Utilization of Biosolids: Soil Fertilization & Energy Production

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Executive Summary

The Clemson University wastewater treatment plant (CU WWTP) currently produces over 800 tons of biosolids each year. Unfortunately, these carbon, nitrogen, hydrogen, and phosphorus dense materials are discarded in the Anderson County landfill, increasing carbon and nitrogen emissions as greenhouse gases and decreasing the amount of phosphorus content in the environment. In order to increase the sustainability of Clemson University, two alternative disposal methods are explored in this report: land application for soil fertilization on Simpson Research Farm and gasification for energy production. For both processes, the pathogen concentration of the biosolids would have to be reduced using a solar dryer heater. In order to land apply biosolids on Simpson Research Farm, a large cylindrical storage tank of radius = 10 ft and height = 13 ft would need to be constructed at the CU WWTP in order to store the solids between applications. Using a Terragator, a maximum of 1,031 tons of 90% dry biosolids could be land applied to Simpson Research Farm each year. This amount of biosolids is much larger than the amount of biosolids produced at the CU WWTP. In the gasification process, the biosolids undergo drying, pyrolysis, combustion, cracking, and reduction before becoming hydrogen gas, carbon monoxide, biochar, ash, and a variety of impurities including tars, sulfur and nitrogen compounds, hydrogen halides, and trace metals. To process all 951 tons of biosolids projected to be produced in 2019, the gasifier would need to complete 1,079 cycles or about 3 cycles per day. Roughly 31,675 kWh of energy would be produced from the gasification process. Between the two options explored, land application of biosolids is much more feasible. Until further research regarding the effects of contaminants within biosolids (microplastics, PFAS, pharmaceuticals, etc.) on the environment is conducted, Clemson University should not land apply their biosolids.

Table of Contents

Background

The CU WWTP, located between Lake Hartwell and the Clemson University track & field facility, processes an average daily flow of 0.60 million gallons daily (MGD) from an estimated 29,000 students and employees. In the near future, this flow rate is projected to increase to 0.75 MGD. On the day of a home football game, with an estimated 100,000 people using the facilities of Clemson University, the processing plant treats an average flow of 0.90 MGD. This flow rate is projected to increase to 1.1 MGD in the near future (Clemson University Facilities, 2019). In **Figure 1** below, Memorial Stadium is pictured in the top right corner, while the water treatment facility is is indicated by the yellow arrow.

Figure 1. View of CU WWTP in relation to Clemson's main campus

A closer aerial view of the facility is shown below in **Figure 2**.

Figure 2. Aerial view of the CU WWTP

At the CU WWTP, inlet wastewater is first pumped into a primary clarifier, where the majority of untreated solids, known as sewage sludge, settle to the bottom by gravity filtration. These settled solids are then pumped into the first aerobic digester, while the liquid is routed to one of the two sequencing batch reactors (SBRs). The liquid that enters the SBRs is treated to remove phosphorus, nitrogen, heavy metals, and pathogens. After this liquid spends an average of 4.3 hours in the SBR, the mixture is either pumped into the secondary clarifier when pollutant concentrations are low or pumped back into the primary clarifier for further treatment. In the secondary clarifier, any remaining solids that settle to the bottom are recycled back into the primary clarifier. The remaining liquid is then disinfected in the chlorine contact basin to kill remaining pathogens and is then dechlorinated before being discharged into Lake Hartwell. The solids that were pumped into the first aerobic digester are consumed by the aerobic bacteria present in the digester. For an average of 40 days, these microorganisms consume the solids, reducing the biological oxygen demand (BOD) to an acceptable level. Each day, roughly 2 ft in depth of wastewater is transferred from the primary digester to the secondary aerobic digester for further consumption. In these digesters, a blower aerates the mixture, accelerating the decomposition of the solids and formation of a biosolid slurry. The contents of the secondary aerobic digester, typically containing 2-3% solids, are pumped to a mechanical press where the dewatering phase occurs. The slurry is flocculated with the addition of polymer Praestol K274FLX, as shown in **Figure 3** and **Figure 4**. In 2018, 4.1 tons of this flocculant was utilized.

Figure 3. Praestol K274FLX

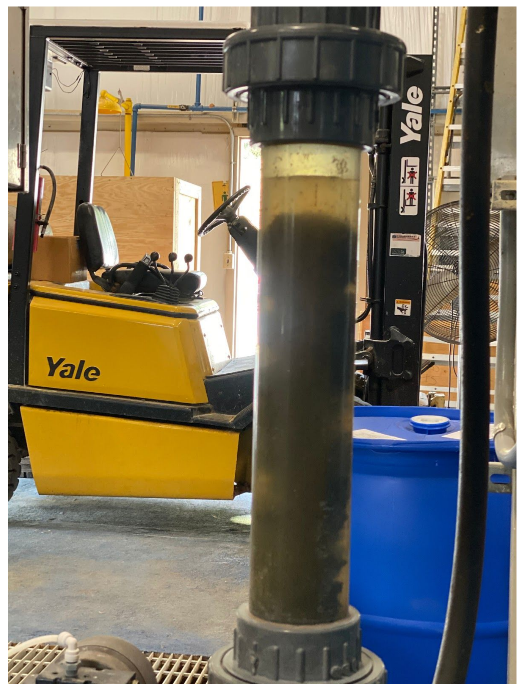

Figure 4. Biosolid flocculation with polymer

This chemical drives the dewatering of the pressed solids. According to the safety data sheet (SDS) of this compound, this polymer is harmful to aquatic life with long lasting effects. Additionally, Praestol K274FLX should not be allowed to enter drains, waterways, or soil and should not be inhaled by humans. The EC50 concentration for Daphnia, also known as the water flea, is listed as 0.17 mg/L (Solenis, 2017). This alarming concentration effect for a low trophic level species should be taken heavily into consideration of design. Although believed to be biodegradable, the exact characteristics of this polymer are unknown, as trade secrets are patented. At the end of the process, an average 18% biosolid is produced dry weight, as shown below in **Figure 5**.

Figure 5. Biosolids produced from CU WWTP awaiting transport to the Anderson landfill

The excess liquid removed from the dewatering process is recycled back into the primary clarifier for further treatment (Banks et al., 2017). The dewatered biosolids are removed from Clemson University property and deposited into the Anderson County landfill. The current wastewater treatment process performed by the CU WWTP is shown below in **Figure 6**.

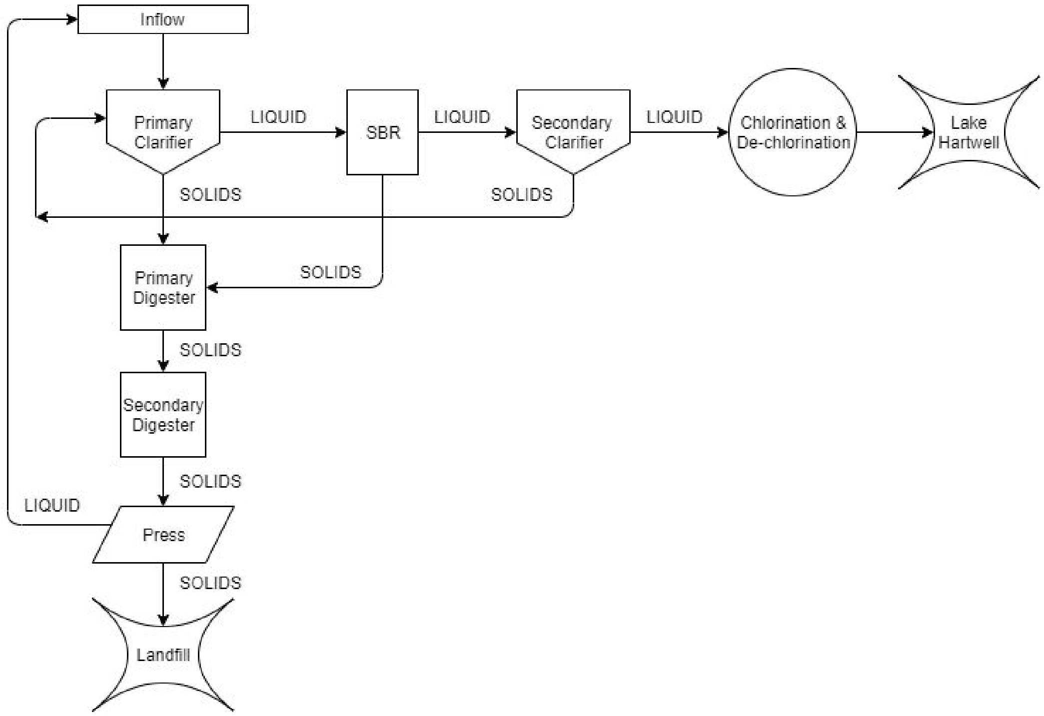

Figure 6. Current CU WWTP process flow diagram

The historical masses of produced biosolids are shown below in **Table 1** (Clemson University Facilities, 2019).

Table 1. Record of biosolid production

Year	Produced Biosolids (tons)
2017	745.08
2018	871.49
2019 (as of 11/11/19)	786.91

These masses are projected to increase as the student population increases and the university opens the new College of Business building.

Testing of the biosolids revealed the following concentrations of nutrients and heavy metals, shown in **Table 2** and **Table 3**, respectively (Clemson University Facilities, 2019).

Table 2. Biosolid nutrient concentrations

Nutrient	Concentration (mg/kg-dry)	Minimum Detectable Limit (mg/kg-dry)
Phosphorus	46400	363
Nitrogen, TKN	42900	1870
Nitrogen, total	43200	50
Nitrite	BRL	8.55
Nitrate	262	2.14
Ammonia	2610	112

Table 3. Biosolid heavy metal concentrations

Metal	Concentration (mg/L)	Minimum Detectable Limit (mg/L)
Mercury	BRL	0.00048
Arsenic	BRL	0.0705
Barium	0.0802	0.0155
Cadmium	BRL	0.008
Chromium	BRL	0.0125
Lead	BRL	0.014
Selenium	BRL	0.044
Silver	BRL	0.0065
Potassium	2380	39.7

BRL = below reporting limits

Rationale

The CU WWTP currently produces more than 800 tons of dewatered biosolids per year. Unfortunately, these nutrient-dense materials are currently being sent to the Anderson County landfill. Alternative uses of the biosolids produced from the CU WWTP must be developed to make Clemson University carbon neutral, economically feasible, and socially sustainable.

Objective

The objective of this project is to design a viable pathway to utilize the biosolids coming from the Clemson University wastewater treatment facility.

Approaches

In this section, the tasks required to meet the objective are listed.

Task 1. To review information regarding the CU WWTP, land application, gasification, and the related regulations.

Task 2. To determine fecal coliform concentrations by sampling the biosolids produced at the CU WWTP.

Task 3. To identify a process to reduce pathogen concentration.

Task 4. To investigate alternatives to hazardous flocculation methods.

Task 5. To select locations and estimate volumes for the land application of biosolids.

Task 6. To design and model a gasification process for energy utilization.

Task 7. To perform a cost analysis of land application and gasification.

This is an interdisciplinary project that connects technology, sustainability, and people, as shown below in **Figure 7**.

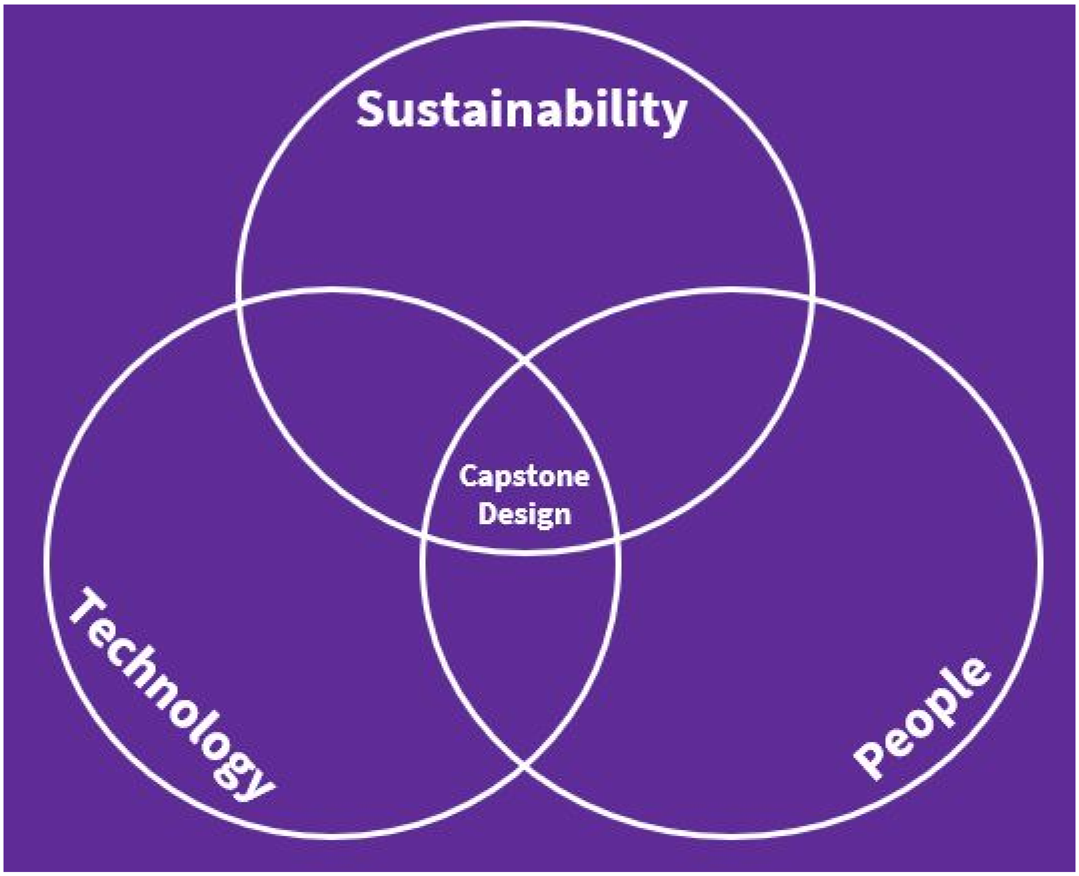

Figure 7. A venn diagram showing the connections between approaches.

Literature Review

Waste disposal has been a major societal concern for centuries. In ancient civilizations, simple drainage systems transported human feces to wide channels that emptied into large waterways. In the Middle Ages, humans discarded their waste in public streets. These feces remained until rainwater washed them into nearby waterways. After disease outbreaks caused by fecal-oral transmission, like typhoid fever, cholera, and hepatitis, humans began to develop alternative strategies to safely dispose of their waste. In the early 19th century, the first household toilet was installed. Though an improvement, these toilets were not connected to sewage systems, which caused frequent overflowing in densely populated areas. Sewage treatment plants similar to wastewater treatment facilities seen today were not developed and constructed until the late 19th and early 20th centuries (Nathanson, 2019).

At the most elementary level, modern wastewater treatment facilities remove contaminants from municipal and/or industrial wastewater streams in order to reintroduce these liquids to local bodies of water with as little environmental impact as possible. The unit operations involved in this removal process vary; however, there are three main stages of wastewater treatment: primary treatment, secondary treatment, and tertiary treatment. In primary treatment, the majority of solid materials are separated from liquids through sedimentation and filtration by grates and screens. In secondary treatment, dissolved organic matter is degraded by bacteria and other microorganisms, reducing the BOD. In tertiary treatment, pollutants and excess nutrients are removed by bacteria in order to comply with the Environmental Protection

Agency (EPA) and state standards. The two main products of this entire process include treated water and biosolids (Rudolph, 2018).

Biosolids contain both beneficial and negative compounds. The positive components include organic compounds, micronutrients (B, Cu, Fe, Mn, Mo, Zn), and macronutrients. The negative components include flocculation polymers, pathogens, heavy metals, pesticides, endocrine disruptors, polyfluoroalkyl substances (PFAS), microplastics, toxic organic compounds, detergents, salts, and nutrients in excess (Li, 2018).

