3-4: Suitability map of Mid-Coast region

3.1.5 SOUTHERN REGION


Suitability map of the Southern region if Fiberight is operational and sludge is co-digested

Suitability map of the Southern region if Fiberight is operational and sludge is not co-digested

Suitability map of the Southern region if Fiberight is not operational and sludge is co-digested

Suitability map of the Southern region if Fiberight is not operational and sludge is not co-digested

Figure 3-5: Suitability map of Southern region

3.1.6 WESTERN REGION

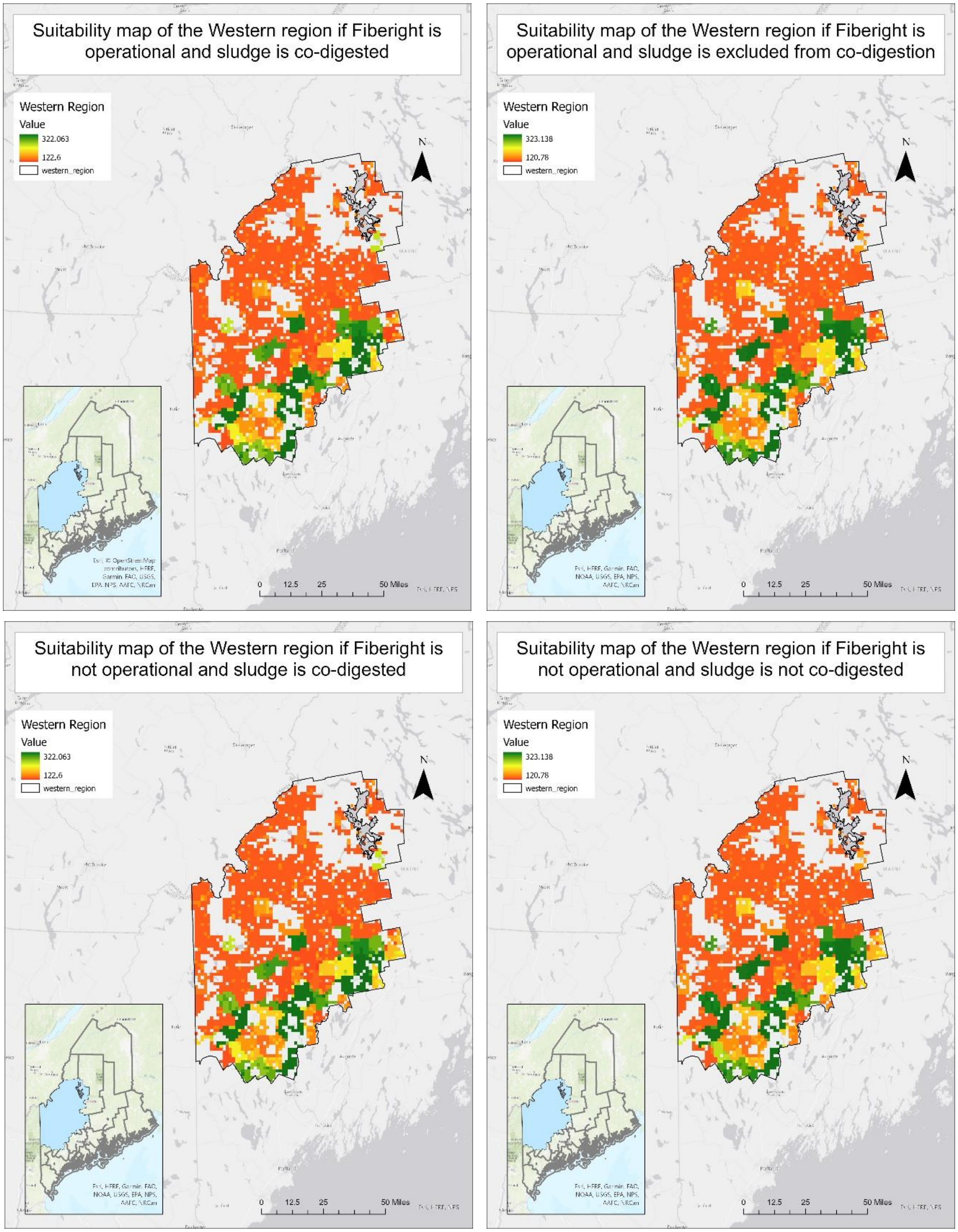


Figure 3-6: Suitability map of the Western region

3.2 APPENDIX B: CRITERIA WEIGHTS BY AHP

3.2.1 ECONOMIC FACTORS

3.2.1.1 Sludge exclusion

Table 3-1: Assigned AHP numbers to economic factors in sludge exclusion

	A1	A2
A1	1	2
A2	0.5	1
sum	1.5	3

Table 3-2: Normalized matrix for sludge exclusion

Normalized			
	A1	A2	Criteria Weights
A1	0.67	0.67	0.67
A2	0.33	0.33	0.33
sum	1.00	1.00	1.00

Table 3-3: Consistency Index for sludge exclusion

	A1	A2	Criteria Weights	Eigen value
A1	0.67	0.67	0.67	1.333333333
A2	0.33	0.33	0.33	0.666666667
sum	1	1	1	2
			Consistency Index	0

3.2.1.2 Sludge Inclusion

Table 3-4: AHP numbers assigned to sludge inclusion

	A1	A2	A3
A1	1	2	2
A2	0.5	1	2
A3	0.5	0.5	1
sum	2	3.5	5

Table 3-5: Normalized matrix for sludge exclusion

	A1	A2	A3	Criteria Weights
A1	0.5	0.571429	0.4	0.490476
A2	0.25	0.285714	0.4	0.311905
A3	0.25	0.142857	0.2	0.197619
sum	1	1	1	1

Table 3-6: Consistency Index for sludge exclusion

	A1	A2	A3	Criteria Weights		
A1	0.490476	0.62381	0.395238	0.490476	1.509524	3.07767
A2	0.245238	0.311905	0.395238	0.311905	0.952381	3.053435
A3	0.245238	0.155952	0.197619	0.197619	0.59881	3.03012
