Anaerobic pre-treatment of agro-industrial wastes in Kansas: biogas, economic and environmental potential

by

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Abstract

Currently in the US, agro-industrial wastes are, for the most part, treated and disposed of off-site at municipal treatment plants and landfills, imposing a burden on municipalities and the environment. Anaerobic pre-treatment of these wastes has long been known to be an effective and environmentally sustainable biotechnology, as biogas is generated in the process and the volume of biosolids is significantly reduced in comparison to aerobic treatment. This biotechnology is widely distributed internationally but less so in the US. This thesis sets forth relevant principles of the biotechnology, evaluates some cases where it is currently adopted in the US, and provides conceptual reactor designs for two case studies. In both cases, biogas yield, solids reduction and organic loading reduction were found to be significant, but economic returns were modest. For the first case study, a meat packing plant, wastewater flow and characteristics data were obtained and analyzed, and an upflow anaerobic sludge blanket reactor design was prepared. For the second case study, a dairy ranch, reactor design results were compared with AgSTAR spreadsheet models available from the USEPA. In order to evaluate the potential to implement this biotechnology throughout agro-industry in Kansas, data was independently gathered, using specific protocols to ensure accuracy and relevance, which allowed the statewide median flow and organic loading parameters from agro-industry to be estimated. A model was developed to estimate biogas potential from flow and TSS, both of which are required NPDES reporting parameters. The estimated biogas yield for the two case studies was consistent with model results. The model results indicate that, if anaerobic wastewater pre-treatment were fully adopted in Kansas agro-industry, a median estimate of 19,800 MMBtu of biogas (methane) could be generated, equivalent to the natural gas demand of about 500 homes. The quantity of biosolids diverted from publicly owned treatment works would be 1,000 – 1,200 tonnes/year.

The median BOD_5 received from agro-industrial users would be reduced from 1,500 to 420 mg/L. However, a survey of industrial pre-treatment coordinators at agencies receiving agro-industrial wastewater found somewhat unfavorable attitudes towards using anaerobic wastewater pre-treatment. Recommendations for future research and engagement activities are provided.

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Dedication

This thesis is dedicated to Jesus of Nazareth, with humble gratitude for all that he has graciously done and continues to do in my life.

List of Abbreviations

AnMBR.....Anaerobic membrane bioreactor

BOD_5.....Five-day biochemical oxygen demand

C.....Carbon

COD .....Chemical oxygen demand

CH_4 .....Methane

KDA .....Kansas Department of Agriculture

KDHE .....Kansas Department of Health and Environment

HRT .....Hydraulic residence time

MGD .....Million gallons per day

N .....Nitrogen

NPDES .....National Pollutant Discharge Elimination System

OLR .....Organic loading rate

P .....Phosphorus

POTW .....Publicly owned treatment works

RFS .....Renewable Fuel Standard

RIN .....Renewable Identification Number

RNG .....Renewable natural gas

SIU .....Significant Industrial User

SRT .....Solids retention time

TCOD .....Total chemical oxygen demand

TKN .....Total Kjeldahl nitrogen

TSS .....Total suspended solids

USEPA .....United States Environmental Protection Agency

VS .....Volatile solids

VSS .....Volatile suspended solids

WWTP .....Wastewater treatment plant

Chapter 1 - Objectives

Anaerobic biotechnology has the potential to improve current methods of treating agro-industrial wastewater. If anaerobic pre-treatment is applied at industrial sites upstream of the aerobic, activated sludge, biotechnology that is most commonly used at municipal wastewater treatment plants, there are potential benefits to the industry, the municipality and the environment. A two-stage approach to treating agro-industry wastewater, in which organic loads are reduced and energy recovered in an initial anaerobic stage, is an efficient approach, from a systems point of view.

Using anaerobic biotechnology to treat or pre-treat industrial wastewater is a widely adopted biotechnology worldwide (C. A. Chernicharo, 2007; C. A. L. Chernicharo, van Lier, Noyola, & Bressani Ribeiro, 2015; Jules B. van Lier, Mahmoud, & Zeeman, 2008; Jules B van Lier & Lettinga, 1999; C. Zhang, Su, Baeyens, & Tan, 2014). J. B. van Lier et al. (2008) provided a census as of 2007, which identified 2,266 high-rate anaerobic reactors in operation which were treating industrial wastewater. Although the location of these reactors was not identified, none of the contractors listed in this source were US-based.

Given that the current centralized method of treating wastewater aerobically through the activated sludge process consumes 3% of US electrical supply due to the large blowers required and that anaerobic biotechnologies have demonstrated the potential to be energy neutral or positive (McCarty, Bae, & Kim, 2011), as well as the fact that agro-industrial wastewaters are well-suited to anaerobic treatment (Buswell & Mueller, 1952; Gasper & Searchinger, 2018; Hansupalak et al., 2016; Milbrandt, 2013; Rajagopal, Saady, Torrijos, Thanikal, & Hung, 2013; Rittmann & McCarthy, 2001; Tchobanoglous, Burton, & Stensel, 2003; Jules B van Lier &

Lettinga, 1999), the topic is timely and appropriate and is well aligned with the Kansas State University Global Food System Initiative.

Agro-industrial wastes are defined as concentrated organic wastes, either liquid or solid, from industries that produce, process or store food/agricultural materials.

The overall objective of this thesis is to help those engaged in agro-industry in Kansas and those supporting them (agro-industry managers, academic faculty, researchers, extension agents, policy-makers, regulators, and municipal employees) to assess the potential of this biotechnology. To do so, the following specific objectives were completed:

1. Gather previously unpublished data to characterize Kansas agro-industry
2. Compare agro-industry location data with publicly available POTW data
3. Use an on-line survey to gather flow, BOD5 and TSS data from POTWs that may receive agro-industry wastewater
4. Determine the median flow, BOD5 and TSS from Kansas agro-industry
5. Investigate and apply available models to estimate biogas potential from available data
6. Gather data about two agro-industry case studies, use data to estimate biogas potential using conceptual reactor designs
7. Compare model results with case study results
8. Use the same on-line survey to assess awareness and attitudes
9. Investigate existing examples where biotechnology is in use

Figure 1 lays out the overall approach to the thesis in graphical form.