Biosolids produced from the wastewater treatment process can be disposed of through landfilling, composting, land application and gasification. Some of these methods provide useful products, while others simply provide a method to dispose of the solids. If done so sustainably, the creation of useful products is more preferred, compared to disposal. Although landfilling is a cheap way to discard of biosolids, studies show landfilling biosolids is a potentially harmful, unsustainable practice. In one study, it was concluded that landfilling biosolids containing organic pharmaceutical compounds correlated to the formation of stronger pathogens in leachate (Holm et al., 1995). Thus, landfilling biosolids can help cause antibiotic resistance. Additionally, landfilling organic material releases greenhouse gases into the atmosphere. For this reason, landfills require monitoring and in some cases remediation (Rich et al., 2008). Lastly, the valuable nutrients may simply be unused in landfilling. In order to take advantage of the properties of biosolids, land application and gasification will be explored for the remainder of this report.

Since biosolids contain carbon, nitrogen, and phosphorus, land application of biosolids will affect the carbon, nitrogen, and phosphorus cycles. These processes determine the amount of available nutrients in the soil. In the carbon cycle, inorganic atmospheric carbon (carbon dioxide) is fixed by plants into organic carbon (glucose) through photosynthesis. This glucose is then converted to complex organic compounds required by the plants. Primary consumers eat these plants, before higher-level consumers eat the primary consumers. After these plants and animals die, their bodies undergo decomposition, in which carbon is returned to the soil as detritus. Detritivores consume this detritus for growth. As detritivores and consumers respire, carbon dioxide is returned into the atmosphere, where it can then be fixed again by plants. Additionally, carbon dioxide diffuses into and out of bodies of water. Unfortunately, in today's world, the combustion of wood and fossil fuels also releases carbon dioxide into the atmosphere. (The Environmental Literacy Council, 2019.). A diagram of the carbon cycle is shown below in **Figure 8.**

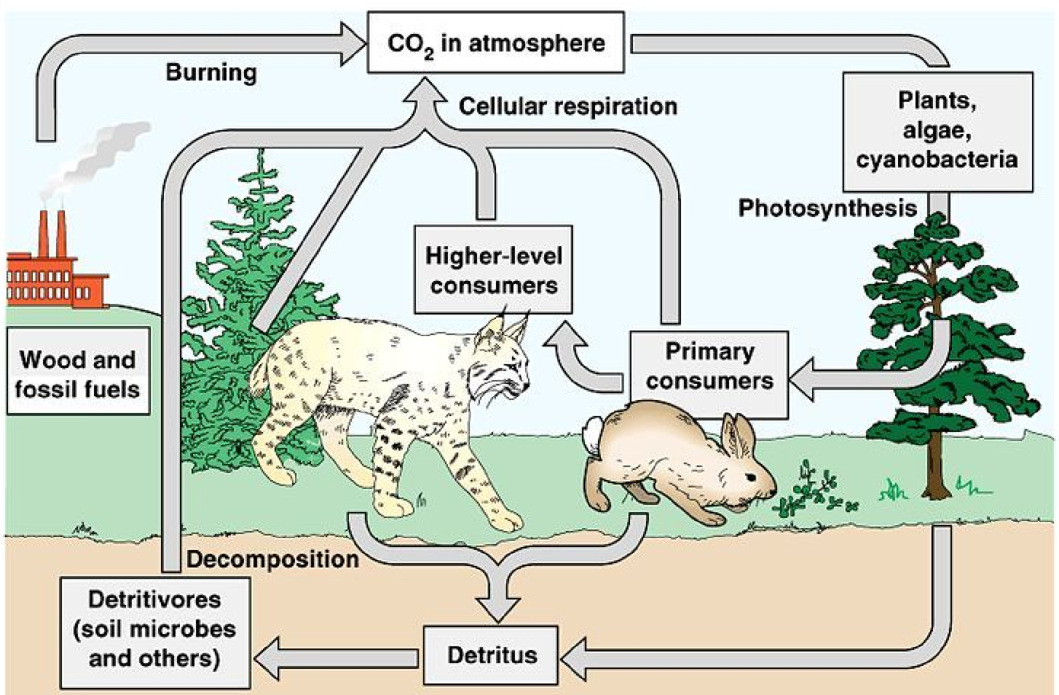

Figure 8. Carbon cycle (The Environmental Literacy Council, 2019)

The nitrogen cycle is highly dependent on microbes in the soil to convert atmospheric nitrogen into a form that vegetation can utilize. The first step of the cycle is nitrogen fixation, in which nitrogen-fixing bacteria convert atmospheric nitrogen (N_2) into ammonium (NH_4^+) and ammonia (NH_3). Nitrifying bacteria, typically *Nitrobacter* and *Nitrospira* species, then convert ammonia to nitrite (NO_2^-) and nitrate (NO_3^-). The opposite of this reaction is called assimilative reduction. Ammonium is also created by decomposers digesting plant material. These are forms of nitrogen that plants can assimilate and use. If nitrates are not uptaken by plants, they are denitrified by bacteria into atmospheric nitrogen (N_2) (Biology Dictionary, 2019). Additionally, nitrogen is added to the cycle via lightning strikes. A diagram of the nitrogen cycle is shown below in **Figure 9**.

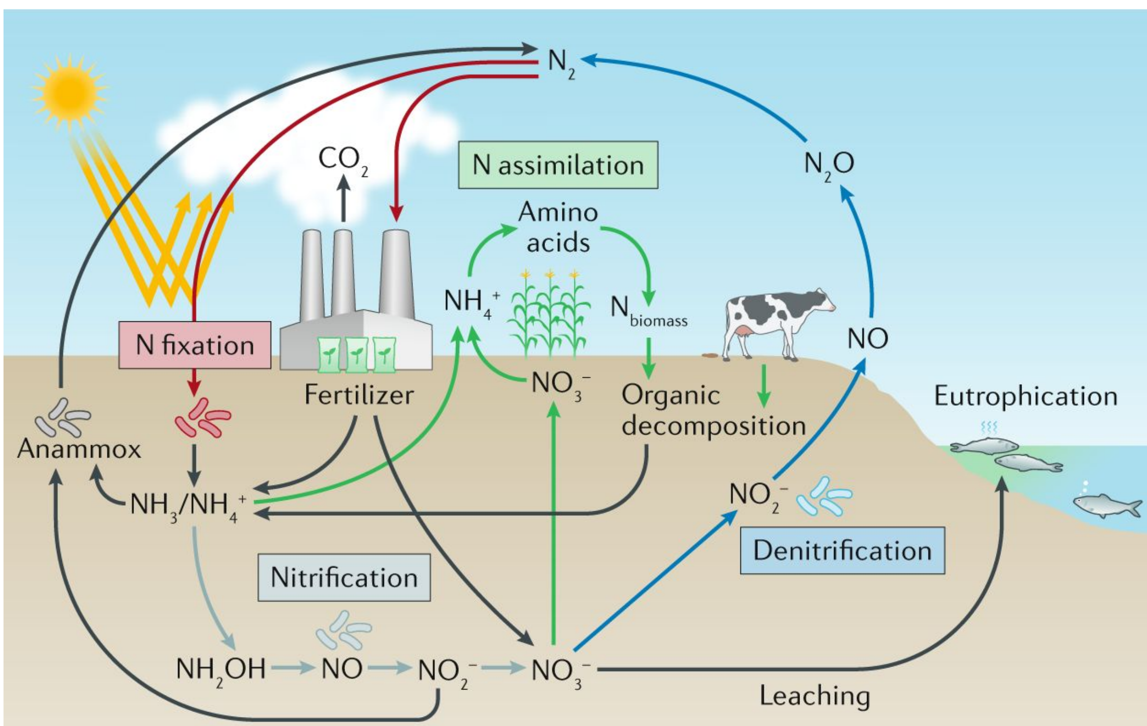

Figure 9. Nitrogen cycle (Biology Dictionary, 2019)

Another relevant nutrient process is the phosphorus cycle. Unlike other cycles, the phosphorus cycle never goes through a gaseous phase because Earth's standard temperature and pressure do not support phosphorus's phase change parameters. The phosphorus cycle begins when rain falls on weathering rocks, removing phosphorus and allowing it to enter the soil. Plants then uptake phosphorus ions from soil and are consumed by animals. Finally, animals excrete phosphorus as feces or release it when they decompose (The Environmental Literacy Council, 2019). A diagram of the phosphorus cycle is shown below in **Figure 10**.

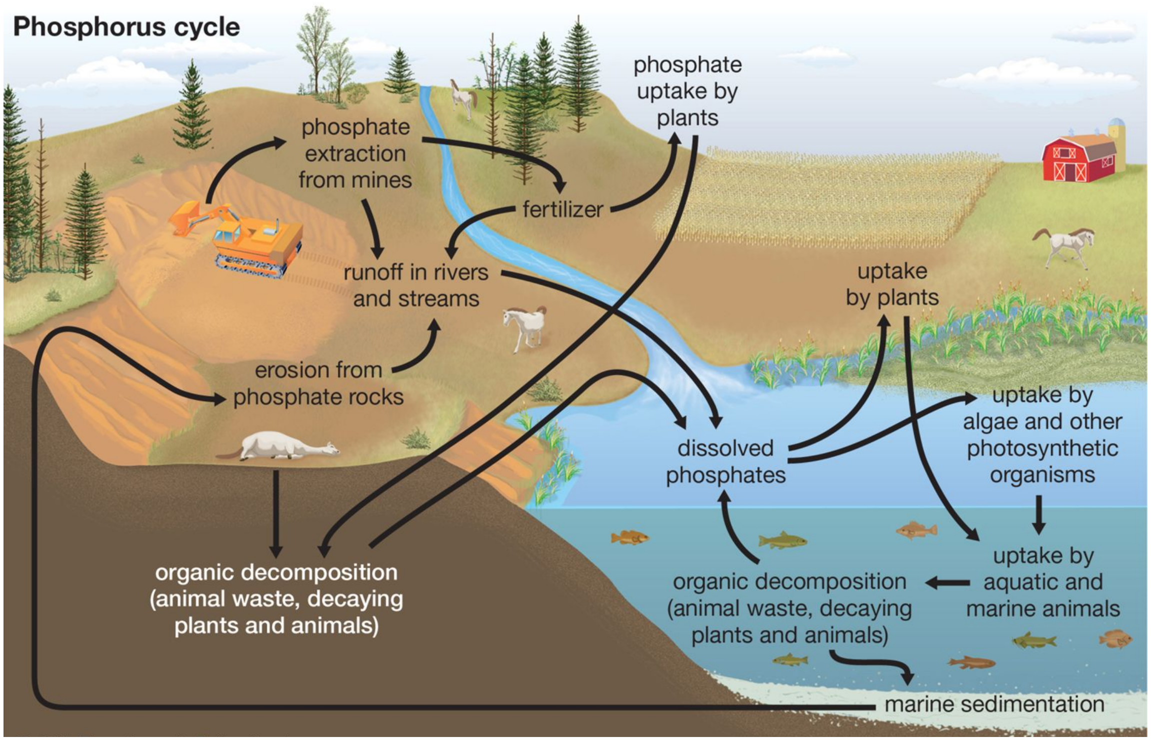

Figure 10. Phosphorus cycle (The Environmental Literacy Council, 2019)

The three nutrient cycles mentioned above are examples of closed-loop systems. In a closed loop system, elements are recycled back into their original forms. The landfilling of biosolids is an example of an open-loop system. Open-loop systems take resources such as carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and their organic compound forms out of their respective feedback loop cycles in the environment. As a result, these elements are not recycled efficiently. **Figure 11** below shows a simple schematic of an open and closed-loop feedback system.

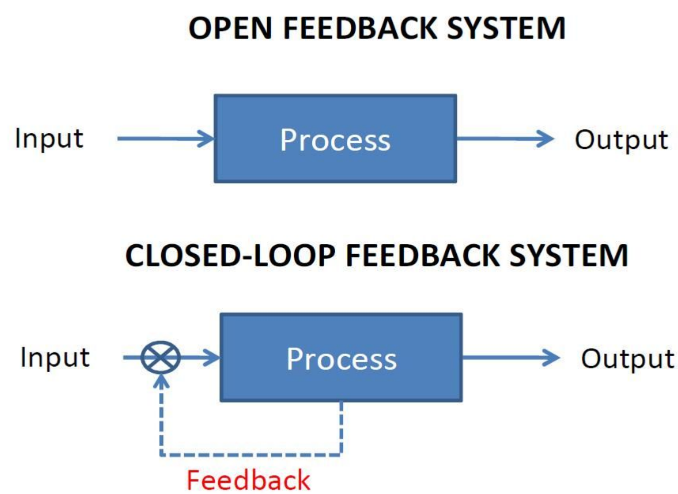

Figure 11. Open and closed feedback systems (Boettjer, 2012)

Land Application

Land application of biosolids involves the incorporation of treated biosolids into soil as fertilizer. The method of application depends on the physical state (liquid slurry or dry solid) of the biosolids. Dry solids are typically dispersed on the surface of soils with a terragator, while liquid slurries are typically injected beneath the soil surface.

The land application of biosolids can improve soil health and productivity of flora by adding essential nutrients like nitrogen and phosphorus. Adversely, biosolids can contain these nutrients in excess, as well as pollutants like heavy metals, detergents, salts, pesticides, hormone disruptors, per-polyfluoroalkyl substances (PFAS), microplastics, polymers and toxic organic compounds (Singh and Agrawal, 2008). As a result, there are strict governmental regulations that those land applying biosolids must follow.

To legally manage biosolids various permits are required. First, all wastewater treatment facilities must obtain a National Pollutant Discharge Elimination System (NPDES) permit. Elements to this permit include a complete application, contact information, copies of additional permits already obtained, regional topographical maps, human population density of the wastewater region, the facility's maximum design flow rate, a process flow diagram, and the location and flow rate of the treated effluent wastewater. To land apply biosolids, supplementary information including the location and size of the land application site, average daily volume (gallons per day) applied to each site, and whether land application is continuous or intermittent, are needed too. If an existing wastewater treatment facility wants to start land applying their biosolids a new NPDES permit is not required; the existing permit would just need to be modified (Control, 2019)

To land apply biosolids in the state of South Carolina, an additional permit is required from the South Carolina Department of Health and Environmental Control (SCDHEC). Applicants must supply SCDHEC with the following information:

- Nutrients concentration (mg/kg on a dry weight basis)
  - Total Kjeldahl nitrogen (TKN)
  - Inorganic nitrogen
  - Ammonia nitrogen
  - Phosphorus
  - Potassium
- Pollutant concentrations (mg/kg on a dry weight basis)
  - Arsenic
  - Cadmium
  - Copper
  - Lead
  - Mercury
  - Molybdenum
  - Nickle
  - Selenium
  - Zinc
- Other parameters
  - total suspended solids (TSS)
  - 5-day BOD sampling
- Effluent
  - pH
  - Temperature
  - Cyanide concentration
  - Total phenol concentration
  - Residual chlorine concentration
  - Oil and grease concentrations
  - Fecal coliform concentrations.

Various additional regulations are included in Regulation 61-9: Water Pollution Control Limits (Control, 2019). The following restrictions apply:

- Biosolids cannot be applied to land if their presence would negatively affect threatened or endangered species under section 4 of the Endangered Species Act
- Biosolids cannot be applied to lands where they would runoff into a wetland or other waters of SC
- Biosolids cannot be applied to lands within 10 meters of a body of water of SC
- Biosolids applied to agricultural fields must be applied at a rate less than or equal to the agronomic rate of the nutrients found in the biosolids and agricultural fields

The agronomic rate is the amount of biosolids that can be applied per acre of land and the frequency at which these biosolids can be applied. These rates are determined by the EPA and SCDHEC based on the nitrogen requirements of the crop(s) grown on the land.