sum	0.980952	1.091667	0.988095	1		3.053742
				Consistency Index		0.026871

3.2.2 TECHNICAL FACTORS

Table 3-7: AHP numbers assigned to technical factors

	B1	B2	B3
B1	1	5	3
B2	0.2	1	0.5
B3	0.333333	2	1
sum	1.533333	8	4.5

Table 3-8: Normalized matrix for technical factors

Normalized				
	B1	B2	B3	Criteria Weights
B1	0.652174	0.625	0.666667	0.647947
B2	0.130435	0.125	0.111111	0.122182
B3	0.217391	0.25	0.222222	0.229871

Table 3-9: Consistency Index for technical factors

	B1	B2	B3	Criteria Weights		
B1	0.647947	0.61091	0.689614	0.647947	1.94847	3.007145
B2	0.129589	0.122182	0.114936	0.122182	0.366707	3.001318
B3	0.215982	0.244364	0.229871	0.229871	0.690217	3.002627
						3.003697
				Consistency Index		0.001848

3.2.3 ENVIRONMENTAL FACTORS

Table 3-10: AHP numbers assigned to environmental factors

	C1	C2
C1	1	2
C2	0.5	1
Sum	1.5	3

Table 3-11: Normalized matrix for environmental factors

	C1	C2	Criteria Weights
C1	0.67	0.67	0.67
C2	0.33	0.33	0.33
sum	1	1	1

Table 3-12: Consistency Index for environmental factors

	C1	C2	Criteria Weights		
C1	0.67	0.67	0.67	1.33	2
C2	0.33	0.33	0.33	0.67	2
sum	1	1	1		2
					0

Table 3-13: Criteria weights for sludge exclusion (Case 1)

Global Factors	**Global Weight**	**Criteria**	**Symbol**	**Sludge Exclusion**		**Transformative weight in Modeler**
				Local Weights	**Global Weights**	
Economical	0.24	Transportation Cost	A1	0.67	0.160	3
		Food Waste Availability	A2	0.33	0.080	1.5
		Sludge Availability	A3	-	-	-
Technical	0.6	Airports	B1	0.65	0.389	7.29
		Land Cover	B2	0.12	0.073	1.37
		Slope	B3	0.23	0.138	2.59
Environmental	0.16	Sensitive Areas	C1	0.67	0.107	2
		Residential Areas	C2	0.33	0.053	1
Sum	**1**			**3**	**1**	**18.75**