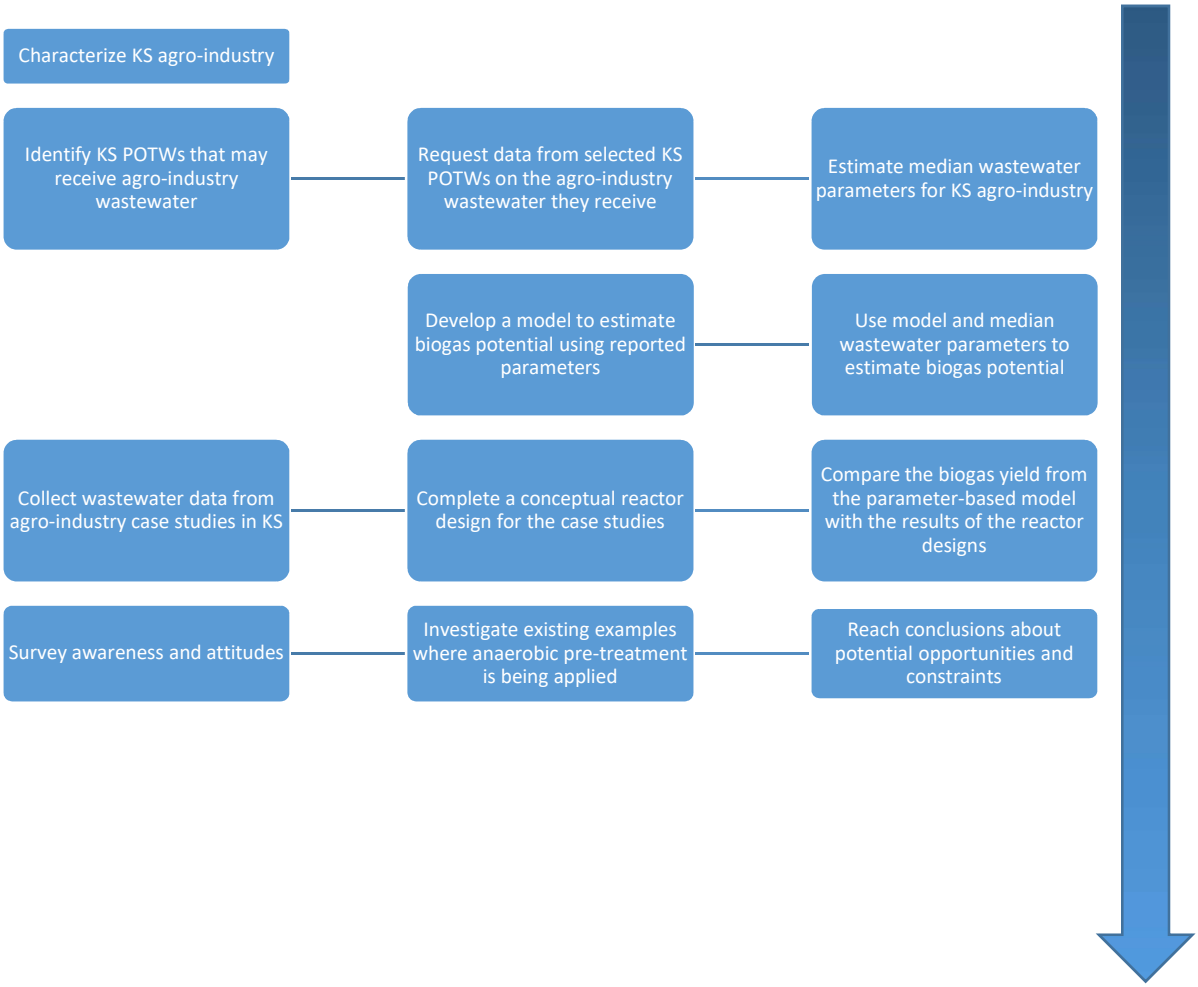


Figure 1 - Overview of thesis methodology

Chapter 2 - Introduction

2.1 Why does industrial pre-treatment matter?

Many authors (Buswell & Mueller, 1952; McCarty, 1964; Rittmann & McCarthy, 2001; Speece, 1983; Tchobanoglous et al., 2003; Water Environment Federation, 1998) note the contrast between the relatively low strength wastewater and predictable flow patterns associated with typical municipal loads and the unpredictable shock loads that can come from industrial users. Municipal WWTPs are designed primarily for residential loads, and industrial sources can quickly upset the typical activated sludge process, causing a violation of discharge standards. The City of Manhattan expressed concerns to this effect with respect to agro-industrial loads from certain Kansas State University facilities according to Abdu Durar (personal communication, February 23, 2018). To protect water quality, the USEPA established the National Pre-treatment Program, in which certain types of special industrial users are required to obtain a permit in order to discharge to POTWs. Under this program, the agencies which receive wastewater from special industrial users are required to establish and maintain industrial pre-treatment programs (USEPA, 2011). There are 17 pre-treatment cities in Kansas, according to a directory obtained from Steve Caspers, Pre-treatment Specialist for the Kansas Department of Health and Environment (email communication, June 12, 2018).

2.2 How does anaerobic treatment apply to agro-industrial wastewater?

The term anaerobic treatment, rather than anaerobic digestion, is used herein because the biotechnologies that will be studied do not necessarily accomplish complete stabilization of the particulate organic substrate.

Anaerobic wastewater treatment has been well-described by others (C. A. Chernicharo, 2007; Rittmann & McCarthy, 2001; Tchobanoglous et al., 2003; Jules B van Lier & Lettinga, 1999; Water Environment Federation, 1998). Key aspects of this biotechnology that could benefit Kansas agro-industry are as follows.

Heavy organic loads can be partially oxidized with lower biosolids generation, less nutrient requirements and smaller reactor volumes, as compared with aerobic wastewater biotechnologies such as activated sludge processes.

The anaerobic process can be energy neutral or energy positive as a result of biogas generation. Aerobic oxidation of heavy agro-industrial loads is highly energy intensive.

Nutrients do not normally need to be added when agro-industrial wastewaters are treated anaerobically for two reasons: 1) the biosynthesis rate is significantly lower than aerobic processes, and 2) the wastes normally contain sufficient N and P. (However, lack of trace elements can be an inhibiting factor, according to Speece, 1983 and Q. Zhang, Hu, & Lee, 2016)

Disadvantages of anaerobic wastewater treatment include its operational complexity and its slow startup and recovery. The very nature of the multiple communities of anaerobic organisms is specialized; thus, they are sensitive to inhibition, adapted to narrow temperature and pH ranges and slow to grow and multiply. A high skill level is required to design and operate anaerobic wastewater treatment plants. Perhaps for this reason, it is common to use design-build-own-operate (DBOO) contractors for agro-industrial pre-treatment. Asia Biogas, for example, has 90 DBOO anaerobic agro-industrial pre-treatment plants in Thailand, Malaysia and Singapore (Asia Biogas, 2019). The Dodge City, KS south wastewater plant, which uses anaerobic biotechnology to generate biogas from slaughterhouse waste, uses a national engineering contractor to operate their plant (Slattery & Unruh, 2018).

It is also important to recognize that anaerobic biotechnologies are not suitable to attain water quality standards on their own. The BOD_5 and TSS reductions, while significant on a percentage basis, would typically not reach the level required to meet Clean Water Act standards. N and P are not removed. Other biotechnologies, such as aerobic treatment or membrane filtration, must be used after anaerobic treatment to polish the effluent prior to discharge to the environment.

Chan, Chong, Law, & Hassell (2009) reviewed the use of anaerobic and aerobic biotechnologies in series to treat industrial wastewater and found a high level of overall treatment efficiency. Fig 2 is an illustration of their conclusions. The initial anaerobic phase reduced and equalized heavy organic loads while significantly reducing energy costs and biosolids generation. The latter aerobic phase produced a consistent, high quality effluent that met stringent nutrient discharge requirements.

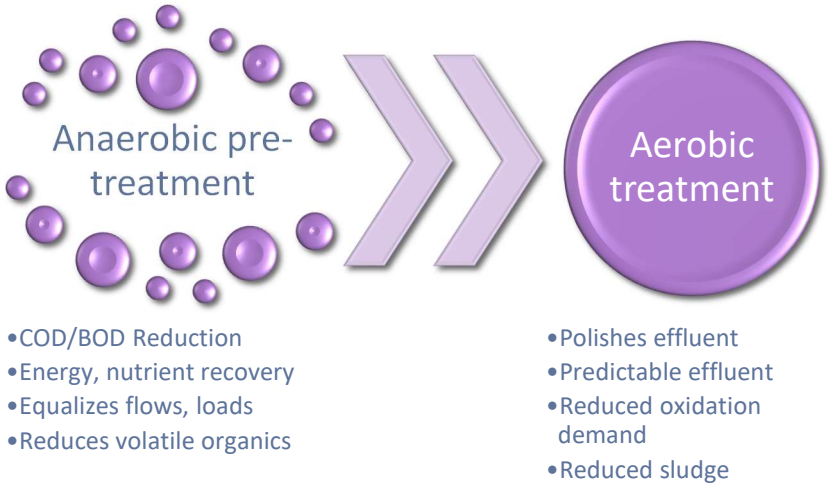


Figure 2 – Illustration of anaerobic/aerobic overall treatment efficiency (Credit: Weil)

The proposed design hypothesis in this thesis is that anaerobic biotechnologies would be applied at new pre-treatment facilities on site at agro-industrial facilities and that aerobic treatment/polishing would occur at existing POTWs receiving these discharges. The aerobic

phase would be accomplished with activated sludge biotechnology, which is the most common form of POTW wastewater treatment in Kansas (USEPA, 2016a).

Advantages to the agro-industrial users would include: improved corporate sustainability profile, reduced risks of fines and penalties, and reduced risk of plant shutdowns due to wastewater violations.

Advantages to the POTWs would include: reduced organic loading in their influent; reduced solids loading; reduced energy costs; reduced biosolids disposal costs; and reduced risk of NPDES non-compliance. Debris loading at the headworks could also be reduced.

2.3 What is biogas?

Biogas is a generic term referring to any gas generated by anaerobic biological processes. The CH_4 portion of biogas generated by methanogenesis is more correctly referred to as biomethane. However, biogas is the term used herein as it is the one used in the literature.

Khanal (2008) provides a useful history of biogas. From ancient times, bubbles arising from the anaerobic environment in swamps were observed, but it was Volta in 1776 who theorized the connection between anaerobic digestion and the formation of methane. Development of biogas as an energy source has occurred in three waves, according to Deublein & Steinhauser (2010): the 19th century, the early 20th century and the current era. Biogas has never represented more than a modest share of the energy supply portfolio. The first two waves of interest ended when the economics tipped heavily in favor of fossil fuel sources.

In the US, A. M. Buswell, during his long tenure at the Illinois State Water Survey Division, contributed significantly to the use of anaerobic digestion in wastewater treatment. Along with Neave, he developed the well-known Buswell equation (Neave & Buswell, 1930) by which CH_4 yield can be calculated if the chemical composition of the substrate is known. In an

article published toward the end of his career, Buswell (Buswell & Mueller, 1952) remarked on the ubiquity and reliability of the anaerobic process, which attains predictable yields even though a wide range of microbiological cultures are involved. It is interesting that, in his longest work, Buswell (Buswell & Hatfield, 1936) analyzed how anaerobic biotechnologies could be used to treat seven different industrial wastes and to produce biogas.

Raw biogas that is produced from anaerobic pre-treatment of agro-industrial wastes will typically have about 60% methane (CH_4) content, but the percentage can be higher or lower, depending on the biodegradability of the substrate and the efficiency of the anaerobic reactors. After CH_4, CO_2 forms the next largest percentage of biogas; together these two compounds represent almost 100% of the volume of biogas. ((Rittmann & McCarthy, 2001). However, ammonia (NH_3) and hydrogen sulfide ($H2_S$) will also be present in small percentages, to the extent that nitrogen (N) and sulfur (S) are represented in the substrate (Neave & Buswell, 1930). Moisture, siloxanes, and other trace gases may also be present (Angenent et al., 2017; Harikrishnan, 2008).