Table 4 below lists the maximum allowable heavy metal concentration of land applied biosolids.

Table 4. Ceiling concentrations of heavy metals in land applied biosolids (Control, 2019)

Pollutant	Ceiling Concentration (mg/kg) Dry Weight Basis
Arsenic	75
Cadmium	85
Copper	4,300
Lead	840
Mercury	57
Molybdenum	75
Nickel	420
Selenium	100
Zinc	7,500

Biosolids with pollutant concentrations greater than their corresponding ceiling concentrations will be denied a permit for land application (Control, 2019).

Additionally, since heavy metals can be toxic in high concentrations, the presence of these pollutants must also be monitored. The metal application rates are shown below in **Table 5** (Walker et al., 1994).

Table 5. Annual pollutant loading rates

Metal	Sewage Sludge Concentrations (milligrams/kilogram)	APLR* (kilograms/hectare/year)	ASWAR** (Metric tons/hectare/year)
Arsenic	10	2.0	200
Cadmium	10	1.9	190
Chromium	1,000	150	150
Copper	3,750	75	20
Lead	150	15	100
Mercury	2	0.85	425
Molybdenum	-	-	-
Nickel	100	21	210
Selenium	15	5	333
Zinc	2,000	14	70

*Annual pollutant loading rate
**Annual whole sludge application rate

The land application of biosolids is beneficial to soil health. Not only do biosolids contain the beneficial nutrients mentioned above, but biosolids increase the micro and macroporosity of the soil. This increase in porosity directly increases the infiltration rate and water-holding capacity of the soil. Increases in water infiltration rate lead to decreases in the amount of runoff and soil erosion during a rainfall event (Larney and Angers, 2012). Biosolids are commonly applied to agricultural lands, forests, disturbed lands, reclamation sites, recreational sites, home lawns, and gardens (Vanatta & Slingsby, 2003).

Fertilizers derived from organic matter are preferred to synthetic fertilizers. Biosolids are rich in readily available forms of nitrogen, phosphorus, and ammonia. Synthetic additives contain slow-release forms of nitrogen which need to be processed by bacteria in order to be uptaken by plants. This leads to large amounts of nitrogen runoff, which can cause eutrophication in bodies of water, shown in **Figure 12**.

Figure 12. Eutrophication due to excess nutrient runoff (NOAA, 2019)

Phosphorus, when derived from inorganic substances, can be immobilized due to high levels of calcium carbonate in the topsoil (Larney and Angers, 2012).

Land application of biosolids also improves the soil biota in application sites by increasing enzymatic activities and overall soil biodiversity. Several studies have shown that amending soil with animal manure results in an increase in earthworm abundance. This is due to the readily available carbon added to the soil (Larney and Angers, 2012). In terms of enzyme activity, it has been found that after the addition of biosolids there is a two to fourfold increase in activity (Martens et al., 1992). Enzymes function as both free and microbial associated processes acting as indicators of soil health due to their effects on nutrient cycling through biological catabolism and other processes (Das and Varma, 2010). In regards to soil monitoring, enzyme activity reacts quicker to environmental changes and should be considered as an indicator for land application parameters.

As mentioned before, biosolids can contain various harmful compounds. Thus, the land application of biosolids can have adverse effects on the environment. Some highlighted contaminants include pharmaceuticals from house wastewater streams, bioaerosols formed during land application, and microplastics from home, industrial, and storm runoff. Fortunately, processes such as ozonation and carbon filters have been developed in order to reduce the concentration of these contaminants (Bienkowski, 2013).

When biosolids are flocculated, any pharmaceuticals present settle within the solids. If land applied, these pollutants could be toxic. When studied, it was found that of eight major pharmaceuticals, only triclosan posed significant toxicological risk (Edwards et al., 2009). In a separate study, the concentrations of twenty-two pharmaceutically active compounds were tested in sludge produced from aerobic digestion, anaerobic digestion, composting, and lagooning. Of these methods, anaerobic digestion was the most effective at reducing the concentration of pharmaceuticals, reducing the average concentration of the studied compounds from 142 μg/kg to 8 μg/kg. Aerobic digestion reduced the average concentration of the studied compounds from 142 μg/kg to 70 μg/kg. Additionally, the researchers calculated the risk quotients (the ratio between predicted environmental concentration and predicted non-effect concentration) for biosolids application onto soils. These ratios were less than one for all pharmaceutically active compounds. Taking this into account, the scientists concluded that the application of biosolids containing pharmaceuticals is not expected to pose significant risks (Martín et al., 2015).

Although this article comes to this conclusion, further research should be conducted on the impact of pharmaceuticals in biosolids that are regularly land applied.

Bioaerosols are defined as particulate matter of microbial, plant, or animal origin often used synonymously with organic dust. Bioaerosols are extremely toxic to humans and can cause infectious diseases, respiratory disease, and cancer (Douwes et al., 2003). It was found that for one kilogram of applied biosolids, an estimated 7.6 ± 6.3 mg of bioaerosols were formed (Paez-Rubio et al., 2007). Bioaerosols are commonly formed from very dry forms of biosolids and can lead to disease by airborne pathogens (Vanatta & Slingsby, 2003). Although there is currently no regulated exposure limit for bioaerosols, and the exposure limits for human harm are currently unknown, this small amount of bioaerosols would not be expected to be detrimental to humans (Douwes et al., 2003).

Microplastics are another component of biosolids that can have negative environmental impacts. Defined as plastics smaller than five millimeters in diameter, microplastics are believed to be carcinogenic (Murphy et al., 2016). These compounds have toxic properties if broken into their respective monomers. Additionally, these materials could easily transport pathogens and heavy metals via adhesion. For an average sample of municipal wastewater, 1.60 - 56.4 x 10^3 microplastic particles per kilogram of biosolids were found. As the world's consumption of plastic continues to increase, this concentration of microplastics is expected to increase. Further research is needed to design a more efficient process for removing microplastics from the products of a wastewater treatment facility (Li et al., 2018).

The EPA and SCDHEC have stringent microbial activity restrictions. Subpart D of part 503 of the Clean Water Act mandates guidelines concerning pathogen control and vector attraction in biosolids for the following groups: owners and operations of domestic sewage treatment, developers or marketers of sewage sludge treatment processes, groups that distribute and market biosolid products, individuals involved in applying biosolids to land, government officials responsible for implementing and enforcing this regulation, and consultants to these groups. This regulation not only guides public health and environmental impact design, but also outlines the requirements needed to reduce potential human contact with pathogenic microorganisms present in the biosolids. These regulations help increase livestock health and decrease the transportation of pathogens by organisms or through weathering (Vanatta & Slingsby, 2003).

Pathogens in sewage sludge and biosolids, mostly concentrated in insoluble suspended solids, are classified as either bacteria, enteric viruses, protozoa, and/or viable helminth ova. Many strains of pathogenic species are present in human solid waste and wastewater; however, the process of monitoring pathogens focuses on the quantification of fecal coliform bacteria. The four indicator species according to the Clean Water Act include fecal coliforms, *Salmonella* species, enteric viruses, and viable helminth ova. These microorganisms are shown below in **Figure 13**, **Figure 14**, **Figure 15**, and **Figure 16**, respectively.

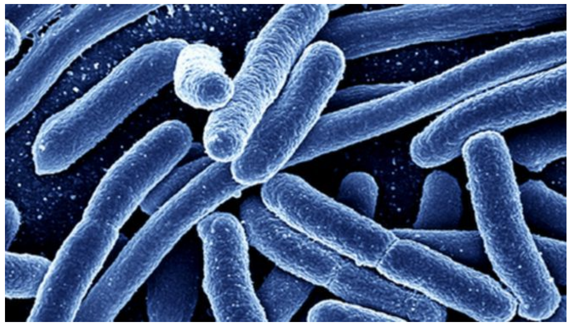

Figure 13. Fecal coliform, *E. coli* (Mundasad, 2011)

Figure 14. *Salmonella* species (European Food Safety Authority, 2017)

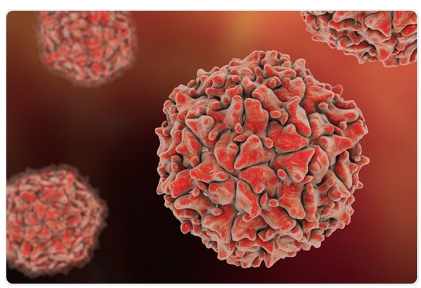

Figure 15. Enteric virus, *Poliovirus* species (Shaffer, 2019)

Figure 16. Viable helminth ova, *Ascaris lumbricoides* (Fletcher, 2018)

In reference to pathogen concentrations, biosolids are typically classified as either Class A or Class B. Class A biosolids contain pathogen counts below detectable limits, while Class B biosolids contain a maximum of 1 to 2 million Most Probable Number (MPN) per 4 grams per dry weight, or 100 mL per wet weight basis, of fecal coliforms. Class A biosolids can be land applied; however, they are restricted by the nutrient concentrations already present in the application site(s). Thus, nutrient concentration testing must be performed to ensure the addition of biosolids does not cause excess nutrient buildup. Class B biosolids can be land applied once one of the following requirements is met: monitoring of indicator organisms, usage of a process to significantly reduce pathogens (PSRP), or the usage of processes equivalent to PSRPs approved by the Pathogen Equivalency Committee (PEC). Monitoring of fecal coliform requires seven samples of treated biosolids to be collected and tested. The results of these tests must confirm that there are less than 2 million MPN or Colony Forming Units (CFUs) per gram of biosolids on a dry weight basis. Monitoring is also used as a contingency plan if temperature and time requirements cannot be met by the specified design treatment plant processes implemented. The second option to meet Class B standards, the usage of a PSRP, must result in a 2-log reduction in fecal coliform density. Alternatives to meet Class A requirements are listed in **Table 6** while the alternatives to meet Class B are shown in **Table 7.**The processes and parameters of acceptable PSRPs are shown below in **Table 8** (Vanatta & Slingsby, 2003). Currently, the CU WWTP utilizes aerobic digestion.

Table 6: Class A alternative methods

Class A Alternatives	
Alternative 1: Thermally Treated Sewage Sludge	Use one of four time-temperature regimes
Alternative 2: Sewage Sludge Treated in a high pH- High Temperature Process	Specifies pH, temperature, and air-drying requirements
Alternative 3: For Sewage Sludge Treated in Other Processes	Demonstrate that the process can reduce enteric viruses and viable helminth ova. Maintain operating conditions used in the demonstration.
Alternative 4: Sewage Sludge Treatment in Unknown Processes	Demonstration of the process is unnecessary. Instead, test for pathogens - *Salmonella* sp, bacteria, enteric viruses, and viable helminth ova - at the time the sewage sludge is used or disposed, or is prepared for sale or give-away in a bag or other container for application to the land, or when prepared to meet the requirements in 503.10(b), (c), (e), or (f)
Alternative 5: Use of PFRP	Sewage sludge is treated in one of the processes to further reduce pathogens (PFRP)
Alternative 6: Use of a Process Equivalent to PFRP	Sewage sludge is treated in a process equivalent to one of the PFRPs, as determined by the permitting authority

Table 7: Class B Alternative methods

Class B Alternatives	
Alternative 1: Monitoring of Indicator Organisms	Test for fecal coliform density as an indicator for all pathogens at the time of sewage sludge use or disposal
Alternative 2: Use of PSRP	Sewage sludge is treated in one of the process to significantly reduce pathogens (PSRP)
Alternative 3: Use of Process Equivalent to a PSRP	Sewage sludge is treated in a process equivalent to one of the PSRPs, as determined by the permitting authority Note: Details of each alternative for meeting the requirements for Class A and Class B designations are provided in Section 3.4

Table 8. PSRPs Listed in Part 503 of the CWA

Process	Specifications
Aerobic Digestion	Sewage sludge is agitated with air or oxygen to maintain aerobic conditions for a specific mean cell residence time (i.e., solids retention time) at a specific temperature. Value for the mean cell between 40 days to 20°C (68°F) and 60 days at 15°C (59°F).
Air Drying	Sewage sludge is dried on sand beds or on paved or unpaved basins. The sewage sludge dries for a minimum of 3 months. During 2 of the 3 months, the ambient average daily temperature is above 0°C (32°F)
Anaerobic Digestion	Sewage sludge is treated in the absence of air for a specific mean cell residence time (i.e., solids retention time) at a specific temperature. Values for the mean cell residence time and temperature shall be between 15 days at 35°C to 55°C (131°F) and 60 days at 20°C (68°F).
Composting	Using either the within-vessel, static aerated pile, or window composting methods, the temperature of the sewage sludge is raised to 40°C (104°C) or higher for 5 days. For 4 hours during the 5 day period, the temperature in the compost pile exceeds 55°C (131°F)
Lime Stabilization	Sufficient lime is added to the sewage sludge to raise the pH of the sewage sludge to 12 for ≥ 2 hours of contact

As previously mentioned, the third option to meet Class B standards is the usage of processes equivalent to PSRPs approved by the PEC. Various specific processes are outlined in **Table 9** below (Stein et al., 1995).

Table 9. PFRPs Listed in Part 503 of the CWA

Process	Specifications
Composting	Within-vessel composting or static aerated pile: temperature of sludge maintained at 55°C or higher for 3 days Windrow: temperature of sludge maintained at 55°C or higher for at least 15 days with a minimum of 5 turnings of each windrow
Heat Drying	Sludge dried by direct or indirect contact with hot gases to reduce moisture content to a maximum of 10%. Either temperature of sludge exceeds 80°C or wet bulk temperature of the gas in contact with the sludge as the sludge leaves the dryer exceeds 80°C
Heat Treatment	Liquid sludge heated to 180°C for a minimum of 30 min.
Thermophilic Aerobic Digestion	Liquid sludge agitated with air or oxygen to maintain aerobic conditions. Mean cell residence time of sludge is 10 days at 55°C - 60°C
Beta Ray Irradiation	Sludge irradiated with beta rays from electron accelerator at dosages of at least 1.0 megarad at room temperature
Gamma Ray Irradiation	Sludge irradiated with gamma rays from certain isotopes, like Cobalt 65 or Cesium 137, at dosages of at least 1.0 megarad at room temperature
Pasteurization	Temperature of sludge maintained at 70°C or higher for at least 30 min.

If common PSRP and PFRP methods are not utilized, equivalent PSRPs and PFRPs are an additional option for pathogen reduction. These methods require extensive testing before the PEC can determine if they successfully reduce the fecal coliform counts. **Figure 17** below outlines the design process (Vanatta & Slingsby, 2003).