Table 3-14: Criteria Weights for the sludge inclusion (Case 1)

Global Factors	**Global Weight**	**Criteria**	**Symbol**	**Sludge Inclusion**		**Transformative weight in Modeler**
				Local Weights	**Global Weights**	
Economical	0.24	Transportation Cost	A1	0.49	0.118	2.48
		Food Waste Availability	A2	0.31	0.075	1.58
		Sludge Availability	A3	0.2	0.047	1
Technical	0.6	Airports	B1	0.65	0.389	8.2
		Land Cover	B2	0.12	0.073	1.55
		Slope	B3	0.23	0.138	2.91
Environmental	0.16	Sensitive Areas	C1	0.67	0.107	2.25
		Residential Areas	C2	0.33	0.053	1.12
Sum	**1**			**3**	**1**	**21.08**

3.3 APPENDIX C: CALIBRATION CHARTS

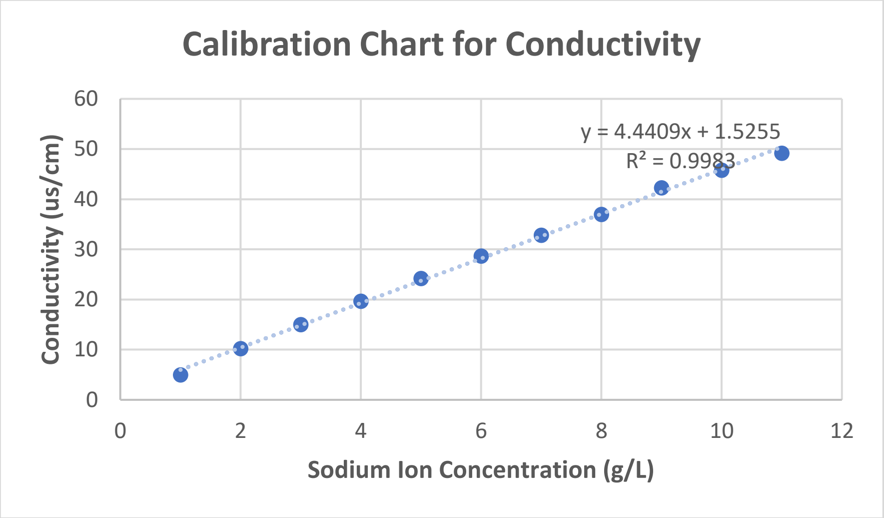


Figure 3-7: Calibration chart for conductivity. Different known concentrations of sodium were used to find the conductivity. This chart is used to calculate the actual sodium salt concentration in samples