The CH_4 portion of biogas is a valuable source of renewable energy, as it has the same chemical composition as fossil-based natural gas (Gasper & Searchinger, 2018; Mathews, 2014; McCarty et al., 2011; Milbrandt, 2013). The CH_4 produced from anaerobic pre-treatment of agro-industrial wastes can be used on site, offsetting natural gas consumption and providing a beneficial closed-loop in terms of life cycle cost analysis. In some cases, all that is needed is to remove moisture and H_2S from the biogas to avoid corrosion and odors. Alternatively, the CH_4 can be used to generate electricity, for use on-site use, for feeding the grid, or both (Angenent et al., 2017; Harikrishnan, 2008). If economies of scale allow, the biogas can be upgraded to meet the standards of compressed natural gas (CNG). This product is called renewable natural gas

(RNG). The US renewable fuel standard (RFS) provides significant economic benefits to producers of RNG. In some cases, the value of RNG can be ten times the market value of CNG (Gasper & Searchinger, 2018; Murray, Galik, & Vegh, 2017; Rapport et al., 2008).

2.4 What are some applicable anaerobic reactor designs?

2.4.1 Lagoon systems

Anaerobic lagoons are widely used (Hamawand & Baillie, 2015; Laginestra & Allan, 2014; Laginestra & Van-Oorschot, 2009) and are often the first adaptation from aerobic or facultative biotechnology for agro-industrial users. A relatively low investment is needed to cover an existing waste stabilization lagoon with an impermeable membrane in order to recover biogas. One of the immediate benefits from a lagoon cover is containment of odors and other gases.

Covered lagoons are the most common form of anaerobic pre-treatment of cassava starch factory wastewater in Thailand (Hansupalak et al., 2016).



Figure 3 – Anaerobic lagoon for industrial wastewater treatment, Dodge City, KS

(Credit: ngvglobal.com)

Dodge City, KS (Fig 3) uses covered anaerobic lagoons as the first stage of its South Wastewater Plant. Slaughterhouse wastewater is diverted to these lagoons and biogas is generated for beneficial use. This example is further discussed in Section 2.7.

Anaerobic lagoon biotechnology is best suited to tropical climates and steady-state loading conditions. In its typical configuration, the process lacks mixing and recycling. Thus, it operates as a chemostat, in which SRT = HRT. The operator of such a lagoon lacks the controls

needed to adjust SRT to accommodate changes in loading. Temperature changes, which cover a wide range in Kansas, change kinetic rates. Again, the operator lacks the ability to compensate for these changes.

When the treatment process is inhibited in anaerobic lagoons, strong odors are produced, which may be one of the reasons why anaerobic biotechnology as a whole is perceived as problematic in the US. See Section 4.9 for more information on attitudes towards anaerobic biotechnology.

2.4.2 Upflow anaerobic sludge blankets (UASB)

The UASB reactor is a good choice for industrial pre-treatment because of its relatively simple design (Fig 4) and low hydraulic retention time, which equates to small reactor volume. It has no moving parts, as the wastewater flows upward through a sludge blanket without mechanical mixing. Granules of sludge establish a suspended growth process, provided that suitable conditions are maintained for the growth of beneficial microorganisms. It is a suitable biotechnology for treating agro-industrial wastewater with COD below 20,000 mg/L and TSS below 4,000 mg/L, according to Bernet & Paul (2006), who report that 78% of industrial pre-treatment processes based on granular anaerobic principles use UASB reactors. It should be noted that other reactor designs

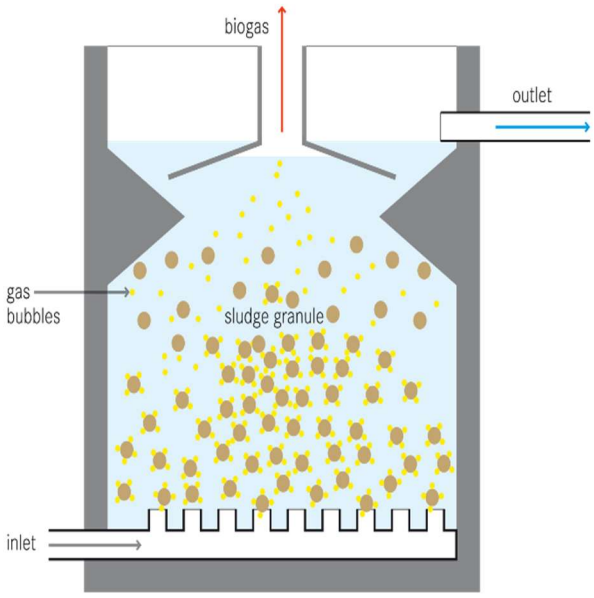


Figure 4 – UASB Schematic

(Credit: Creative Commons)

such as expanded bed granulated sludge beds (EGSB) and internal circulation (IC) have become more popular than UASB reactors (J. B. van Lier, van der Zee, Frijters, & Ersahin, 2015). However, the UASB design is a well-adapted biotechnology internationally, and is one for which design guidelines are readily available (C. A. Chernicharo, 2007).

The UASB reactor is most commonly used in tropical climates where the wastewater temperature is consistently above 15°C; however, agro-industries can also produce wastewater above this temperature threshold.

The UASB reactor type represents 17% of municipal wastewater installations in Latin America, the third most popular behind stabilization ponds (38%) and activated sludge (26%), according to (C. A. L. Chernicharo et al., 2015).

Table 1 summarizes recent studies of the performance of UASB reactors treating a variety of agro-industriL wastewater. These lab scale reactors operated in a temperature range between 20°C and 39°C, with HRT between 3h and 8d, and attained COD removal rates between 69% and 96%. The combination of moderate operating temperature (at ambient temperatures in tropical climates), low HRT and high COD removal rates account for the growth in use of UASB reactors, especially in the developing world (Chong, Sen, Kayaalp, & Ang, 2012; Latif, Ghufran, Wahid, & Ahmad, 2011; J. B. van Lier et al., 2015; J. van Lier & Zeeman, 2009; Jules B van Lier & Lettinga, 1999).

Table 1 – Selected results for UASB reactors

Reference	*Scale*	*Type of Wastewater*	*Operating Temp*	*OLR*	*HRT*	*SRT*	*COD Removal Rate*	*BOD Removal Rate*	*TSS Removal Rate*
Chávez P. et al. (2005)	Lab scale, 3.0 L	Poultry slaughterhouse wastewater	25°C – 39°C	31 kg BOD_5/ m^3·d	3.5-4.5h	Not stated	Not stated	95%	Not stated
Sánchez et al. (2005)	Lab scale, 5.0 L	Piggery wastewater	30°C-35°C	2 kg TCOD/ m^3·d	4d	32d	74%	Not stated	61%
Ramasamy, Gajalakshmi, Sanjeevi, Jithesh, & Abbasi (2004)	Lab scale, not stated	Synthetic dairy wastewater, 1440 mg/L COD	30°C	3.6 kg COD/ m^3·d	3h	Not stated	90%	Not stated	Not stated
Ramasamy et al. (2004)	Lab scale, not stated	Synthetic dairy wastewater, 1440 mg/L COD	30°C	10.8 kg COD/ m3·d	12h	Not stated	96%	Not stated	Not stated
Tawfik, Sobhey, & Badawy (2008)	Lab scale, 5.0 l	Actual dairy plant effluent	20°C	1.9 – 4.4 kg COD/ m^3·d	24h	76d	69%	75%	72%

2.4.3 Anaerobic membrane bioreactors

Anaerobic membrane bioreactors (AnMBRs) have been found to be well-suited to industrial wastewater pre-treatment because the membranes serve to retain the slow-growing methanogenic culture in the reactor vessel while enabling high treatment capacity at superior treatment efficiencies. Dereli et al. (2012) reviewed the potential of AnMBR to treat problematic industrial wastewaters. Results for pilot-scale and full-scale as well as lab-scale AnMBRs were reported. Typical HRTs were in the range of 0.5 days to 10 days, while SRTs averaged 190 days. Biogas yield averaged 0.30 and 0.32 m^3 CH_4/kg COD destroyed in the lab-scale and pilot-/full-scale studies respectively, which accords well with Tchobanoglous et al. (2003). Dereli describes COD removal rates averaging 97.7% for five pilot-/full-scale AnMBRs treating a variety of agro-industrial wastes. It was noted that AnMBRs are not sensitive to rapid changes in organic loading rates (OLR), which is often the case in agro-industrial wastewater. Table 2 summarizes two other studies, in which AnMBR technology was applied to agro-industrial wastewater. In both studies, high levels of COD removal were attained.