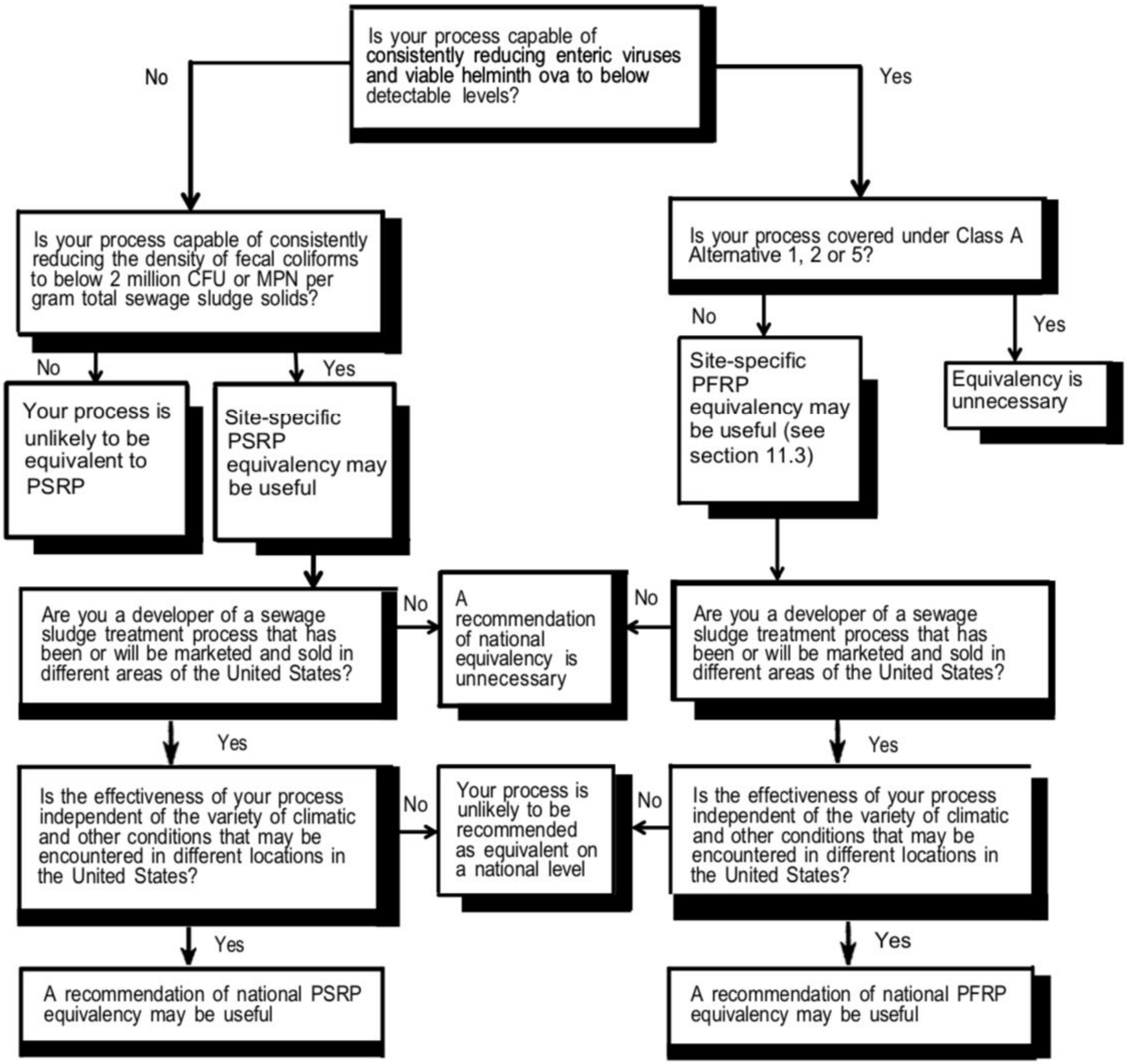

Figure 17. Design process for alternative PSRPs and PFRPs (Vanatta & Slingsby, 2003)

The PEC reviews the design and decides is the process is acceptable or not. Class B preventative guidelines include treating sewage sludge to discourage attraction, putting barriers between applied biosolids and vectors, using liquid application to decrease bioaerosols, and environmentally conscious site application.

For food crops grown on land fertilized by biosolids, there are three components that lead to exposure: pathogens applied to land, pathogens transferred from crops to the crops, and ingestion of crops before pathogen concentrations are reduced. Of the three components, only one needs to be eliminated to meet EPA standards. To eliminate pathogens, the pH, temperature, or an additional parameter should be altered to a level that cause pathogen death. Biosolids being land applied to crop fields require a specific set of parameters to ensure human and environmental safety. These crop-applied biosolids should follow the following processes below in **Figure 18**.

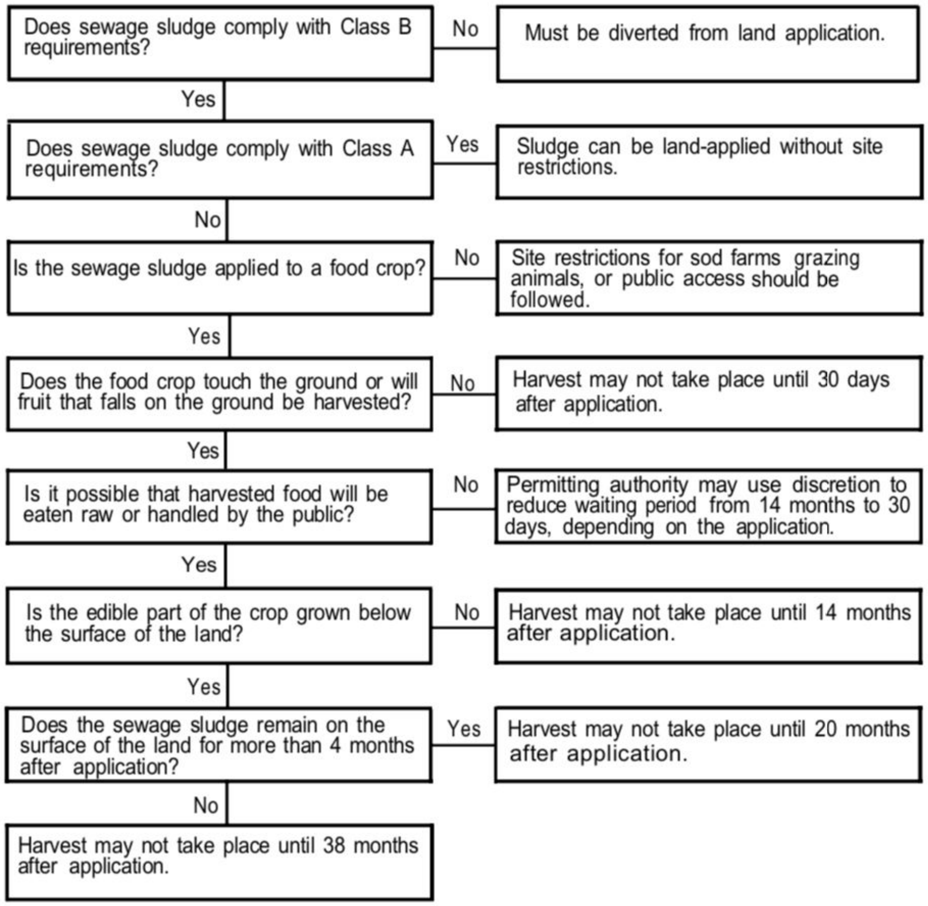

Figure 18. Flow diagram for harvesting and site restrictions (Vanatta & Slingsby, 2003)

Biosolids applied to crops that fail to undergo these processes are not eligible for land application to crop fields and must be disposed of by other means (Vanatta & Slingsby, 2003). Important highlights from **Figure 18** include animal grazing is not permitted for 30 days after application, turf harvesting cannot be harvested for 1 year after application, and public access is denied for 1 year on land applied fields.

Reducing the chance of transporting pathogens is essential. Conventional vector attraction reduction methods can be found below in **Table 10**.

Table 10. Vector attraction reduction processes options (Vanatta & Slingsby, 2003)

Option	Requirements
1	Minimum 38% reduction in volatile solids
2	Less than 17% additional volatile solids loss during bench-scale anaerobic batch digestion of sewage sludge for 40 additional days at 30℃ to 37℃
3	Less than 15% additional volatile solids reduction during bench-scale aerobic digestion for 30 additional days at 20℃
4	Standard Oxygen Uptake Rate (SOUR) at 20℃ is ≤ 1.5 mg oxygen/hr/g total sewage sludge solids
5	Aerobic treatment of sludge for at least 14 days with temperature greater than 40 °C and average temperature greater than 45℃
6	Addition of alkali to raise pH to minimum 12 at 25℃ and maintain pH ≥ 12 for 2 hours and pH ≥ 11.5 for 22 more hours
7	Percent solids ≥ 75% prior to mixing with other materials
8	Percent solids ≥ 90% prior to mixing with other materials
9	Sludge injected into soil so that no significant amount of sewage sludge is present on land surface 1 hour after injection, except Class A sludge which must be injected within 8 hours after pathogen reduction process
10	Sludge incorporated into soil within 6 hours after land application, except Class A sludge which must be land applied within 8 hours after the pathogen reduction process
11	pH raised to ≥ 12 at 25℃ by alkali addition and maintained ≥ 12 for 30 minutes without adding more alkali

These preventative strategies help decrease potential pathogen transportation that may occur from grazing, precipitation, rodents, insects, bioaerosols, and foot traffic (Vanatta & Slingsby, 2003).

Gasification

Stored potential energy derived from solar radiation, infrared radiation, and visible light can power processes like photosynthesis and the production of fossil fuels. Additionally, other sources of energy including wind, hydroelectric, and nuclear are commonly used to generate heat and electricity. While heat is generally limited in its uses, electricity is much more versatile in its application. The breakdown of electricity sources generated in 2015 in the United States can be seen below in **Figure 19**.

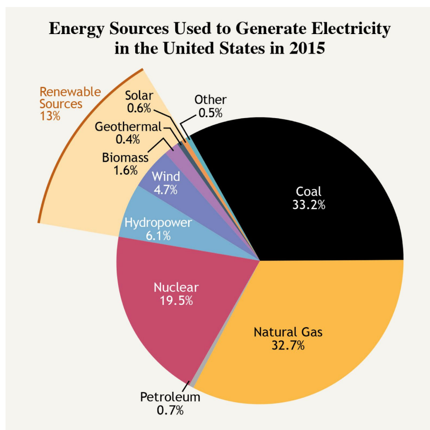

Figure 19. **Energy consumption of America** (The National Academies, 2019)

According to **Figure 19**, biomass only accounted for 1.6% of the electricity produced. (The National Academies, 2019). Although it is commonly viewed as a low value waste product, biomass still contains stored potential energy. Gasification is a process capable of converting this energy into valuable gases that can be oxidized to generate electricity.

Gasification is the burning of solid biomass without enough oxygen to allow complete combustion. This creates a gas, known as producer gas, capable of being combusted after the gasification process. There are five general steps in the gasification process: drying, pyrolysis, cracking, combustion, and reduction. Drying usually occurs between 100°C and 150°C. Pyrolysis, heating in the absence of oxygen, occurs at a temperature between 200°C and 500°C. As a result, the feedstock is converted to biochar and tar gas. Biochar is a carbon rich solid, while tar gases contain a mixture of gases and liquid fragments from the feedstock. Cracking and combustion then occur together at a temperature between 800°C and 1200°C. Cracking is the breakdown of hydrocarbons into smaller alkanes and alkenes through high heat radicalization. In the cracking process the tars are broken into H_2O, H_2, CO_2, CO, and impurities. Combustion is the production of CO_2, CO, and H_2O from the oxidation and reduction of tar gases and biochar. This reaction occurs in the presence of oxygen. Reduction, the final process of gasification, occurs between 650°C and 900°C. The reduction step further removes carbon atoms from the biochar, enabling more producer gas to form. As the biochar and tar gas are degraded, any impurities, namely heavy metals, are removed. These impurities are collectively called ash. After an initial input of external energy, the heat released from the combustion step is capable of driving the entire gasification process (ALL Power Labs, 2019). A general process flow diagram of the gasification process can be seen below in **Figure 20**.

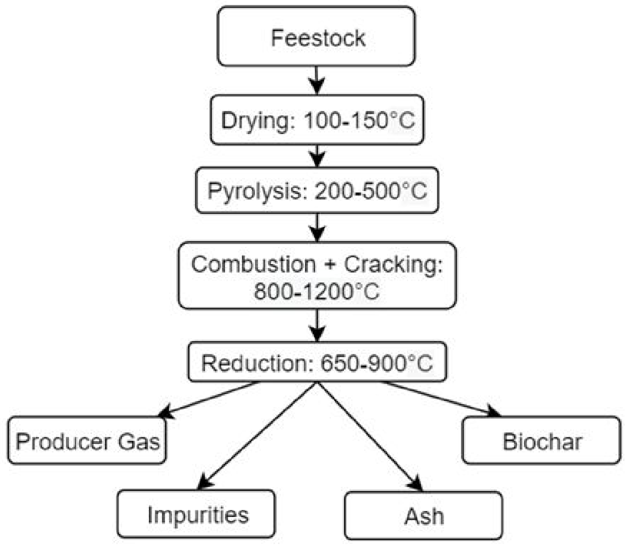

Figure 20. Gasification Process

The products of gasification include producer gases, impurities, biochar and ash. A more detailed diagram of the inputs and outputs for each step in the gasification process can be seen in **Figure 21.**

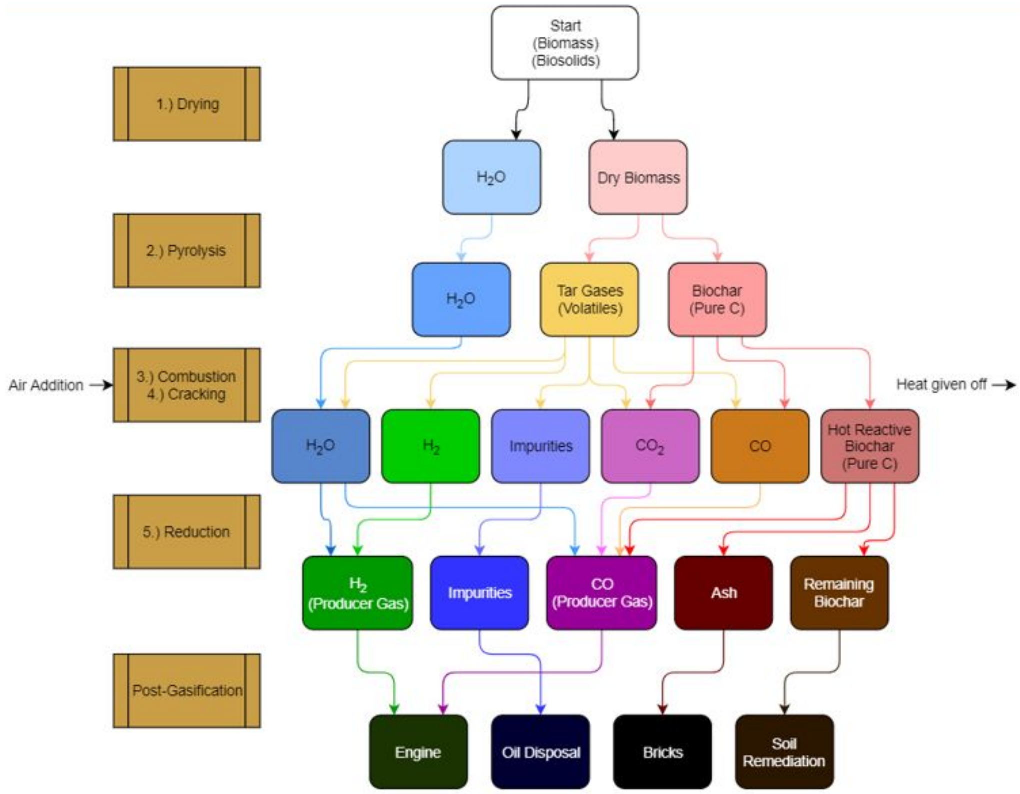

Figure 21. Flow diagram of the gasification process

When the carbon dioxide and water flow over the high heat biochar in the reduction step, carbon monoxide and hydrogen gas are formed. **Figure 22** below exemplifies these reactions.