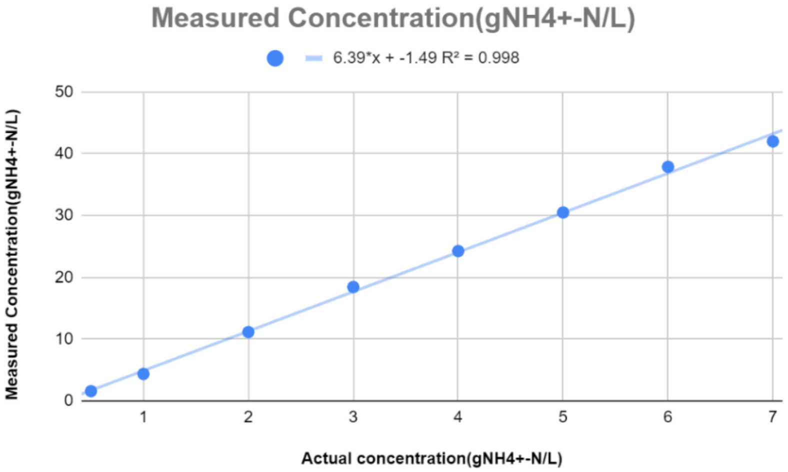
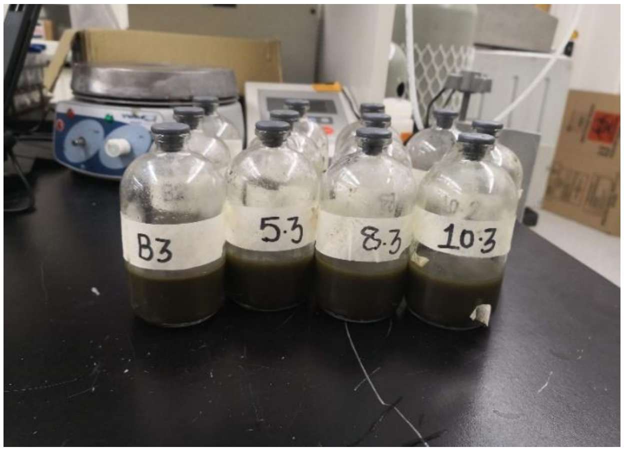
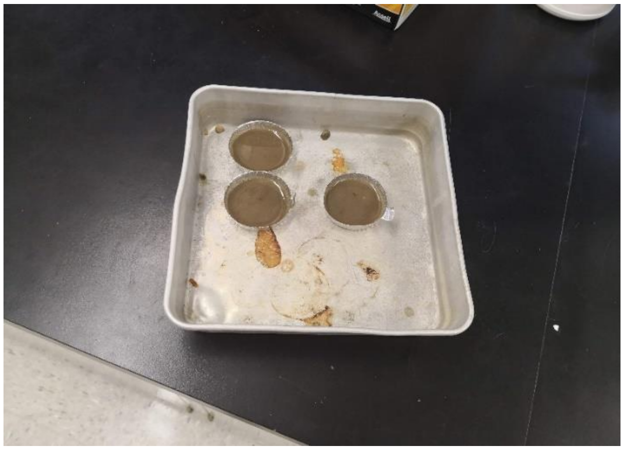


Figure 3-8: Calibration chart for ammonium concentration

3.4 APPENDIX D: SODIUM EXPERIMENT





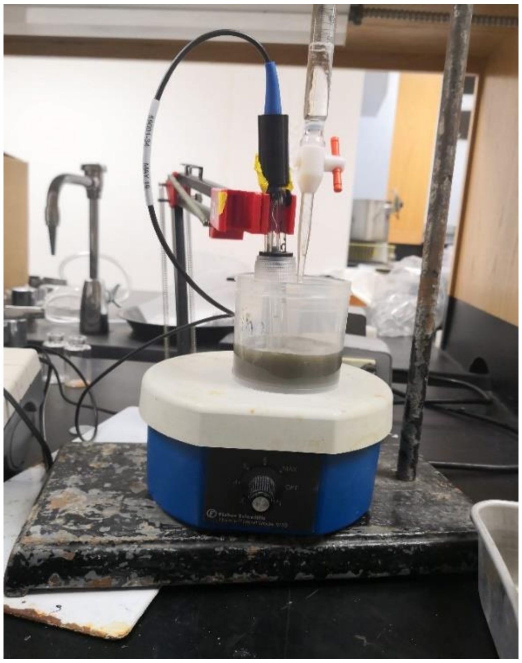


Figure 3-9: Experimental pictures for salt toxicity test. The top left image represents the samples ready to be clamped and incubated. The bottom left represents the sample in an aluminum dish prepared to put in the oven for VS measurement. The bottom right picture shows the alkalinity test.

3.5 APPENDIX D: AMMONIA EXPERIMENT

Figure 3-10: The top left picture represents the pre-autoclaved labeled serum bottles just before the experiment. The top right image represents the flushing of nitrogen gas into the batch after the addition of feed. The bottom right shows the labeled vials for the HPLC samples