Table 2 – Selected results for anaerobic membrane bioreactors

Reference	*Scale*	*Type of Wastewater*	*Operating Temp*	*OLR*	*HRT*	*SRT*	*COD Removal Rate*	*BOD Removal Rate*	*TSS Removal Rate*
He et al. (2005)	Pilot scale, 500 L	Food factory wastewater	~37°C	Not stated	60h	50d	83%	Not stated	99%
Kang et al. (2002)	Lab scale, 5 L	Pre-treated alcohol distillery wastewater	55°C	3.5 kg COD/ m^3·d	13h	∞	>90%	Not stated	Not stated

2.5 How could co-digestion of different wastes be of benefit?

Anaerobic co-digestion is a factor in biogas yield potential. Co-digestion occurs when two or more dissimilar organic substrates are fed to an anaerobic bioreactor (Hagos, Zong, Li, Liu, & Lu, 2016). One common type of co-digestion scheme being actively researched involves mixing waste activated sludge and food waste (Xu, Li, Yang, Ge, & Li, 2018). A review article by Zhang, Su, Baeyens, & Tan (2014) reported that co-digestion of other substrates together with food and food-processing wastes served to increase methane yield and improve process stability in a number of studies. This was attributed to enhanced buffer capacity and better balance in C/N ratios. Along these lines, Parameswaran & Rittmann (2012) found that co-digestion of pig waste and paper waste yielded higher methane production and higher levels of treatment as compared with anaerobic digestion of pig waste alone. Also, Hobbs, Landis, Rittmann, Young, & Parameswaran (2018) evaluated a range of co-digestion rates for synthetic food waste and anaerobic digester sludge (ADS) and found increased methane production could be attained with higher food waste:ADS ratios, although this was limited at higher ratios by inhibition of the process. Nonetheless, the promising overall results reported in the literature would indicate that co-digestion should be considered as an option for potential anaerobic biotechnology projects.

2.6 Are agro-industrial wastes best treated at POTW anaerobic digesters?

There are three typical schemes for using anaerobic biotechnology to treat agro-industrial wastes: 1) Aerobic treatment of agro-industrial wastewater, mixed with other flows, at a POTW using the activated sludge process, then anaerobic digestion of the resulting waste activated sludge; 2) Adding agro-industrial wastewater trucked to a POTW to existing anaerobic sludge digesters; and 3) Anaerobic pre-treatment at agro-industrial plants then aerobic treatment at a downstream POTW. Table 3 compares the pros and cons of each approach. Case 2) has limited

applicability, in that only high solids or high COD wastes are suitable for being fed to POTW anaerobic digesters; nonetheless, it is a common practice and is worthy of comparison. Case 3), which is the subject of this thesis, offers advantages in reducing shock loading, recovery of resources, and the combined effect of anaerobic-aerobic treatment described by Chan et al. (2009).

Table 3 – Comparison of options to treat agro-industrial wastewater using anaerobic biotechnology

Case 1): Aerobic treatment of agro-industrial wastewater, mixed with other flows, at a POTW using the activated sludge process, then anaerobic digestion of resulting waste activated sludge		**Case 2): Adding agro-industrial wastewater trucked to a POTW to existing anaerobic sludge digesters**		**Case 3): Anaerobic pre-treatment at agro-industrial plants then aerobic treatment at a downstream POTW**	
Pros	**Cons**	**Pros**	**Cons**	**Pros**	**Cons**
Certified wastewater operators	Potential for shock loads to POTW	Certified wastewater operators	Can involve trucking, with enviro impacts and odors	No trucking of wastewater, reduced enviro impacts, odors	Economies of scale less favorable
Biogas revenues accrue to POTW	Large volume of biosolids	Biogas revenues accrue to POTW	Typically only high COD wastes accepted; some agro-industrial wastes not eligible	Often, elevated temps → higher biogas yield	Wastewater operators may not be certified
Economies of scale favorable	High energy costs to aerate organic loads	Economies of scale favorable	Not suitable for co-digestion of solid wastes	Biogas revenues offset treatment costs; typically, high natural gas demand on site	
	Solids screened at headworks a waste management issue	Can be energy neutral or positive	Inhibition and shock loading of the anaerobic digesters due to agro-industry loads	Nutrients and solids can be recovered for ag use	
	Lack of anaerobic → aerobic treatment effect		Lack of anaerobic → aerobic treatment effect	Positive anaerobic → aerobic treatment effect	
				Shock loads mitigated; wastes dealt with at source	
				Potential for co-digestion of solid wastes	

2.7 What are some example installations where anaerobic pre-treatment is currently in use?

Table 4 summarizes four installations/sites in which anaerobic biotechnology is currently being applied to pre-treatment of agro-industrial wastewater.

Strictly speaking, the Dodge City project is not an agro-industrial pre-treatment application because the anaerobic reactor is located within a WWTP instead on site at the industry. However, this project follows the principles of combined anaerobic and aerobic treatment and attains a high overall treatment efficiency. The project was recognized by the American Biogas Council as a Project of the Year for 2018 and also was selected by the USEPA in 2019 as one of the five exceptional projects for excellence and innovation within the Clean Water State Revolving Fund.

In all of the cases outlined in Table 4, the impetus for the application of anaerobic biotechnology was either a need for expansion of capacity in the agro-industrial plant or a problem complying with local NPDES discharge limits for industrial wastewater. These same themes emerged in the survey, as will be discussed in Section 4.9.

Three of the four cases used a combination of anaerobic followed by aerobic treatment on site to meet discharge limits. All of these three reported favorable water quality results, consistent with the review article by Chan et al. (2009)

Table 4 – Selected applications of anaerobic biotechnology to agro-industrial pre-treatment

Location (Reference)	Type of reactor and wastewater treated	Biogas usage	Performance information	Impetus for installation
Archers Daniel Midland, Decatur, IL (Stephen Bugle, personal communication on October 6, 2017 and site visit on July 12, 2018.)	Reactor: UASB proprietary design: bulk volume fermenters (BVF) by ADI, Inc. See Appendix D for process schematic Wastewater: grain wastes and processing byproducts, including alcohol and salt	Biogas upgraded and marketed for RIN credits	Flow: 56,000 m^3/d. Reactor volume: 130,000 m^3 x 3 = 390,000 m^3 Biogas yield: n/a Pre-treatment efficiency: after aerobic polishing, meets local discharge limits consistently.	Prior pre-treatment system was aerobic, but biosolids disposal became an issue. Anaerobic digesters added, with costs offset by biogas. Aerobic system was retained to polish effluent.
Dodge City KS South WWTP (Slattery & Unruh, 2012; Ray Slattery, personal communication, June 11, 2018)	Reactor: Covered anaerobic lagoons. Wastewater: slaughterhouse wastes	Biogas upgraded and marketed for RIN credits	Flow: 14,000 m^3/d. Reactor volume: n/a Biogas yield: 47,200 m^3 CH_4/d. Pre-treatment efficiency: The combined anaerobic/aerobic process attains a high treatment efficiency, and 100% of the wastewater flow is recycled for irrigation.	Anaerobic lagoons were part of original 1982 design. The WWTP was designed specifically for the slaughterhouse waste stream. Later, lagoons were covered with membranes which reduced odors. Until 2018, biogas was flared. Recent project installed biogas upgrade equipment.
Ken's, Marlborough, MA (Mills, McCarthy, Christian, Wilson, & Grant, 2018)	Reactor: AnMBR. Wastewater: salad dressing wastewater with COD, BOD5, TSS S^o = 39,000, 18,000, and 12,000 mg/L respectively.	Biogas used for sparging of membranes	Flow: 475 m^3/d. Reactor volume: 4 reactors x 100 m^3 = 400 m^3 Biogas yield: n/a Pre-treatment efficiency: effluent COD, BOD5, TSS S = 210, 20, and non-detect, respectively	Expansion of agro-industrial plant. AnMBR chosen because of limited space available on site and reliable treatment efficiency
Monogram Snacks, Martinsville, VA (American Biogas Council, 2017; Dr. Shawn Veltman personal communication, November 2, 2017)	Reactor: Moving bed biological reactor. Wastewater: meat snack processing waste, with high levels of sugar and vinegar.	Electricity with combined heat and power (CHP), partially subsidized through a now-expired tax credit.	Flow: 289 m^3/d plus 1,200 kg/d solids Reactor volume = 400 m^3 Biogas yield: 4,280 m^3/d Pre-treatment efficiency: after aerobic polishing, meets local discharge limits consistently	POTW required a higher level of COD removal. Opportunity was available to earn tax credits.

2.8 How can biogas yield be estimated empirically?

Given sufficient resources, an ideal approach to estimating the potential biogas yield if anaerobic pre-treatment of agro-industry waste was adopted widely in Kansas would be to sample the wastes of actual agro-industry effluent and determine the potential yield empirically.