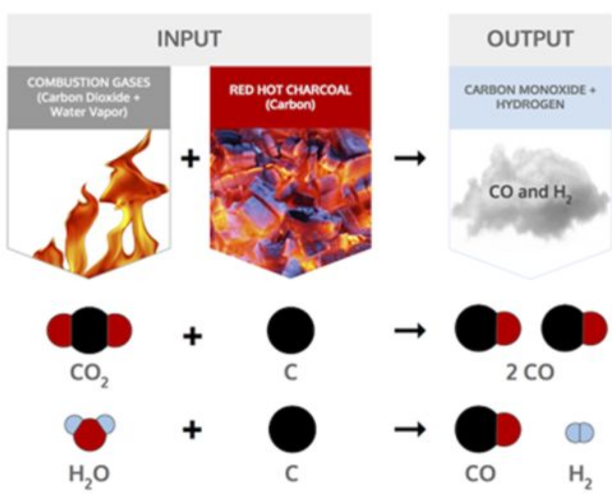

Figure 22. Reduction Step in Gasification

Producer gas is the main desired product of the gasification process. There are various words synonymous with producer gas including wood gas, syngas, town gas, generator gas, and biogas. Several of these terms have processes unrelated to the current project. For this reason, producer gas will be used in this report to describe the product gases (ALL Power Labs, 2019). The producer gas is typically a mix of CO, H_2, N_2, and CO_2 with respective percent compositions of: 29%, 10.5%, 55%, 5.5%. These percentages depend on the temperature of the gasification process and the gasification agent, usually oxygen or mixed air, (Adhikari et al., 2017). For biosolids in a downdraft gasifier, the following percentages have been obtained for H_2, CO, CH_4, C_2H_2, and C_2H_6: 10.48%, 8.66%, 1.58%, 0.72%, and 0.20%, respectively (Midilli, 2000). In another study utilizing a downdraft gasification system investigating ranges of moisture content in biosolids and its effects on producer gas production, H_2, CO, CH_4, and C_mH_n were found to be 18.12%, 15.44%, 9.2%, and 0.5% respectively (Xie et al., 2010). This process resembled the same parameters and characteristics of the Clemson University downdraft gasifier and needed moisture content. Moisture content affects multiple processes of gasification regulating the producer gas, biochar, and ash percentage. In downdraft gasification, a water content close to 20% yielded the highest producer gas and lowest char and ash content. Compared to higher moisture content, 20% moisture produced less CO_2 and ash and more H_2, CO, CH_4, C_mH_n and biochar. This is due to there being a greater opportunity for H_2O and CO_2 to contact with the biochar favoring CO and H_2 production. With a lower ash content more biochar is available to be utilized increased producer gas concentrations (Xie et al., 2010).

The producer gas formed from gasification is a renewable fuel and burns efficiently (Choudhury et al., 2015). The oxidation of produced gases can create electricity via internal combustion engines, diesel engines, dual fuel engines, and combined heat and power systems (Benedetti et al., 2018; Choudhury et al., 2015). Producer gas contains significant amounts of impurities; therefore, a filtration unit operation must be incorporated to remove such contaminates (Adhikari, Abdoulmoumine, Nam, & Oyedeji, 2017). These contaminants, which include aromatics and fine particulates that can negatively affect the respiratory system and have been found to be carcinogenic. Aromatics include tar, sulfur nitrogen compounds, hydrogen halides, and trace metals. Such compounds must be removed from the producer gas to increase output and quality. The impurities will also have deleterious effects and catalysts in downstream energy utilization processes, specifically in large scale processes (Adhikari et al., 2017). Additionally, it is important to notice that producer gas contains a very high nitrogen content, which currently cannot be eliminated at an economically justifiable cost (Adhikari et al., 2017). Inert gases like N_2 and fully oxidized gases such as H_2O and CO_2 cannot be used as an energy source and are considered impurities. They make up a wide range of the effluent producer gas and vary in percentage depending on the gasification system.

The two remaining products of gasification, biochar and ash, are commonly considered waste outputs. Although biochar is degraded throughout the gasification process, no gasifier is capable of completely eliminating this material. As such, there is a small amount of biochar present at the end of the gasification process. Biochar is defined as solid carbon-based material. Biochar is put into two classifications: low-heat and high-heat. Low heat biochar has large pore sizes, while high heat biochar has very small pore sizes. The classifications of biochar and ash depend on the temperature and type of gasifier used. Fly ash is a residue containing the leftover minerals and heavy metals of the gasification process. Such producer gas leftovers include calcium, potassium, palladium, and iron. This ash is commonly cycloned out to increase the purity of producer gas. Ash can also be in the form of powder which exists through the bottom of the pyrolysis chamber. In order to increase the sustainability of the overall gasification process, utilization pathways of biochar and ash must be considered.

Roughly 5 to 10% of the initial mass of the feedstock ends up as the remaining biochar. This co-product can be utilized in a variety of processes including combustion, adsorption, catalyst preparation, tar cracking, and soil fertilization. Additionally, this material could be used as an activated carbon substitute in pharmaceuticals and herbicides and an ingredient for adsorbates.

Research has shown low-heat biochar to have a large surface area and micro and mesopore distribution (Benedetti et al., 2018). This makes low-heat biochar useful for soil remediation, bioseparations, reactor modeling, enzyme kinetics, and biopharmaceutical production. High-heat biochar has a much smaller pore size. This makes high-heat biochar a great remediative carbon source for soil for long retention times. Due to small pore sizes, biosolid contaminants like PFAS can be adsorbed by high-heat biochar (Ahrens et al., 2019).

Ash, the inorganic solids impurities, primarily consists of silica, aluminum, iron, potassium, phosphorous and alkali earth metals. These products are typically landfilled due to high heavy metal concentrations; however, ash from woody or plant biomass has the potential for soil amendment applications (Demeyer et al., 2001). Additionally, ash can be used to increase the compressive strength of clay bricks (Lin and Weng, 2001). Brick or mortar applications should be considered and further researched as a viable pathway for this waste product. In a study considering the efficiency and uses of biochar, a downdraft gasifier produced biochar with

50% ash content, while a different downdraft gasifier produced biochar with only 9% ash content. The researchers of this study did not know why two gasifiers with the same parameters and feedstocks produced such different results. The study stressed that more research is needed due to the inconsistency of results in ash production (Benedetti et al., 2018). Inconsistency in product formation provides difficulty in modeling and process design of gasification, especially economic analysis.

There are several types of gasifiers; however, Clemson University currently has an unused downdraft gasifier. Depending on the feedstock used, downdraft gasifiers can be carbon-negative systems. One of the critical issues with downdraft gasifiers is the high temperature of the effluent producer gas. As this hot gas leaves the gasifier, heat is lost, making the system thermally unfavorable. This waste heat could be captured to dry the feedstock with a heat exchanger. For this reason, known nutrient compositions and steady feedstock supply are desired for downdraft gasifiers (Choudhury et al., 2015). The gasification agent forms producer and impurities with the gasified feedstocks. This process changes significantly as the ratio of oxygen and moisture content to feedstock changes from combustion to gasification conditions. The tar gas formed during devolatilization is thermally cracked and makes up a low percentage of 0.1% in the effluent gas (Benedetti, Patuzzi, & Baratieri, 2018). This is due to condensation of tar gas over the shaft of engine (Choudhury et al., 2015). This benefit makes downdraft gasifiers preferable for internal combustion gas engines and turbines. **Figure 23** below shows a downdraft gasifier design.

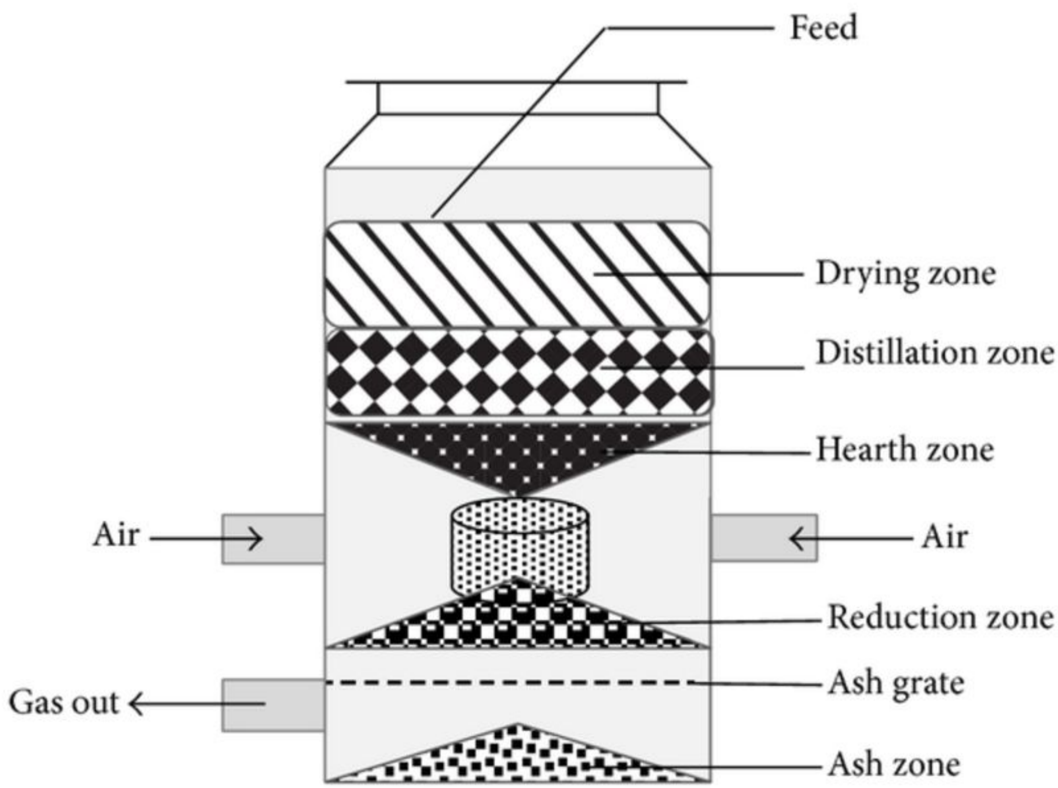

Figure 23. Downdraft gasifier diagram (ChoudhuryAnukam et al., 2014)

In order to identify the volume of the processed biosolids that can be processed by the gasification system, the densities of several different compounds, shown in **Table 11**, were necessary.

Table 11. Density of useful materials

Compound	**Density (ρ) [lb/ft^3]**	**Reference**
Water	62.15	Elliot and Lira, 2012
Biosolid	45.01	AVCalc LLC., 2019
Wood Chip	23.72	McDonald and Donaldson, 2001

In gasification it is important to utilize a normalized feedstock for efficient producer gas production and system optimization. Pelletization is the process of turning biomass into regularly shaped, dense solid pellets. Cylindrical pellets are shown below in **Figure 24**.

Figure 24. Cylindrical pellets (Gemco Energy, 2019)

Due to the ease of storage and biomass handling, pelletization has become a popular operation for different bioprocessing systems like gasification and composting. The general pellet manufacturing process consists of material pretreatment, pelletization, and post-treatment. In pretreatment, a proper feedstock must be selected and filtered. For the California Pellet Mill CL Type 3 pelletizer, which Clemson University currently owns, the moisture content must be reduced to 8-15% moisture, on a wet weight basis (California Pellet Mill Co., 2013).

The low water content and consistent sized feedstock, allows for a greater efficiency of pellet production and formation. In the pelletization process, the material is compressed against a heated perforated metal plate, otherwise known as a die (Zafar, 2019). At high pressure, a roller presses the feedstock through the perforations. As a result, temperature increases from frictional forces, enabling lignin and protein resins to act as binding agents. Generally, pelletization requires a minimum concentration of 15% lignin content to form a cylindrical shape (Abedi and

Dalai, 2017). Some materials have more binding agents, but for materials that do not contain lignin or resins, a binding agent is required. The type and concentration of binding agent is determined from the concentrations of cellulose, hemicellulose, lignin, and inorganic compounds in the feedstock. Before storage, the produced pellets should be cooled and dried. In storage, the pellets should be protected from moisture and pollutants (Zafar, 2019).

Pelletization can efficiently standardize the shape of biosolids. These biosolid pellets can be utilized as a gasification feedstock. To be pelletized, biosolids usually require a feedstock mixture to increase the lignin content to a minimum 15%. At 5-11% moisture content per wet weight basis, biosolids are roughly 10% lignin (Rukayya, 2017). In order to increase the biosolids to the desired lignin content, wood chips are a useful biomass additive. Wood chips are considered to have a moisture content of 50-60% and a lignin content of 20-30% (McDonald 2001).

Materials and Methods

Drying and Dewatering

For the dewatering and drying of the biosolids, prior to land application or gasification, a polyacrylamide-free flocculant (PAMf-FCC) and the HUBER Sludge Turner SOLSTICE solar dryer, shown below in **Figure 25** and **Figure 26**, respectively, would be needed.

Figure 25. Starch polymer (I) and PAMf-FCC starch polymer (II) (FaBuer, 2019)

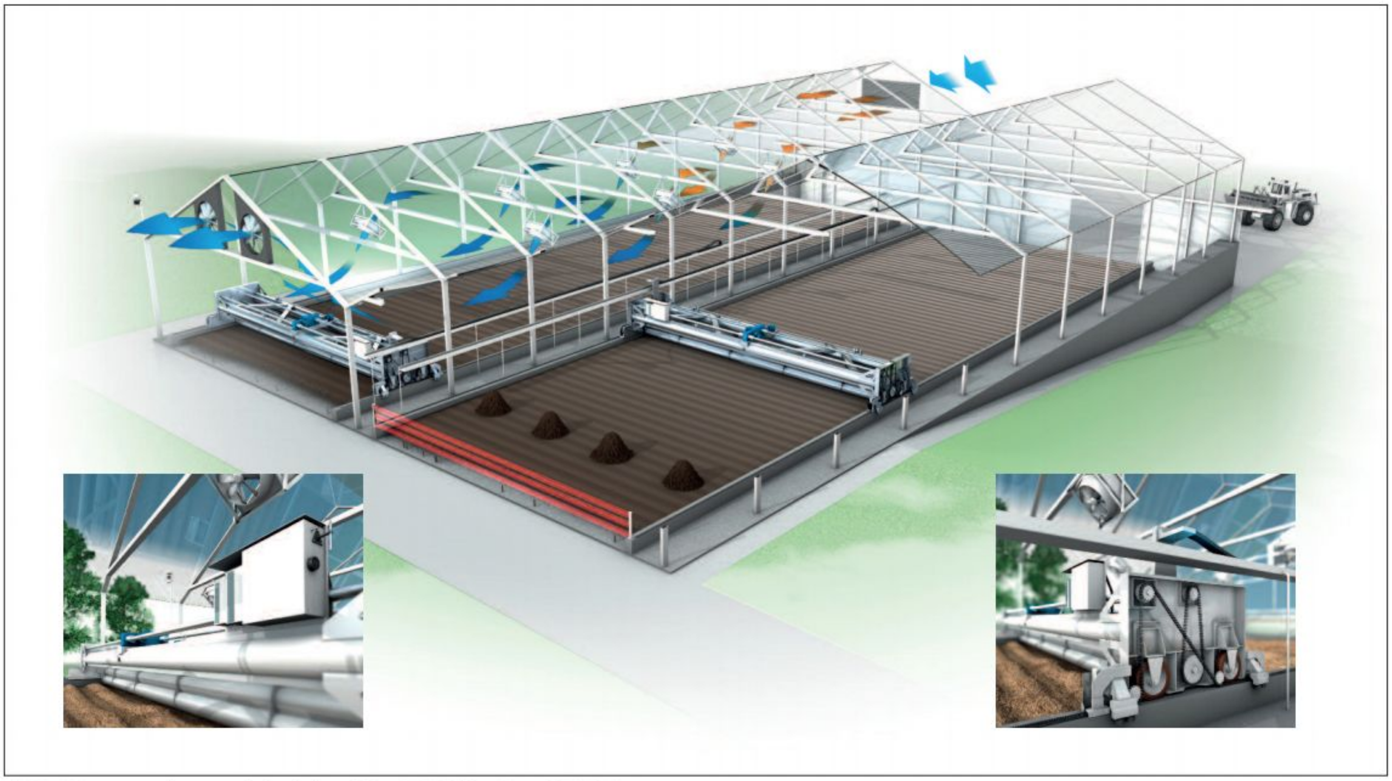

Figure 26. HUBER Sludge Turner SOLSTICE solar dryer (HUBER Technology, 2019)

The PAMf-FCC is produced by the Fraunhofer Institute for Ceramic Technologies and Systems. This polymer is environmentally friendly, highly biodegradable, and amphiphilic. Unfortunately, additional research and development is necessary before this product can be introduced to the market.