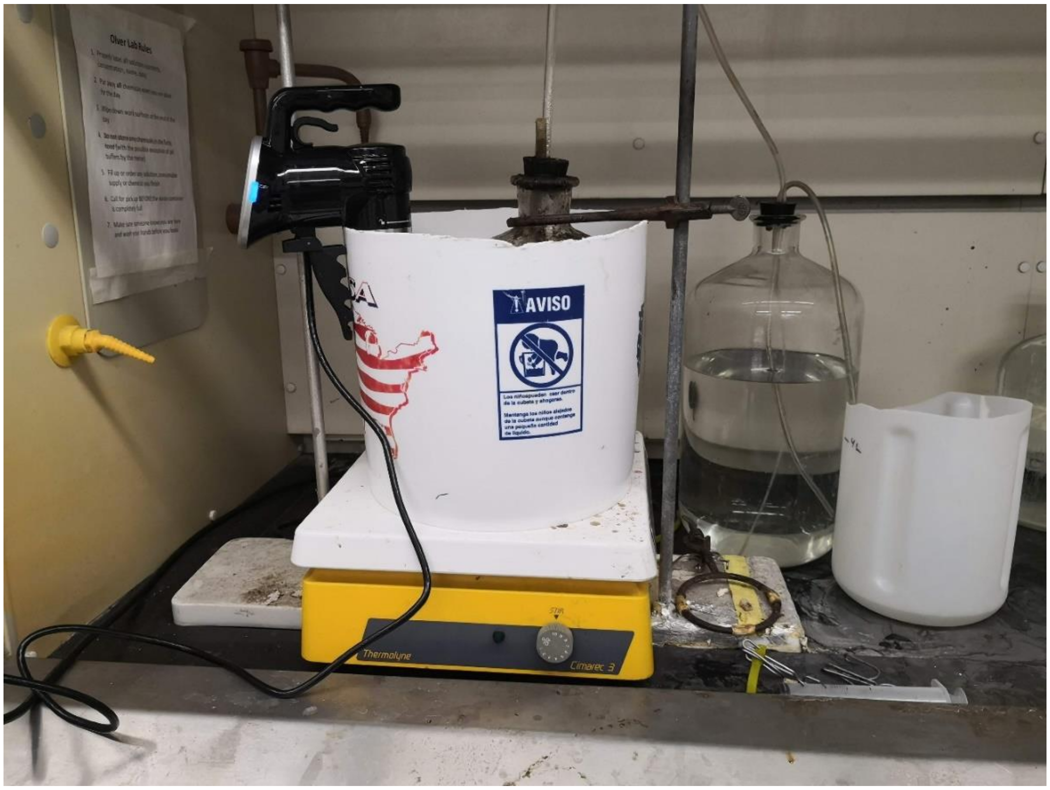


Figure 3-11: The seed digester. The primary digester is in the water bath, and the water displacement method is used to measure the volume of the gas

CHAPTER 4

BIOGRAPHY OF THE AUTHOR

Usha Humagain, was born in a small village near Kathmandu, Nepal, in 1993. She graduated high school from SOS Village, Bharatpur, in 2011 and joined Tribhuvan University for her undergraduate degree in Civil Engineering. During her undergraduate project, she studied the status of wastewater management in Pokhara, Nepal. She conducted different lab tests and analyzed the drainage system. In April 2015, during the earthquake, she volunteered for Nepal Government to determine the earthquake risk assessment in Thumki V.D.C of Kaski. She was actively involved in student clubs during her college days.

After graduation in 2015, she started working full time for a consulting firm, S.W. Nepal Pvt. Ltd., in Kathmandu as a Rural Infrastructure Engineer. She worked for USAID Sajheedari Bikaas Project from Dec 2015- Dec 2017 by constructing and rehabilitating small scale drinking water projects, community centers, and roads through the firm. She has also worked for OXFAM to monitor its drinking water projects, household profiling, and severity mapping of Nepal's flood-affected districts. She has worked for Concern Worldwide through the consulting firm to provide technical oversight of school construction in three districts- Sindhuli, Ramechhap, and Dhading. She was involved in different small-scale projects like lime stabilization tests with Bee Rowan, training the sub-engineers and overseers on small scale projects through the Karnali Employment program, constructing a bamboo school, surveying and estimating on the widening of the Ranibari trail.

In fall 2018, she pursued her masters at the University of Maine in Civil Engineering. Usha has a high interest in traveling the rural regions of Nepal and understanding people's lives. She will be working again in Nepal after receiving her degree. Usha is a candidate for the Master of Science degree in Civil Engineering from the University of Maine in December 2020.