The biochemical methane potential (BMP) test (Angelidaki et al., 2009; Owen, Stuckey, Healy, Young, & McCarty, 1979) is the most widely used empirical test. In a review article on the valorization of food waste (Capson-Tojo et al., 2016), 11 prior studies on the BMP yields of various food wastes were summarized, with values ranging from 210 to 648 mL CH_4/g VS destroyed. Noting the wide range of results, these authors describe some of the factors that can lead to such variation. However, Parameswaran, Hobbs, Landis, Rittmann, & Young (2017) attained small standard deviations in three replications of BMP tests performed on a mix of food waste and ADS. Methods were used to ensure the inoculum remained viable over time and the pH was carefully monitored. Also, negative controls were used, and the methane production from these controls was subtracted to attain a net methane yield from the samples. Additionally, the Gompertz equation was used to fit the batch methanogenic data over the time period of the BMP tests, and there was a close fit between experimental results and the model estimates. This study would seem to provide a sound methodology for future research on the biogas potential of agro-industry waste in a given geographic area.

Yet, there are cautions in the literature about using BMP tests to evaluate potential anaerobic biotechnology projects, even when the results are highly repeatable. Batstone, Tait, & Starrenburg (2009) noted that BMP tests take place under different conditions than full-scale reactors. Comparing results from identical substrates and inocula in BMP tests and two full-scale digesters, they found that the hydrolysis rates, k_h, were generally an order of magnitude

lower in the BMP tests. The extent of degradability, f_d, was comparable under both conditions. The difference in k_h, which is typically the rate-limiting step at full scale, has implications on using BMP results to evaluate the feasibility of full-scale projects, according to these authors. They note that a low BMP result could unnecessarily eliminate a project from consideration which would actually have environmental and financial benefits.

Given that resource constraints precluded the collection of representative samples from Kansas agro-industry, this thesis tested the use of models based on reported wastewater parameters to estimate the potential benefits of anaerobic pre-treatment of agro-industry wastewater, as will be discussed in Chapter 4.

Chapter 3 - Methods

3.1 Data collection for case study #1: meat packing plant

Data was collected for case study #1 through an internship (Weil, 2017). The meat-packing plant collects wastewater samples for analysis using an autosampler on its discharge line. The collection of weekly samples is performed by the municipal POTW staff, then the samples are sent to an independent lab for analysis of constituent loading. Flow, temperature, and pH data are continuously collected through automated instruments. A spreadsheet tabulating the analytical results for 2016 was provided to the author for the purpose of estimating biogas potential.

3.2 Data collection for case study #2: Kansas State University dairy ranch

Data about the number of cows and the types of wastewater generated at the facility was collected from the Kansas State University web site and confirmed by email (Dr. Joel DeRouchey personal communication, October 12, 2018). The estimated flow and constituent loading per cow were based on values published in the literature.

3.3 Identifying POTWs with agro-industrial users

Data regarding wastewater flow in Kansas was obtained from the USEPA's Clean Water Needs Survey (CWNS, USEPA, 2016a) which was conducted to provide the US Congress with an estimate of the capital funding required to meet water quality objectives. The database (USEPA, 2018b), which was downloaded and analyzed in Microsoft Access, provides data such as existing total flow, industrial flow, present design total flow, and projected design total flow for 624 wastewater treatment plants in Kansas.

A minimum threshold of 1.0 MGD for a survey of agro-industrial wastewater flows was set after reviewing the CWNS data. Of the 624 plants, only 49 indicated that industrial flow is received, and 93.3% of industrial flow is received at the 50 plants greater than or equal to 1.0 MGD.

3.4 Quantifying the agro-industrial sector in Kansas

Data representing a significant fraction of agro-industry in Kansas was obtained from the Kansas Department of Agriculture (KDA) through an open-records request. Fig 5 is a map of Kansas food manufacturing facilities (Kansas Department of Commerce, 2017). The map is based on data gathered by KDA in 2013. Analysis of the food manufacturing facility data found that there are 101 facilities greater than 5,000 square feet in floor area. The types of facilities are: food storage (28), meat processing (23), baked goods/snack foods (15), grain milling/processing (12), ingredients (11), prepared foods (11), and pet food (1). The data on food manufacturing facilities does not capture the entire agro-industrial sector, as defined in the objectives. Animal health facilities, which are prevalent because of the presence of the Kansas City Animal Health Corridor, are not included in this database. Also, waste from bio-energy facilities, of which the

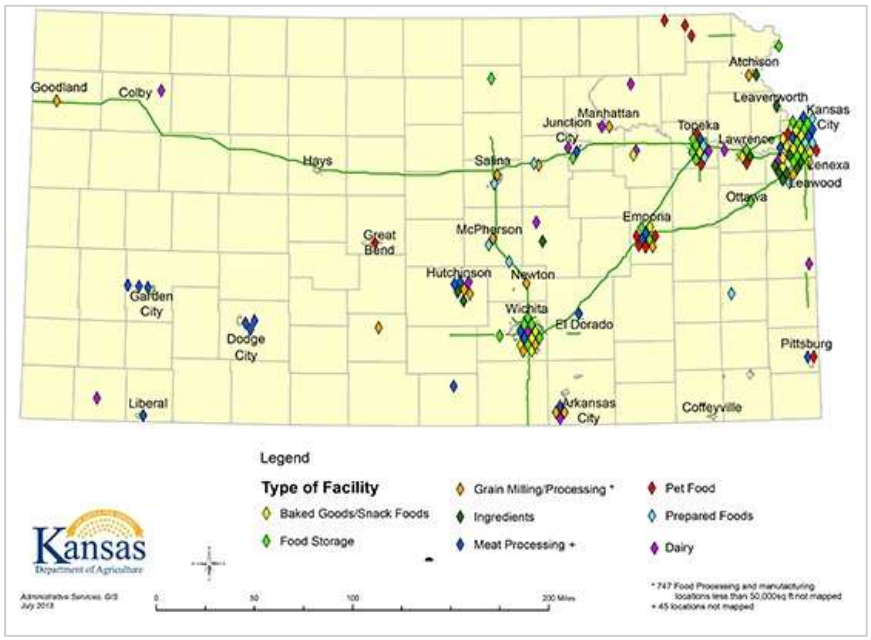


Figure 5 – Kansas food manufacturing facilities

sole example in Kansas is the Western Plains Energy plant in Colby, KS, are not counted. Data was not readily available regarding these non-food agro-industrial discharges. However, the regional biogas yield results would not be affected by this partial count of agro-industrial users, because the data was only used to identify agencies with POTWs that serve agro-industry.

3.5 Estimating wastewater discharges from the agro-industrial sector

Cross-tabulation of the CWNS wastewater treatment plant data and the agro-industrial facility data found that, of the 101 agro-industrial facilities, 87 are in cities with wastewater treatment plants with an existing total flow greater than or equal to 1.0 MGD. This provides another basis for setting a minimum threshold of 1.0 MGD for a survey of agro-industrial wastewater flows.

To collect data regarding wastewater flows from agro-industrial facilities, publicly-owned wastewater treatment works (POTWs) were surveyed. One reason for this survey strategy is data availability. POTWs receiving wastewater from significant industrial users are required by the National Pre-treatment Program (USEPA, 2011) to collect information regarding the BOD_5, TSS and flow from those users. This data is publicly held, although in some cases it was necessary to complete an open records request to access the data.

Another reason for collecting data from wastewater treatment professionals was this population's anticipated awareness of anaerobic biotechnologies within the context of wastewater treatment. It was thought that this population would have a valuable perspective on opportunities and constraints regarding implementation of anaerobic pre-treatment.

There are 17 cities in Kansas with pre-treatment programs (Steve Caspers, KDHE Pre-treatment Specialist, email 6/12/2018). Cross-tabulation of this data with the CWNS database indicates that the existing total flow, 183 MGD, to these 17 cities represents 82% of the flow to

all POTWs receiving greater than or equal to 1.0 MGD. However, to capture as much of the data as possible, it was decided to include all Kansas agencies with POTWs greater than or equal to 1.0 MGD. This added 21 other agencies, some of which may have agro-industrial users whose industrial wastewaters are not expected to interfere with the operation of the POTW. These agencies are not required to have pre-treatment programs, according to the terms of the National Pre-treatment Program (USEPA, 2011). As of 2011, only 10% of the POTWs in the US were required to have pre-treatment programs. However, those POTWs represent 80% of the wastewater flow in the US (USEPA, 2011), similar to Kansas.

An internet-based survey (See Appendix A) using Qualtrics as the platform was designed to collect this information. KDHE provided the names and email addresses of the pre-treatment coordinators for the 17 agencies in the NPDES pre-treatment program. The names and email addresses of wastewater treatment managers for the 21 agencies operating POTWs not in the National Pre-treatment Program but greater than or equal to 1.0 MGD were obtained by calling those agencies. The survey was sent by email to these 38 individuals on 8/13/18 and the survey was closed on 9/6/18.

The survey asked for information about "agro-industrial users" and defined that term as "industries that discharge heavy organic loads." This definition was thought to reflect the intent of the thesis objective in a clear way with a small number of words.