The HUBER Sludge Turner SOLSTICE dryer uses solar radiation to dry biosolids. Some characteristics of this dryer are shown below in **Table 12**.

Table 12. HUBER Sludge Turner SOLSTICE characteristics (HUBER Technology, 2019)

Characteristic	Value
Facility dimensions	185 ft x 40 ft
Biosolid bed width	~36 ft
Biosolid bed length	~136 ft
Depth of biosolids	1 ft
Maximum volume of biosolids	5,868 ft^3
Normal temperature range	30 - 40 ℃
Retention time	2-3 weeks

A side-view AutoCAD drawing for the dryer is shown below in **Figure 27** (HUBER Technology, 2019)

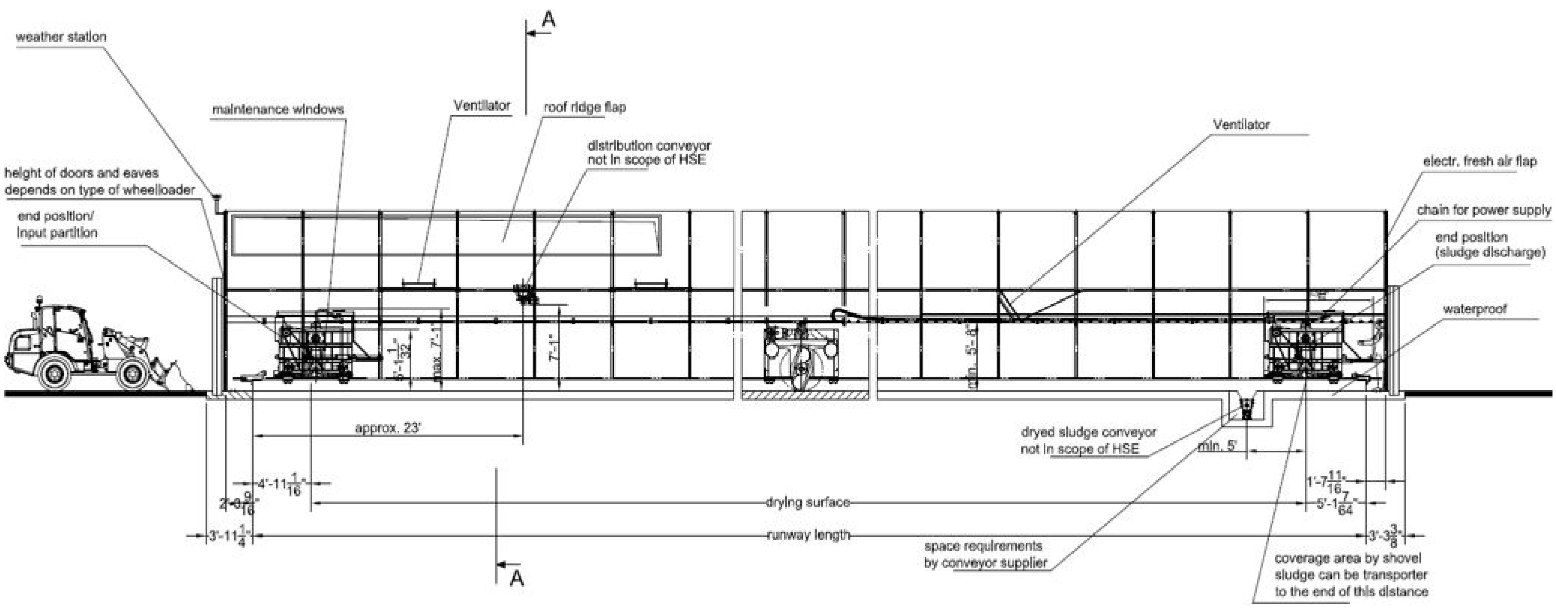

Figure 27. HUBER Sludge Turner SOLSTICE (HUBER Technology, 2019)

After determining that this dryer would be necessary, the location of the system had to be decided. Additionally, the volume of biosolids that would be held in the dryer was calculated based on the percent dryness desired. The following equation was used to calculate the volume needed for the biosolids on a three week retention time in the dryer.

$$V_d = \frac{\frac{M_{T,dry}\left(\frac{21}{365}\right)}{\rho_{dry}} + \frac{M_{T,wet}\left(\frac{21}{365}\right)}{\rho_{wet}}}{2} \quad (1)$$

V_d = Volume of biosolids in the dryer, ft^3

$M_{T,dry}$= Total mass of biosolids at a certain dry percentage, lbs

$M_{T,wet}$= Total mass of the biosolids at 18% dry, lbs

ρ_{dry}= Density of the biosolids at a certain dry percentage, lbs/ft^3

ρ_{wet}= Density of the biosolids at 18% dry, lbs/ft^3

The amount of water that enters and leaves the press and solar dryer was determined simply by looking at the moisture content percentages.

Land Application

For the land application of biosolids, a biosolid storage tank, Simpson Research Farm fields, and a Terragator would be necessary. These materials are shown in **Figure 28**, **Figure 29**, and **Figure 30**, respectively.

Figure 28. Proposed biosolid storage tank (Spirac, 2019)

Figure 29. Simpson Research Farm Field

Figure 30. Terragator (Epsom Environmental Services, 2019)

After selecting the parcels of land at Simpson Research Farm where biosolids can be land applied, soil samples were taken to determine the soils' nutrient concentrations. Nine soil samples were taken from lot 29, where fertilizer was last applied in 2016, while three samples were taken from lot 23, where fertilizer has not been applied in the past three years. The soil sampling locations are shown below in **Figure 31**.

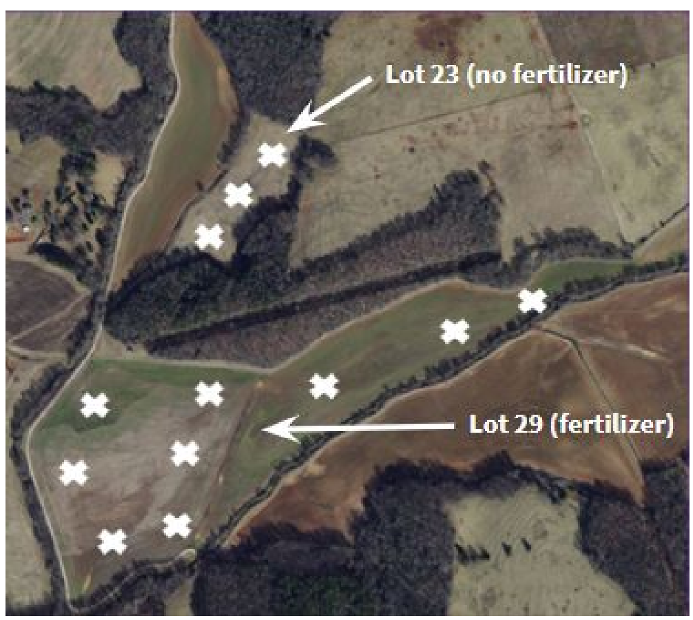

Figure 31. Soil sampling locations within Simpson Research Farm

Next, the concentration of fecal coliforms within the biosolids produced at the CU WWTP had to be measured. Two samples were taken after treatment within each of the following operations: primary aerobic digester, secondary aerobic digester, and mechanical press. The samples are shown in **Figure 32**, **Figure 33**, and **Figure 34**, respectively.

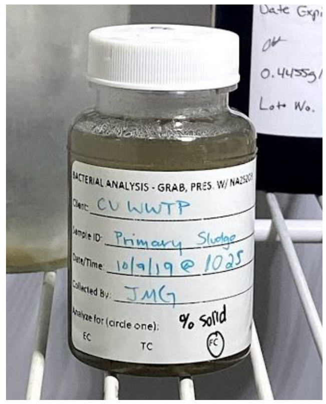

Figure 32. Biosolid sample after primary digestion

Figure 33. Biosolid sample after secondary digestion

Figure 34. Biosolid sample after mechanical press

After calculating the acceptable biosolid volume to be land applied based on nutrient concentrations in the soil and biosolids, area of land, and agronomic rate of the crop grown on the field, a method to reduce the pathogen concentration was chosen. Additionally, a method that reduces vector attraction was chosen. Once all of the steps above were completed, a terragator would be used to land apply biosolids.

Gasification

For the gasification process, the California Pellet Mill CL Type 3 pelletizer and PP20 Power Pallet downdraft gasifier would be necessary. As previously mentioned, Clemson University currently owns the California Pellet Mill CL Type 3 Series. An image of the pelletizer can be seen below in **Figure 35**.

Figure 35. California Pellet Mill CL Type 3 Series

This pelletizer is currently not in use. Some characteristics of the pellet mill and its output pellets are shown below in **Table 13**.

Table 13. California Pellet Mill characteristics (California Pellet Mill Co., 2013)

Pelletizer Characteristic	Value
Pellet Mill Length	45.5 ft
Pellet Mill Height	34.25 ft
Pellet Mill Width	63 ft
Pellet Output	30-200 lbs/h
Produced Pellet Diameter	1-38.1 mm
Produced Pellet Length	2.5X pellet diameter
Main Motor	5 HP and 1,800 RPM
Feeder Motor	0.25 HP and 1,800 RPM
Volt Current	3-phase, 60 Hz, 230-460 volt

The downdraft gasifier owned by Clemson University, shown below in **Figure 36**, is the PP20 Power Pallet model made by All Power Labs.

Figure 36. PP20 Power Pallet

This downdraft gasifier consists of a feedstock holding tank, pyrolysis chamber, combustion/cracking/reduction zone, char collector, cyclone to filter out fine ash, filter to catch tar gases, internal combustion engine, and automation system to optimize the process.

The particle size of the feedstock should be from 0.5 to 1.5 inches and should contain a concentration of 70-90% solids. About 1.2 kg of feedstock creates 1 kWh of electrical energy, but of course this varies based on the load, moisture content, and quality of the feedstock (ALL Power Labs, 2019). Specifications for the PP20 Power Pellet are shown below in **Table 14**.

Table 14. PP20 Power Pellet characteristics (ALL Power Labs, 2019)

Characteristic	Specifications
Max. Continuous Power Output	15 kW @ 50 Hz & 18 kW @ 60 Hz
Fuel Moisture Tolerance	10% - 30%
Dimensions	1.4 m x 1.4 m x 2.2 m
Weight	2350 lb
Feedstock Hopper Capacity	88 gallons

Knowing the pelletization process requires a lignin content of at least 15% mass, wood chips would need to be added in order to obtain this desired content. Wood chips are used as a case study for modeling this system; however, any high lignin component could be added as long as the moisture content and lignin content would balance to the correct amounts.

Once the equipment was chosen, the mass flow rate of biosolids through each process was quantified. The amount of wood chips necessary for pelletization was determined, a storage tank for the wood chips was designed, and the moisture content of the wood chips at the Cherry Crossing Compost Facility was measured. Once this information was determined, the outputs of gasification and the amount of energy produced were estimated.

The following equations below were utilized for these calculations.

$$m_P = m_b + m_{wc} \quad (2)$$

Solid Content before Pelletization:

$$95\%(m_b) + MC_{wc}(m_{wc}) = 91\%(m_P) \quad (3)$$

Lignin:

$$10\%(m_b) + 25\%(m_{wc}) = 15\%(m_P) \quad (4)$$

m_P= Mass of total solid entering the pelletizer, lbs
m_b= Mass of biosolids, lbs
m_{wc}= Mass of wood chips, lbs
MC_{wc}= Moisture content of wood chips (%)

It was then necessary to identify the density of the total biosolids after pelletization. The following equation was used to obtain a weighted average for the density:

$$(\rho_T) = \left(\frac{m_{water}}{m_T}\right)(\rho_{water}) + \left(\frac{m_{wc}}{m_T}\right)(\rho_{wc}) + \left(\frac{m_b}{m_T}\right)(\rho_b) \quad (5)$$

m_T = Total mass of pellet, lbs
m_{water} = Mass of water, lbs
m_{wc} = Mass of wood chips, lbs
m_b = Mass of biosolids, lbs
ρ_T = Total density of pellet, $\frac{lbs}{ft^3}$
ρ_{water} = Density of water, $\frac{lbs}{ft^3}$
ρ_{wc} = Density of wood chips, $\frac{lbs}{ft^3}$
ρ_b = Density of biosolids, $\frac{lbs}{ft^3}$

In order for the gasifier to process the biosolids safely, a higher water content is required than what exits the pelletizer. To accomplish this by hand, another system of equations can be derived to find the mass of water that is needed to be added. In **Equation 6**, the 85% can be chosen to be in a range of 70-90%, but 85% was selected. Alternatively, a SuperPro Designer model can give the amount of water that needs to be recycled.

$$m_G = m_P + m_{water} \tag{6}$$

Water Content Before Gasification:

$$91\%(m_p) + 0\%(m_{water}) = 85\%(m_G) \tag{7}$$

m_G= Mass of solid entering the gasifier, lbs
m_P= Mass of total solid entering the pelletizer, lbs
m_{water}= Mass of water, lbs

The amount of storage for the wood chips can be determined by the following equation.

$$V_{storage} = \frac{m_{wc}}{\rho_{wc}} \tag{8}$$

$V_{storage}$ = Volume of storage tank, ft^3
m_{wc}= Mass of wood chips needed for the whole year, lbs
ρ_{wc}=Density of wood chips, lbs/ft^3

In order to assess the feasibility of this process the total number of cycles needed to process all the biosolids needed to be calculated. In order to calculate the total number of cycle the total volume of biosolids produced and that was then compared to the volume of the reactor.

$$V_b = \frac{m_G}{\rho_T} \tag{9}$$

V_b= Volume of biosolids, ft^3
m_G= Total mass of pellet, lbs
ρ_T= Total density of pellet, $\frac{lbs}{ft^3}$

$$Cycle = \frac{V_T}{V_G} \tag{10}$$

Cycles= Total number of cycle
V_T= Total Volume of Pellets (ft^3)
V_G= Volume of Gasifier (ft^3)

In order to determine the energy produced by combusting the producer gas and the profit from producing the energy two equations were used.

$$Q_{combustion} = \frac{m_{gas} * \Delta H_{combustion} * \eta_{engine} * \eta_{generator}}{3600} \tag{11}$$

$Q_{combustion}$= Energy of combustion (kWh)

m_{gas}= Mass of gas (kg)

ΔH = Enthalpy of combustion

η_{engine} = Efficiency of engine

$\eta_{generator}$ = Efficiency of generator

$$C = Q_{combustion} * P \tag{12}$$

C= Cost of energy ($)

$Q_{combustion}$= Energy of combustion (kWh)

P = Cost of energy ($/kWh)

Results and Discussion

Land Application

For the land application of biosolids, the biosolids would need to be dried to 90% solids. The volume of biosolids in the dryer (V_d) is shown below.

$$V_d = \frac{\frac{M_{T,dry}\left(\frac{21}{365}\right)}{\rho_{dry}} + \frac{M_{T,wet}\left(\frac{21}{365}\right)}{\rho_{wet}}}{2}$$

V_d = 0.5*[[(380,400 lbs)*(21/365)/(46.74 lbs/ft^3)]+[(1,902,000 lbs)*(21/365)/(59.20 lbs/ft^3)]] = 1,158.37 ft^3

The current process for treating biosolids at the CU WWTP does not meet Class B standards. A fecal coliform test concluded that the concentration of fecal coliforms was 10.6 million MPN per gram of solid. This is much higher than the Class B concentration of 1-2 MPN per four grams of solid.

Using Google Earth, the specific fields for land application within Simpson Research Farm were chosen. This was done by analyzing each plot of land that grows bermuda or fescue grass. The fields that were within 10 m of a body of water were excluded. The eligible acreage for each type of grass are shown below.

Eligible Area in Simpson Research Farm

- 90.54 acres of Bermuda pasture
- 530.34 acres of Fescue pasture

The results of the soil sampling within Simpson Research Farm are shown below in **Table 15**.

Table 15. Soil sampling results

	Soil pH	P (lbs/A)	K (lbs/A)	Ca (lbs/A)	Mg (lbs/A)	Zn (lbs/A)	Mn (lbs/A)	Cu (lbs/A)	B (lbs/A)	Na (lbs/A)	NO_3-N (lbs/A)
Lot 23	5.76	3.67	302.00	920.00	279.00	3.50	32.00	0.47	0.60	10.00	1.67
Lot 29	5.98	24.60	125.00	1454.00	373.00	5.31	39.80	1.68	0.46	16.40	32.90

As predicted, the nitrogen concentration of the fertilized field (Lot 29) was much larger than the nitrogen concentration of the unfertilized field (Lot 23).

This results of the fecal coliform test indicated that the pathogen concentration of the biosolids needed to be significantly reduced before land application. Several different options were taken into consideration including modification to the current process, anaerobic digestion, lime stabilization, and heat treatment. The most effective method for reducing pathogens would be to modify the current process in order to meet the requirements set by the EPA and SCDHEC. This would involve either increasing the retention time of the digester or increasing the temperature in the digester. The limiting variable could not be determined for this study so recommending an improvement to the system could not be made with full certainty that it would be effective at reducing pathogens. The second option was to utilize to anaerobic digestion. This was taken into account; however, the CU WWTP recently changed from anaerobic to aerobic. Reverting back to anaerobic digestion was not something that the CU WWTP wanted to consider. Lime stabilization would be a viable alternative as well. The main concern with this process is that biosolids land applied with a high pH would cause significant damage to beneficial microbes in the soil. There is an option to raise the pH above 12, until the pathogens are killed, and then lower the pH below 10.5 before land application. This process creates a strong odor, which was one of the main constraints of this project. The final option to reduce the pathogen count was using a dryer to heat treat the solids. Although this was the most energy-intensive option considered, it produces a Class A biosolid, reduces vector attraction, and some of the energy cost could be offset by implementing a solar dryer. The main constraint of this system was that the space required for a solar dryer was much greater than the space needed for a traditional dryer.

In order to accommodate the amount of biosolids that are limited by the frequency of applications allowed by the EPA, a storage tank was needed to hold the biosolids in between applications. For this project, the volume of the tank was calculated to hold the total amount of 90% dry weight biosolids produced in a four month span. The calculations for the volume of the storage tank are shown below.

Amount of biosolids projected to be produced in 2019 = 1,902,000 lb/yr

Density of biosolids = 45.01 lb/ft^3

Volume of biosolids produced per year

Choose maximum mass of biosolids produced = 2,000,000 lbs

$$V = \frac{m}{\rho}$$

$$V = (2{,}000{,}000 \text{ lbs}) / (45.01 \text{ lb/ft}^3)$$

$$V = 8{,}135.7 \text{ ft}^3 \text{ of biosolids}$$

Due to the fact that biosolids would be applied twice a year this number can be altered.

$$V_{\text{Storage Tank}} = (8{,}135.7 \text{ ft}^3)/2$$

$$V_{\text{Storage Tank}} = 4{,}067.8 \text{ ft}^3$$

Storage tank dimensions

Choose radius = 10 ft

$$V = \pi * r^2 * h$$

$$4{,}067.8 \text{ ft}^3 = \pi * (\text{ ft})^2 * h_{min}$$

$$h_{min} = 12.9 \text{ ft}$$

Dimensions of Storage Tank

$$V = 4{,}085 \text{ ft}^3$$

$$r = 13 \text{ ft}$$

$$h = 13 \text{ ft}$$

In order to determine if storing the solids would be a safe practice water activity had to be investigated. The water activity was found by relating the water content to the moisture sorption isotherm. Following this line allowed the value of water activity to be found at around 0.3. The graph that was used is shown in **Figure 37.**

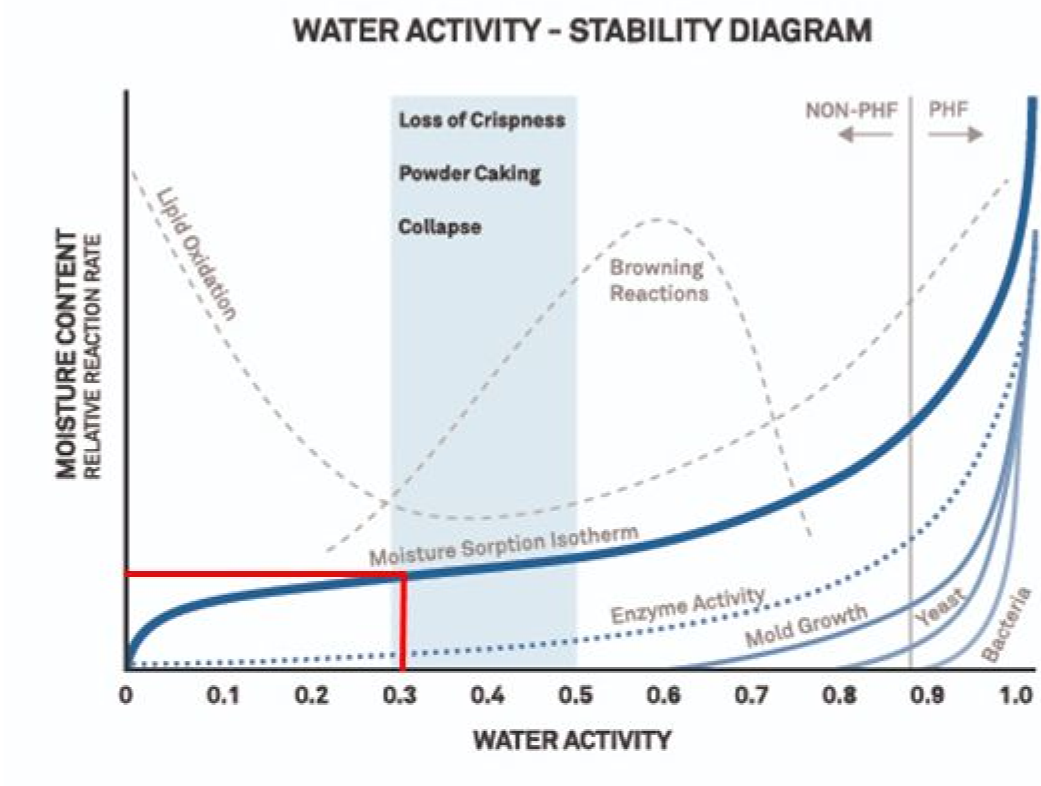

Figure 37. Water activity (Meter Food, 2019)

This storage tank is required in order to store the biosolids in the intermittent time when biosolids cannot be applied. With little available space at the CU WWTP, it was decided that the biosolid storage tank would replace two of the drying beds. An aerial view of this location is shown below in **Figure 38**.

Figure 38. Storage Tank Location

The final parameter calculated is a representative application rate of biosolids in order to ascertain the feasibility of the process. Using the agronomic rate provided by SCDHEC for hay, the amount of biosolids per year that can be applied to a plot of land is calculated. These calculations can be found below.

Agronomic Rate of nitrogen for Bermuda and Fescue grasses

- Nitrogen requirement for bermuda and fescue grasses:

  5 lbsN/1000 ft^2/yr = 217.77 lbsN/acre/yr
- Nitrogen concentration in CU WWTP biosolids: 0.0432 lbsN/lb dry biosolid
- Estimated nitrogen already present in soil: 74.22 lbsN/acre/yr
- Estimated allowable addition of nitrogen to soil

  (217.77 lbsN/acre/yr) - (74.22 lbsN/acre/yr) = (143.6 lbsN/acre/yr)
- Agronomic rate of nitrogen

  (143.6 lbsN/acre/yr) / (0.0432 lbsN/lb CU WWTP dry biosolid) / 2000

  = 1.66 tons of CU WWTP dry biosolids/acre/yr

Application rates

For Bermuda Pastures

$$V_{\text{Apply to Bermuda}} = 90.54 \text{ acres} * 1.66 \text{ Tons of CU WWTP dry biosolids/acre/yr}$$

$$V_{\text{Apply to Bermuda}} = 150.30 \text{ Tons of CU WWTP dry biosolids/yr}$$

For Fescue Pastures

$$V_{\text{Apply to Fescue}} = 530.34 \text{ acres} * 1.66 \text{ Tons of CU WWTP dry biosolids/acre/yr}$$

$$V_{\text{Apply to Fescue}} = 880.36 \text{ Tons of CU WWTP dry biosolids/yr}$$

Total amount of solids Applies

1030.72 Tons of CU WWTP dry biosolids/yr

Application schedule

- Fall: apply to Bermuda pastures
- Spring: apply to Fescue pastures

The total amount of dry biosolids that can be land applied to Simpson Research Farm each year is significantly larger than the amount of biosolids that are currently produced by the CU WWTP. This shows that this process can continue to be utilized as biosolid production increases over time. An overall process flow diagram can be seen in **Figure 39.**

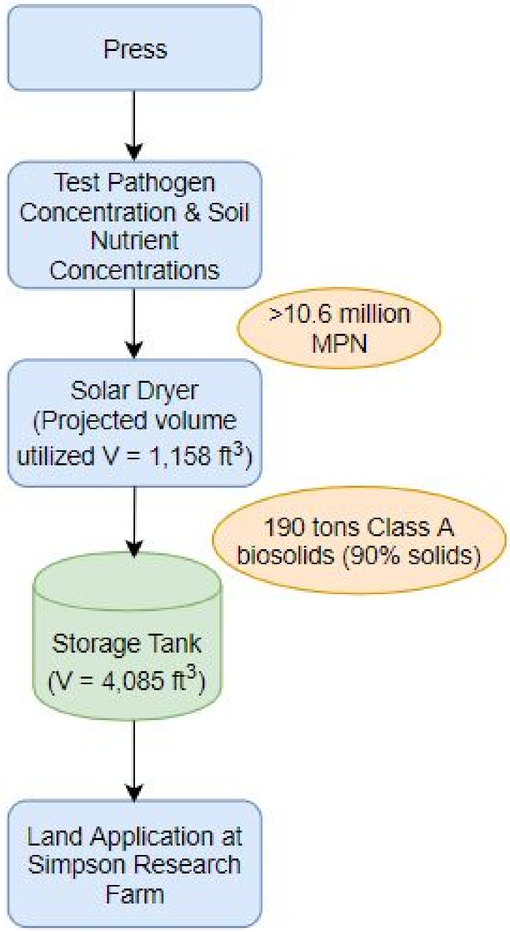

Figure 39. Land application process flow diagram

Figure 40 below lists the pros and cons of the land application of biosolids.

Pros

- Increases porosity of soil
  - Increases infiltration rate
  - Increases water holding capacity
  - Decreases rate of runoff
- Addition of vital nutrients to soil
  - C, N, P
- Capable of land applying 1,031 tons of dry biosolids/yr
  - Accommodates an increase in student population

Cons

- Possible nutrient leaching into groundwater
- Potential runoff into nearby bodies of water due to extreme weather events
- Effects of pharmaceuticals, hormones, and microplastics on soil unknown
- Purchase 2,828 ft^3 storage tank necessary

Figure 40. The pros and cons of land application

Gasification

The gasification process has several steps and parameters that need to be calculated. An overall process flow diagram for this process is shown below in **Figure 41.**

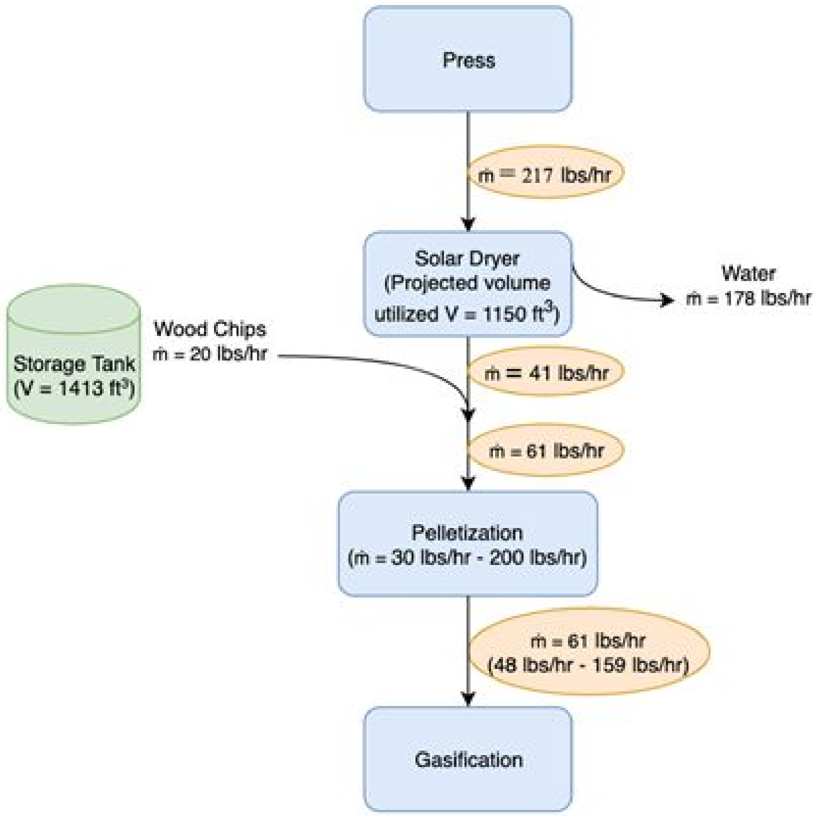

Figure 41. Process flow diagram for gasification

For the mass flow balances of the different operations were done in the units of lbs/hr. In order to get the amount of a stream per batch, simply multiply the mass flow rate by the hours taken for a single batch. In the case of this design, the hours per batch is 8 hrs, although it could vary between 3 and 10 hrs for the gasification system. A batch cycle of 8 hrs was selected because of the recommendation of the operator of the Gasifier to have a cycle length of 8 hrs.

The mass flow rate can also be multiplied by the amount of hours in a year to get the total mass in operation per year.

The process begins by identifying the amount of solids coming from the press per hour. Biosolids at 18% come out of the press at 217 lbs/hr. These biosolids go to the dryer.

The biosolids are then dried to a solid percentage of 95% through convection, conduction, and radiation forces. The biosolids dry for a time period of 2 to 3 weeks. And the amount of water cast off from the press and drying system can be seen in **Table 16.**

Table 16. The amount of water lost and retained in gasification press and drying steps

	Entering Water Mass (Tons)	Retained Water Mass (Tons)	Lost Water Mass (Tons)
Press	8,387.82	779.82	7,608.00
Solar Dryer	779.82	9.01	770.81

From the dryer, a mass flow rate of biosolids of 41 lbs/hr (180 tons per year) leaves to go to the pelletization process, while 178 lbs/hr (771 tons per year) exits as water in the air . The volume of biosolids in the dryer (V_d) is shown below.

$$V_d = \frac{\frac{M_{T,dry}\left(\frac{21}{365}\right)}{\rho_{dry}} + \frac{M_{T,wet}\left(\frac{21}{365}\right)}{\rho_{wet}}}{2}$$

V_d = 0.5*[[(360,378.95 lbs)*(21/365)/(45.88 lbs/ft^3)]+[(1,902,000 lbs)*(21/365)/(59.20 lbs/ft^3)]]

= 1,150.20 ft^3

A parameter that must be found is the amount of wood chip stock that must be added to the influent biosolids in order to meet two criteria. The first is the lignin content required for pelletization to succeed. The second is a low enough moisture content for gasification to run to completion. For pelletization, the lignin content needs to be around 15% and moisture content of 91% solid. for gasification the moisture content at or below 9%. The calculations can be shown below.

$$m_T = m_b + m_{wc}$$

$$10\%(m_b) + 25\%(m_{wc}) = 15\%(m_T)$$

$$.10*342360+.25*m_{wc}=(m_{wc}+342360)*.15$$

$$m_{wc}=17,1180 \text{ lbs}$$

$$95\%(m_b) + MC_{wc}(m_{wc}) = 91\%(m_P)$$

$$.95*342360+MC_{wc}*171180= .91*(342360+171180)$$

$$MC_{wc}=0.83$$

From the results of this equation, it can be seen that amount of wood chips needed for a whole year is 171180 lbs (85.59 tons) and the moisture content needs to be 83%. The mass flow rate needed to mixed in before pelletization is 20 lbs/hr.