3.6 Surveying attitudes towards anaerobic wastewater biotechnology

A second section of the survey was designed to assess awareness and attitudes towards anaerobic digestion in the survey population. Again, this population consisted of pre-treatment personnel responsible for industrial pre-treatment at agencies with POTWs having a capacity greater than or equal to 1.0 MGD. Various recommended techniques (Vannette, 2018) were used

to improve survey questions, validity and response rate. For example, the length of the survey was kept to less than 10 minutes as that is a key factor in response rate. The initial screen explained why the information was needed and how it would be used, and respondents were encouraged to be thoughtful and accurate in their answers; such statements have proven to be effective in attaining valid responses (Vannette, 2018). The questions were grouped into sections for easy viewing on a computer screen or mobile device. The questions were kept simple, specific and focused on only one topic at a time. Bias towards anaerobic biotechnologies was avoided, and the scale of responses was balanced as to negative and positive choices. One question was reverse-scaled in which the expected reply was on the negative side of the scale. No more than seven possible responses were provided for each question, and an "Other (please specify): _____" response was included; this approach has been shown to maximize the useful responses (Vannette, 2018). All but the "Other" responses were randomized to avoid bias towards the first responses on the list.

The survey was pre-tested on members of the research group, and feedback was used to improve the survey design.

3.7 Statistical methods

The Microsoft Excel 2016 Data Analysis pack was used to determine the median wastewater discharge parameters from Kansas agro-industry and to analyze wastewater data for case study #1 (See Section 4.6). The flow, pH and temperature data for case study #1 were segregated into Thursday and Sunday observations to characterize statistically significant differences in these parameters when the meat packing plant was operating and during its cleaning cycle. The one-tailed t-Test was used with $\alpha = 0.05$. Where variances were approximately equal, the two-sample t-Test was performed with assumed equal variances. The

linearity of the correlations between TCOD and BOD_5, TSS, TKN, Total P, Oils and Grease, and Chlorides for case study #1 was evaluated using the R^2 coefficient of determination, which was also calculated using Microsoft Excel.

Chapter 4 - Results and Discussion

4.1 Evaluation of parameter-based models for regional biogas estimation

Table 5 provides the results of an evaluation of a range of models for estimating potential biogas yield from parameters available for agro-industrial wastewater users in Kansas. The models range from well-established (Batstone et al., 2002; Rittmann & McCarthy, 2001; Symons & Buswell, 1933; Tchobanoglous et al., 2003; Water Environment Federation, 1998) to models based on a review of other works (Harikrishnan, 2008; Lin, Dutta, Daverey, Wenshan, & Ngo, 2016) to novel and untested models (Heidrich, Curtis, & Dolfing, 2011). All are based, either directly or indirectly, on the stoichiometric relationship between the chemical composition of the organic substrate and the yield of CH_4 after methanogenesis, as first set forth by Symons & Buswell (1933).

A difficulty with using some of these models for a regional estimate is that the only parameters required to be reported by special industrial users under the NPDES are flow, BOD_5 and TSS (USEPA, 2011). While it would be theoretically possible to estimate the chemical composition of agro-industrial wastewater in Kansas based on the types of food processing industries located here, it would probably not be accurate, as the range of effluent characteristics from a single industry can be quite wide. For example, the typical BOD_5 from a dairy processor is reported to be 0.5-1.3 g/l for fluid milk and up to 60 g/l for cheese whey (Slavov, 2017). As another example, it might seem plausible to use the percentages of protein, fat, cellulose, hemicellulose and carbohydrates in a typical sausage to estimate methane yield from a meat-packing plant per the methods set forth by the Water Environment Federation (2010). However, on any given day, the wastewater from that plant might include any number of meats, ingredients or other waste products, including cleaning chemicals.

Table 5 – Comparison of parameter-based models for regional biogas yield estimate

Author(s) (Year)	*Theoretical basis*	*Empirical validation*	*Advantages*	*Disadvantages*	*Applicability to regional estimate of biogas yield*
Symons and Buswell (1933)	Generalized stoichiometry based on chemical composition of substrate	Lab-scale experiments based a wide range of substrates	• Widely accepted stoichiometric relationship	• Chemical composition of substrates unknown when preparing a regional estimate • Effects of inhibition, cell synthesis, other factors not accounted for	Not applicable for regional estimate
Lin, Dutta, Davery, Guo and Ngo (2007)	Energy potential of wastewater = 14.7 kJ/g COD	Summarized biogas yield; average of four studies = 0.33 L CH_4/g COD removed	• COD and COD removal rates are relatively common values	• BOD_5, not COD, is a required reporting parameter in industrial pre-treatment program • Authors not clear regarding temperature, pressure of cited studies, scale of plants	Not applicable for regional estimate
Heidrich, Curtis and Dolfing (2011)	Enthalpy of reaction; the authors calculate a higher energy potential of wastewater when higher ratio of H_2 in reducing reactions	Lab-scale measurement of energy yield on freeze-dried wastewater samples, including an industrial sample	• Source highly cited • Finds a higher energy potential than previous authors	• Model not widely accepted or empirically validated	Not applicable for regional estimate; however, it indicates a potentially higher energy yield than previously assumed
Harikishan (2008)	1 kg COD destroyed produces 0.35 m^3 of CH_4 at STP	None provided	• COD and COD removal rates are relatively common values	• Author provides no empirical basis • Author does not address factors that	Not applicable for regional estimate

Author(s) (Year)	*Theoretical basis*	*Empirical validation*	*Advantages*	*Disadvantages*	*Applicability to regional estimate of biogas yield*
			• Author provides clarity regarding temperature, pressure of model	would lower biogas yield below theoretical maximum	
Water Environment Federation/American Society of Civil Engineers (2010), Volume 3	None provided; indirectly based on stoichiometry	Methane yield for sludge digestion estimated at 0.8 – 1.0 m^3/kg of VSS destroyed	• High level of credibility for this reference • Years of full-scale operation inform this estimate • Provides a range of values; useful for regional estimate • TSS is one of the required reporting parameters for industrial pre-treatment program; VSS/TSS ration accepted to be ~80%	• Estimate based on sludge digestion, not agro-industrial waste; there could be different yields for various substrates • Theoretical basis not provided	Highly applicable for regional estimate
Batstone et al. (2002)	First principles of biochemical and physico-chemical processes	A later study, Batstone, Tait and Starrenburg (2008) found good fit between theoretical and actual values	• Internationally accepted model	• Model involves 24 biochemical rate coefficients for 19 processes; these parameters could not be accurately assumed for a regional estimate	Not applicable to a regional estimate
Tchobanoglous, Burton and Stensel (2003) Chapter 7-12, Anaerobic	Mass balance on COD. Influent COD converted to methane = influent COD –	None provided	• Strong theoretical basis, accounts for process fully	• BOD_5, not COD, is a required reporting parameter in industrial pre-	Somewhat applicable to a regional estimate; midpoint of

Author(s) (Year)	*Theoretical basis*	*Empirical validation*	*Advantages*	*Disadvantages*	*Applicability to regional estimate of biogas yield*
Fermentation and Oxidation	effluent COD – influent COD converted to cell biomass			treatment program • Requires assumption of COD removal rate and COD conversion rate (there is a factor of 2 in the range of typical values)	typical values can be used as a cross-check
Tchobanoglous, Burton and Stensel (2003) Chapter 14-9, Anaerobic Digestion of Biosolids	Mass balance on COD, discussed above	Methane yield for sludge digestion estimated at 0.75 – 1.12 m^3/kg of VSS destroyed	• High level of credibility for this reference • Years of full-scale operation inform this estimate • Provides a range of values; useful for regional estimate • TSS is one of the required reporting parameters for industrial pre-treatment program; VSS/TSS ratio accepted to be ~80%	• Estimate based on sludge digestion, not agro-industrial waste; there could be different yields for various substrates • Provides a wider range of values than MOP-8; thus, less useful for a regional estimate • However, the range of values brackets those stated in MOP-8; thus serving to validate those values	Somewhat applicable to a regional estimate; if a broader range with a higher confidence level is needed

A number of studies (Cvetković, Radoičić, Vukadinović, & Kijevčanin, 2014; Harikrishnan, 2008; Kumaran, Hephzibah, Sivasankari, Saifuddin, & Shamsuddin, 2016) use the stoichiometric value of activated sludge fully converted to methane, which is 0.35 m^3 CH_4/kg COD destroyed, to estimate the regional biogas potential if anaerobic biotechnologies were used to pre-treat agro-industrial wastes. However, one disadvantage of this method is the fact that BOD_5, not COD, is a required reporting parameter. Although it is common to use a BOD_5/COD

ratio of 0.5, Tchobanoglous et al. (2003) estimate a wide range for this ratio: between 0.3 and 0.8. The BOD_5/COD ratio for Smithfield Foods was 0.6, and it is likely that each industry would be different. A more significant disadvantage of this method is that it does not consider that the yield of 0.35 m^3 CH_4/kg COD destroyed is a stoichiometric maximum; factors such as inhibition, losses due to biosynthesis and sludge wasting, and biomass washout are not accounted for. While an average yield of 0.33 m^3 CH_4/kg COD destroyed was reported by Lin et al. (2016) in their review of other works, and this value is close to the stoichiometric maximum, the temperature and pressure at which the yield was attained was not stated. Under the Ideal Gas Law, 0.33 m^3 of CH_4 at mesophilic temperature of 35°C would have a much smaller volume, 0.29 m^3, at 0°C.