Moisture content testing was done on the wood chips that are at the composting facility at Clemson University. The wood chips that were sampled were drawn from the bottom and top of both the front and back of the storage area. The results can be seen in **Table 17.**

Table 17. Results of wood chip moisture content test at Cherry Crossing

Sample	Percent Solid
Dry Wood Chips from the Front	81%
Dry Organic Matter from the Front	83%
Wet Wood Chips from the Front	48%
Wet Organic Matter from the Front	35%
Dry Wood Chips from the Back	79%
Dry Organic Matter from the Back	80%
Wet Wood Chips from the Back	63%
Wet Organic Matter from the Back	64%

It is important to note that it rained soon before the sampling, in practice wood chips from the top of the pile would be collected for use, and the storage facility at Cherry Crossing is open on all sides when the storage tank in design would be enclosed. Because of these practical conditions, it is assumed that the wood chips wood be close to 83% dry. If the wood chips had a higher moisture content, they would need to be dried before adding them to the pelletizing process to run effectively.

In order to figure out the volume of storage tank for the wood chips, a calculation must be done based off of purchasing wood chips four times a year. So a fourth of the volume needed for wood chip storage for one year would be needed.

$$V_{storage} = \frac{m_{wc}}{\rho_{wc}}$$

$$V_{storage} = (171{,}180 \text{ lbs}) / (30.28 \text{ lbs/ft}^3)$$
$$V_{storage} = 5653.24 \text{ ft}^3$$
$$V_{storage,1/4} = 1413.31 \text{ ft}^3$$

Therefore, a storage tank must be purchased with a minimum of this volume. A storage tank with a volume of 11,000 gal will be purchased.

When looking at the pelletizing process, the stream coming from the wood chip storage with the stream coming from the dryer will be added together for a total mass flow rate of 61 lbs/hr. A parameter that needs to be calculated is the density of the new wood chip and biosolid feedstock. This was achieved by a weighted average of the three aspects; biosolids, wood chips, and water. This calculation is shown below.

$$(\rho_T) = \frac{m_{water}}{m_T}(\rho_{water}) + \frac{m_{wc}}{m_T}(\rho_{wc}) + \frac{m_b}{m_T}(\rho_b)$$

$$(\rho_T) = \frac{23.56}{265.78} * 62.15\frac{\text{lb}}{\text{ft}^3} + \frac{71.04}{265.78} * 23.72\ \frac{\text{lb}}{\text{ft}^3} + \frac{171.18}{265.78} * 45.01\frac{\text{lb}}{\text{ft}^3}$$

$$(\rho_T) = 40.85\ \frac{\text{lb}}{\text{ft}^3}$$

From this value, the total volume of biosolids that can be processed can be calculated. This is shown below.

$$V = \frac{m}{\rho}$$

$$V_b = \frac{534560\ lb}{40.85\ \frac{lb}{ft^3}}$$

V_b= 13,081.03 ft^3

From this value, the total number of cycles can be calculated.

$$\text{Cycles} = \frac{V_T}{V_G}$$

$$\text{Cycles} = \frac{13081.03\ \text{ft}^3}{11.65\ \text{ft}^3}$$

Cycles = 1,079 cycles

Therefore, based off of this calculation and a batch run cycle of 8 hrs, a total operation time of 350 days of the year the system must be run. This does not allow significant time for maintenance and it requires poor work hours for employees.

It was necessary for the biosolid and wood chip mixture to have a moisture content of 91% dry. Because the biosolids need to be in a range of 70-90% solid as they go through the gasification system, water must be added back to the system so that the pellet feedstock does not cause a fire. Ideally, water vapor would be recycled from the solar dryer to the gasifier, acting as one of the gasification agents entering the combustion zone of the gasifier. Currently there are two air intake valves to the combustion zone. It is believed that one of these valves can be attached to the wet air coming from the solar dryer, but confirmation with the manufacturer should take place before operation. In order to determine the flow rate coming from the solar dryer to the gasifier, a SuperPro Designer model was made. The model can be seen as **Figure 42.**

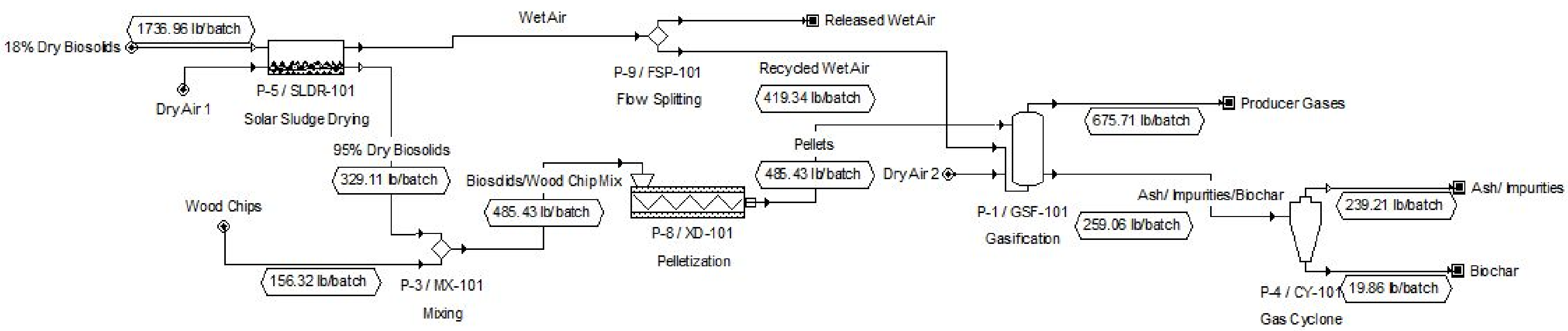

Figure 42. SuperPro model of the gasification process

From this SuperPro model, it is discovered that a flow rate of 52 lbs/hr (420 lbs/batch) of wet air should be coming from the solar dryer. The recycled air would cause the pellets in the gasifier to be at a moisture content of 81% which is within the 70-90% range. It is better to err on the side of caution in this scenario and not plan on having a moisture content of exactly 90%.

The final part of this process was determining the energy produced from the gasification process over a year**.** These values are shown in **Table 18.**

Table 18. Energy produced by each producer gas (Xie et al., 2010)

Compound	Mass (kg)	Gas Fraction	Fraction of Specific Gas	Efficiency of Generator	Efficiency of Engine	Weight (kg)	Enthalpy (kJ/kg)	Energy (kWh)
H_2	244,416	0.4664	0.1812	0.2	0.15	20656.01	141,584.00	24,371.33
CO	244,416	0.4664	0.1544	0.2	0.15	17600.92	10,100.00	1,481.41
CH_4	244,416	0.4664	0.092	0.2	0.15	10487.60	55,514.00	4,851.74
C_mH_n	244,416	0.4664	0.009	0.2	0.15	1025.96	50,285.00	429.92

After the specific energy of different gases were determined the total amount of energy created was determined by adding these numbers together. After this was determined the total cost of this much energy was determined in order to find the profit from gasifier. This is shown in **Table 19.**

Table 19. Profit from energy production

Compound	Energy (kWh)
H_2	24,041.79
CO	1,461.38
CH_4	4,786.13
C_mH_n	2,497.52
Total	32,786.82
Profit	$2,622.95

A sample calculation using these two equations can be shown below.

$$Q_{combustion} = \frac{m_{gas} * \Delta H_{combustion} * \eta_{engine} * \eta_{generator}}{3600}$$

For H_2

$$Q_{Combustion} = \frac{244{,}416 * .4664 * 0.1812 * 141{,}584 * .15 * .2}{3600}$$

$Q_{Combustion}$= 24,371.33 kWh

$$C = Q_{combustion} * P$$

C=24,371.33*0.08

*$0.08 was used to estimate the cost of electricity

C= $1,949.71

This power can be utilized to power the pelletizer along with the input power needed for the gasification process. The waste heat produced by the gasifier can be utilized as an added heat source for the dryer needed for this process, increasing the efficiency of the system. In a downdraft gasifier, the process is thermodynamically unfavorable due to large losses of heat in the outflowing gas. By recycling the process becomes more efficient and sustainable by the utilization of a coproduct. **Figure 43** below lists the pros and cons of the gasification of biosolids.

- Pros
    - Turns a current waste material into an energy source
        - 31,675 kWh/year
        - Equivalent to $2,534
        - Creates a clean gas
        - Potentially carbon neutral
    - Production of high heat biochar and ash
        - Brick and concrete formation
        - Soil remediation
            - PFAS reduction
    - Carbon storage
        - 7.6 tons of C sequestered as biochar from 951 tons of biosolids

- Cons
    - Increased workload
        - Removal of biochar and ash
        - Additional employees required
        - Inconvenient working hours
        - Continuous operation for 350 days
    - Production of impurities
        - Tar gas
    - High levels of waste heat
        - Thermodynamically unfavorable
    - Large quantities of wood chips used
    - Regulations and handling
        - EPA emissions permits
        - Record keeping
        - OSHA worker health safety

Figure 43. Pros and cons of gasification of biosolids

Economic Analysis

After creating a design for both land application and gasification, a cost estimation can be made for the two processes in comparison to the current process of landfilling. The cost analysis can be seen in the following tables.

Table 20. Cost analysis of the current operations using landfilling

Item	Capital Cost	Annual Cost	Operating Cost	Total Cost
Press	$0	$6,554	NA	$6,554
Polymer	$0	$11,844	$6,980	$18,824
Landfill Deposits 2018	NA	$21,787	NA	$21,787
Projected Landfill Deposits 2019	NA	$30,661	NA	$30,661
			Total Cost 2018	$47,165
			Total Cost 2019	$56,039

Table 21. Cost estimation for land application proposal (Plastic Mart, 2017)

Item	Capital Cost	Annual Cost	Operating Cost	Total Cost
Press	$0	$6,554	NA	$6,554
Starch Polymer	$0	$1,215	$6,980	$8,195
Solar Dryer	$1,000,000	NA	$55,840	$1,055,840
Storage Tank (500 gal)	$432	$0	$0	$432
Storage Tank (30,000 gal)	$25,473	$0	$0	$25,473
Total Cost for First Year				$1,096,494

Table 22. Cost estimation for gasification proposal (Plastic Mart, 2017) (Mesquite Wood Chips, 2019)

Item	Capital Cost	Annual Cost	Operating Cost	Total Cost
Press	$0	$6,554	NA	$6,554
Starch Polymer	$0	$1,215	$6,980	$8,195
Solar Dryer	$1,000,000	NA	$55,840	$1,055,840
Solar Dryer Upgrades	$350,000	$0	$0	$350,000
Wood chips	$0	$151,475	$0	$151,475
Wood chip storage	$7,899	$0	$0	$7,899
Pelletizer	$0	$2,498	$0	$2,498
Gasifier	$0	$812	$167,520	$168,332
			Total Cost for First Year	$1,750,793

Table 23. Comparative cost analysis for the current processes and proposed designs.

	Landfilling	Land Application	Gasification
Initial Investments	$0	$1,025,905	$1,365,998
Annual Operational Cost	$56,039	$70,589	$392,895
Annual Income	$0	$0	$2,534
Total Cost for First Year	$56,039	$1,096,494	$1,756,359

It can be seen that both processes are more costly than the current landfilling process. The initial cost of both processes is over a million dollars, but the yearly cost for land application is comparable to landfilling. Although the pay back time for either processes does not exist, both alternatives to landfilling possess pros that do not directly translate to a traditional economic analysis. As the cost of landfilling increases with the increasing amount of tons of biosolids produced, the yearly cost for land application and gasification will increase, but possibly at a lower rate.

Conclusion

It is recommended that the design for land application of biosolids for soil fertilization be utilized. This process would use an environmentally friendly starch-based polyacrylamide free flocculant, a HUBER Technologies solar dryer to meet the specifications for alternative 1 for Class A biosolids production, and a storage tank for these 90% dry Class A solids. Clemson University Simpson Research Farm would be used as the biosolids application site with 620.88 acres available. The acreage contains a variety of field types currently eligible for a waste management plan and is five times greater in surface area than the surface area needed to utilize the total amount of biosolids per year. Although this process costs approximately $14,000 more each year than the current landfilling process, land application was chosen for a variety of factors. The alternative design gasification was observed to be far too expensive to be considered economically feasible. Additionally, the gasification process creates possible hazardous working conditions and toxic impurities. Biosolids would also provide an organic alternative to synthetic anthropocentric inputs of nitrogen into the Earth's soils.

As shown throughout this report, the utilization of biosolids produced from the CU WWTP interrelates technology, sustainability, and people, as shown below in **Figure 44**.

Figure 44. A venn diagram showing the interdisciplinary topics of this report.

Further Research

Endocrine disruptors, flocculants, microplastics, PFAS, and pharmaceuticals should be researched before land application is used. Because of these factors, we suggest land application be postponed at this time. Although other wastewater facilities and engineering professionals view land application as a viable method of biosolids disposal, consideration should be taken in order to implement a sustainable design. Additionally, the "silo effect" should be examined in the storage process of solids that are 90% solid. This has to do with the explosivity of the dry material. Similarly, biosolids with a low moisture content are subject to bioaerosols formation, which presents a health hazard for pathogen transportation and possible respiratory effects. In a recent study of nutrient loading, nitrogen compounds from land application sites have been found in correlation with increased nitrogen levels in nearby waterways. These sites follow regulations and should be investigated further to determine if new regulations and guidelines are needed concerning agronomic rates and nutrient loading as well as the parameters of available sites.

Other Recommendations

Apart from the research needed for a land application process that utilizes a HUBER Technologies solar dryer, the engineering firm Black and Veatch is currently redesigning the CU WWTP. Other pathogen reducing processes may be examined to increase efficiency concerning pathogen reduction. First and foremost, a heater could be added to the current aerobic digesters in order to get a temperature of 59ºF to 68ºF for 40 to 60 days. This PSRP should reduce pathogen levels in the CU WWTP enough to produce Class B biosolids. This process could require longer retention time at peak flow and may require further storage. Alternatively, if the aerobic digesters were converted back to anaerobic, the amount of time the solids have to be contained in the tanks would be reduced, but similarly to aerobic, would require a higher temperature. Although anaerobic digesters previously showed to be inefficient for the CU WWTP, total solids analysis of the plant would need to be done in order to overcome past issues. Engineering firm Black and Veatch is currently designing a new process. In their design process the retention time of solids or cells must be considered in the liquid streams. Retention time of solids recirculation may be too high in the system, decreasing nutrients available to microorganisms before digestion, leading to inconsistent results. Lime stabilization could also be implemented so that biosolids could be applied in a slurry state. The pH, a point of concern in this process, must be reduced before application of biosolids onto the ground. Otherwise, unfavorable environment for soil microorganisms would be created. This process would most likely not be sustainable due to the odor emissions that accompany buffering before application. If implemented, a third party should be used to handle the biosolids application due to the difficulty of implementing Class B processes.

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