The International Water Association Anaerobic Digestion Model No. 1 (Batstone et al., 2002, 2009; Batstone & Keller, 2003), while well-researched and empirically validated, involves 24 biochemical rate coefficients for 19 processes and thus is not well suited for a regional biogas yield estimate, in that the reactors and operating parameters for each user would be unknown.

The work of Heidrich et al. (2011) points to a potentially higher biogas yield, especially for industrial wastewater, than previously modeled. However, the model put forth by these authors is not widely accepted or empirically validated.

The remaining models are from three well-respected sources in the wastewater industry: Rittmann & McCarty (2001); Tchobanoglous et al. (2003); and Water Environment Federation (2010). Whereas Tchobanoglous et al. (2003) uses COD as the input parameter, the other two use VSS. Because VSS is typically about 80% of TSS (Tchobanoglous et al., 2003) and TSS is a required reporting parameter, these two models are well-suited to a regional estimate. It is also helpful that these two models give a range of expected biogas yield, which is realistic and

accounts for the variety of conditions that would be encountered if the biotechnology were widely adopted in Kansas.

For these reasons, the VSS-based model set forth in the Water Environment Federation (1998) reference was selected for estimating regional biogas potential in this thesis. However, it should be noted that this reference is based on the biogas potential of waste activated sludge, a different substrate than raw agro-industrial waste. Also, to be relied upon in the literature, empirical validation would be required, which was not possible, given the limited time and budget for this research. Ideally, a model that also used the BOD_5 parameter could be developed through linear regression of experimental data. Such a model would account more fully for the bioavailable organic Carbon in agro-industrial wastes, which depends on both soluble and particulate substrates. This would be a valuable area for further research.

4.2 Median agro-industry wastewater parameters

Table 6 presents the results of the survey of agencies with POTWs ≥ 1.0 MGD (3,785 m^3/d) in Kansas. A total of 22 out of the 38 agencies responses were obtain for this portion of survey. Nine agencies provided data regarding agro-industry in their jurisdiction via the online survey. One agency provided data about five agro-industries in its jurisdiction via an email response. The data for case study #1 was used for one response. Data was obtained from one agency via an open-records act request. For eight agencies, a negative response (i.e. no agro-industrial users in the facility) was obtained by telephone call. Overall, there was a 58% response rate. Only the online responses are included in the summary report in Appendix A.

Of the nine agencies that participated in the online survey, five completed only the portion of the survey that requested data on agro-industrial users. The remaining four agencies completed the attitude and awareness portion of the survey discussed in Section 4.9.

Of the respondents, 8 agencies (40%) had agro-industrial users. The types of agro-industrial wastes included meat processing waste, grain waste, manure wastes, and animal carcass disposal. The names of the agencies have been anonymized.

Table 6 – Survey responses from Kansas agencies regarding agro-industrial wastewater

Agency/ Industry	Flow (m^3/d)	BOD_5 (mg/L)	TSS (mg/L)	Agency/ Industry	Flow (m^3/d)	BOD_5 (mg/L)	TSS (mg/L)
A/1	238	3,928	2,061	I *	-	-	-
A/2	492	575	623	J *	-	-	-
A/3	55	3,107	378	K *	-	-	-
A/4	276	764	465	L *	-	-	-
A/5	583	1,117	1,435	M	-	-	-
B *	1,325	1,500	300	N	-	-	-
C *	384	3,750	300	O	-	-	-
D *	189	150	100	P	-	-	-
E/1 *	95	200	100	Q	-	-	-
F/1 *	390,423	3,998	2985	R	-	-	-
E/2 *	946	1,500	500	S	-	-	-
F/2 *	254	1,472	251	T	-	-	-
G	1,938	498	455				
H/1	0.4	6,314	96				
H/2	0.2	1,883	153				

* Data received via online survey. Other data received via email, telephone, or open records request.

Data was obtained for 15 agro-industrial users. Of these, 12 (80%) currently pre-treat their wastewater prior to discharging it to the POTW. Two users reported intermittent, high-strength, discharges; the data for these users was converted to daily averages.

Fig 6 summarizes the flow data. The highest and lowest values were omitted from this figure for clarity and from the median calculation (the difference with and without these two data points was not significant). The median value was 276 m^3/d.

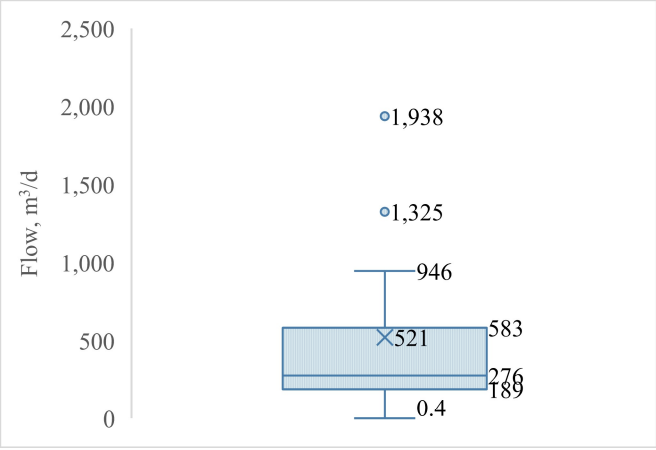


Figure 6 – KS agro-industry wastewater flow

The BOD_5 data is summarized in Fig 7. The median value, 1,500 mg/L, is at a level at which anaerobic treatment is considered beneficial (Tchobanoglous et al., 2003).

See Fig 8 for the TSS data. The median value is 378 mg/L. Outlying data tended to be above the upper quartile.

There was a wide range of responses, with the standard deviation approximately equal to the mean for all three parameters. Thus, the median value, which was lower than the mean for all three parameters, was used for the estimate of regional biogas potential. The estimate could be further refined as a future research project by performing case studies for the discharges most suited to anaerobic pre-treatment.

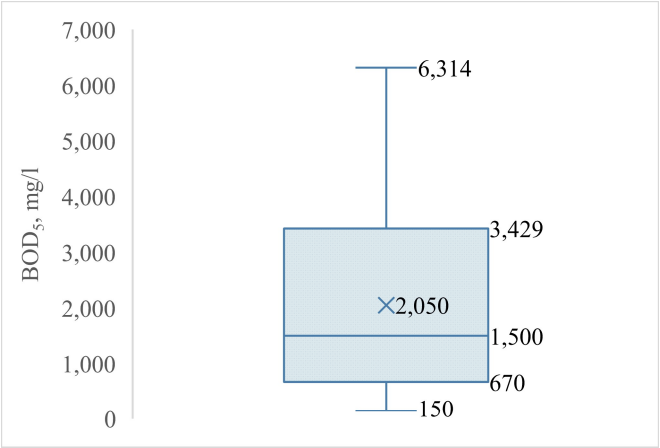


Figure 7 – KS agro-industry wastewater BOD_5

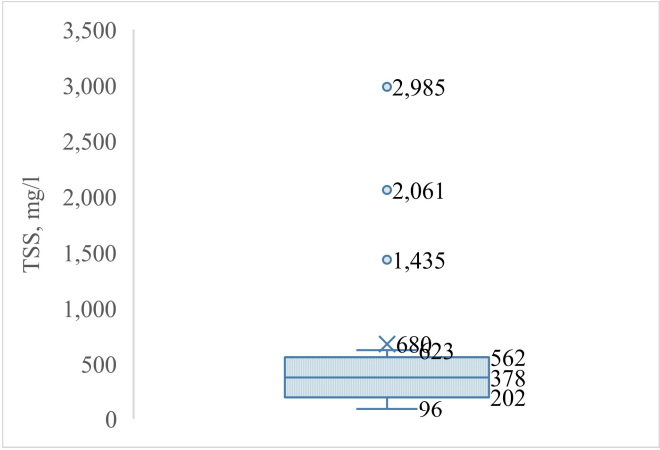


Figure 8 – KS agro-industry wastewater TSS

4.3 Regional biogas yield estimate

Table 7 provides a range of estimates for biogas yield using the two VSS-based models (Tchobanoglous et al., 2003; Water Environment Federation, 1998) and the median agro-industry wastewater parameters in Kansas.

Table 7 – Range of estimated biogas yield

Given the following median values for agro-industrial discharges in Kansas, estimate biogas yield (m^3 CH4/d) using the sources and equations provided:

Q	276	m^3/day
BOD_5	1500	mg/L
TSS	378	mg/L
VSS/TSS Ratio	80%	
VSS Destruction	67%	

Author(s) (Year)	**Additional Inputs/Assumptions**	**Result (m^3 CH_4/d)**
Water Environment Federation (2010), Volume 3, Low Value	CH_4 = 0.8 m^3/kg VSS destroyed	45
Water Environment Federation (2010), Volume 3, High Value	CH_4 = 1.0 m^3/kg VSS destroyed	56
Tchobanoglous et al. (2003), Chapter 14-9, Anaerobic Digestion of Biosolids, Low Value	CH_4 = 0.75 m^3/kg VSS destroyed	42
Tchobanoglous et al. (2003), Chapter 14-9, Anaerobic Digestion of Biosolids, Low Value	CH_4 = 1.12 m^3/kg VSS destroyed	63
Median value (m^3 CH_4 per day)		**50**

The assumed VSS destruction rate of 67% is based on a review of the range of values presented in the literature for various substrates. The average UASB VSS destruction rate in Latin America and India for raw municipal wastewater is reported to be 45% - 81% by Water Environment Federation (2010); the midpoint of that range is 63%. Rittmann & McCarty (2012) provide an upper boundary of 67% for solids reduction, with the qualification that this value applies only to fresh wastes, as is the case in this analysis. Water Environment Federation (2010) reports BOD and TSS reduction for waste activated sludge in the range of 65% to 80% using anaerobic treatment. Higher values have been reported in the literature (e.g. 85% for food

waste by Mao, Feng, Wang, & Ren, 2015, 99% for slaugherhouse waste by Bustillo-Lecompte & Mehrvar, 2017).

It can be observed that the range of estimated biogas yield based on the Water Environment Federation (2010) methodology falls at the midpoint of the estimates. Thus, the average of these two values, 0.9 m^3 CH_4/kg VSS destroyed, will be used in the two case studies in this thesis.

As stated in Section 4.1, the survey indicates that 40% of the 38 agencies in Kansas with POTWs ≥ 1.0 MGD receive wastewater from agro-industrial users, which equates to 15 agencies. The survey also indicates that, on average, each agency receiving agro-industrial wastewater serves two users. Thus, the biogas potential can be estimated by multiplying the yield based on median wastewater parameters by 30, as set forth in Table 8.

Table 8 – Estimated biogas yield

	Low	Median	High
m^3 CH_4 per day	42	50	63
d/y	365	365	365
Agencies	15	15	15
Agro-industrial users/agency	2	2	2
CH_4 m^3/y at STP	460,000	548,000	690,000
MMBtu/y (0.036 MMBtu/m^3 CH_4)	16,600	19,800	25,000

Based on 1,100 m^3/year for an average residence (see Appendix B), the median biogas potential represents enough natural gas to supply about 500 homes.

It should be noted that the data gathered in the survey represents the wastewater received at the POTW after industrial pre-treatment. As stated, 80% of agro-industrial users currently perform some level of pre-treatment. If anaerobic biotechnology were to replace the existing agro-industrial industrial pre-treatment systems, the biogas potential would be significantly higher.

4.4 Validity of parameter-based models

One might ask whether a parameter-based model can reasonably be used to provide a regional estimate of biogas yield. One answer to that question is that there are numerous studies which do so (Cooley & Lee, 2013; Cvetković et al., 2014; Kumaran et al., 2016; Milbrandt, 2013; Moreda, 2016; Murray et al., 2017; Rapport et al., 2008). Also, the work of Kythreotou, Florides, & Tassou (2014) supports this approach. These authors evaluated both scientific and simple biogas yield models. The simple models estimated biogas yield from volatile solids destruction, as considered in this thesis. Kythreotou et al. (2014) then applied the simple models to a test case of 100 dairy cows and 50 sow pigs and found fairly good consistency in the biogas yield results, which were all on the same order of magnitude. These authors supported the use of simple models for an initial estimate of the viability of anaerobic biotechnology projects.

4.5 Other potential environmental benefits and costs

In addition to biogas, potential environmental benefits include a reduction in organic loading and biosolids produced at POTWs as well as greenhouse gas reduction. However, there could be negative greenhouse gas impacts as well, as discussed below.

Water Environment Federation (2010) reports an average BOD_5 reduction of 72% through anaerobic treatment of wastewater. Thus, the median BOD_5 loading discharged by agro-industrial users in Kansas, 1,500 mg/L, could be reduced to 420 mg/L by implementing anaerobic pre-treatment. This value is close to the range of residential BOD_5 loading for which POTWs are designed (Tchobanoglous et al., 2003).

Tchobanoglous et al. (2003) state that biosolids production is reduced by a factor of 6-8 when anaerobic treatment is used in place of activated sludge treatment. Assuming that activated sludge is the current POTW treatment process and using the methods set forth by these authors

(See Appendix B), the estimated biosolids resulting from agro-industry wastewater discharges in Kansas would be 1,400 tonnes/year. Anaerobic pre-treatment would reduce this amount by approximately 1,100 to 1,200 tonnes/year. Given increased regulatory concerns about land application of biosolids, this could be a significant environmental benefit.

The energy required for the activated sludge process would theoretically be reduced, as contemplated by McCarty, Bae, & Kim (2011) and others. However, this benefit would depend on a number of factors and cannot easily be estimated.

Greenhouse gas effects represent both a potential benefit to the environmental as well as a possible negative impact. Gasper & Searchinger (2018) discuss the climate impacts of biogas, noting that methane has 25-34 times the warming potential of CO_2 over a 100-year period. Given that the biogas produced from anaerobic treatment of agro-industrial wastewater is a new source of methane that would not exist in the current case of aerobic treatment at POTWs, this could be a significant impact. Much depends on the leakage rate and the loss of dissolved methane in the wastewater effluent. Gasper & Searchinger (2018) report that methane leakage during anaerobic digestion is typically in the range of 2% - 5%, which is low enough that a climate benefit would be realized. Assuming that the biogas is conditioned and used on site at the agro-industrial facility, there would be no losses due to transmission, distribution, fueling or vehicle emissions. These authors recommend that producing biogas from existing waste streams, as contemplated in this thesis, is beneficial for the climate. Hansupalak et al. (2016) estimated that greenhouse gas emissions in Thailand were reduced by 0.9 – 1.0 million tons CO_2eq/year, as a result of converting 90% of cassava starch factories from fuel oil to biogas generated onsite from anaerobic pre-treatment of factory wastes.

On the other hand, Smith et al. (2014) modeled the energy and climate effects of various means of treating municipal wastewater and found that the AnMBR biotechnology then available had higher energy and climate impacts than selected aerobic biotechnologies, including conventional activated sludge. The key factor in their analysis was the high level of dissolved methane (up to 70% at 15°C operating temperatures). However, the model of Smith et al. (2014) found that if the dissolved methane could be recovered from effluent, AnMBR would be energy- and climate-positive. Evans et al. (2017), working on this issue, successfully applied a membrane cell to AnMBR permeate and recovered a high level of methane. Thus, it appears that relatively simple solutions, such as leak management and methane recovery, can ensure that anaerobic biotechnology has positive climate benefits.

The greenhouse gas benefits from anaerobic digestion of solid waste is more easily quantified. The USEPA (2016) has included anaerobic digestion in its 2016 version of the Waste Reduction Model (WARM). Also, Rapport et al. (2008) provided the California Integrated Waste Management Board with a detailed analysis of the benefits of anaerobic digestion of solid waste and found significant reductions in greenhouse gases as well as noxious air emissions as compared with landfill disposal. It should be noted that biogas leakage rate from landfill gas systems is at 15% - 25%, well above the threshold where the impacts on the climate are negative.

Anaerobic biotechnology can also reduce the emissions of N_2O, a potent greenhouse gas, from wastewater treatment processes. Anaerobic treatment processes preserve nitrogen in the form of NH_4, ammonium, which can then be recovered by various means and used as a fertilizer (McCarty et al., 2011; Mohankumar Sajeev, Winiwarter, & Amon, 2017). Nishio & Nakashimada (2013) proposed a process to strip ammonia as part of a two-stage wet/dry

anaerobic reactor system. Potassium and phosphate were also preserved and included in the fertilizer product.

4.6 Case study #1: meat packing plant

4.6.1 Plant description

The plant produces smoked sausages and hot dogs from a variety of raw meats and other ingredients. The plant does not have a slaughterhouse operation. Its wastewater is discharged to a POTW without pre-treatment. In fact, the POTW was constructed concurrent with the meat packing plant in an economic development partnership according to Kerry Peterson, Veolia Corporation (personal communication, February 5, 2013).

During 2016, the plant operated 24 hours a day for 5 or 6 days a week. The meat-packing operation was typically suspended on Sundays and sometimes on Saturdays. Occasionally, the work week was extended through Sunday to allow for a long holiday break the following week or to meet production quotas.

Metered municipal water was used for many purposes in the plant, with cooling of equipment and washdown of mixers and ovens being significant demands.

4.6.2 Flow, temperature and pH

The flow, temperature and pH data were segregated to analyze Thursday and Sunday readings separately. This enabled a more accurate characterization of these parameters, which have an effect on biogas generation. It also shed light on how an anaerobic pre-treatment system could be affected by the cleaning operation. The data for these three parameters was not skewed.

Fig 9 shows the wastewater flow data. The Thursday flow data showed a high level of consistency, with a mean flowrate of 2,289 m^3/d and a standard deviation of 200 m^3/d. Outlying data tended to be below the bottom quartile and were likely associated with partial shutdowns of packing lines due to operational problems.

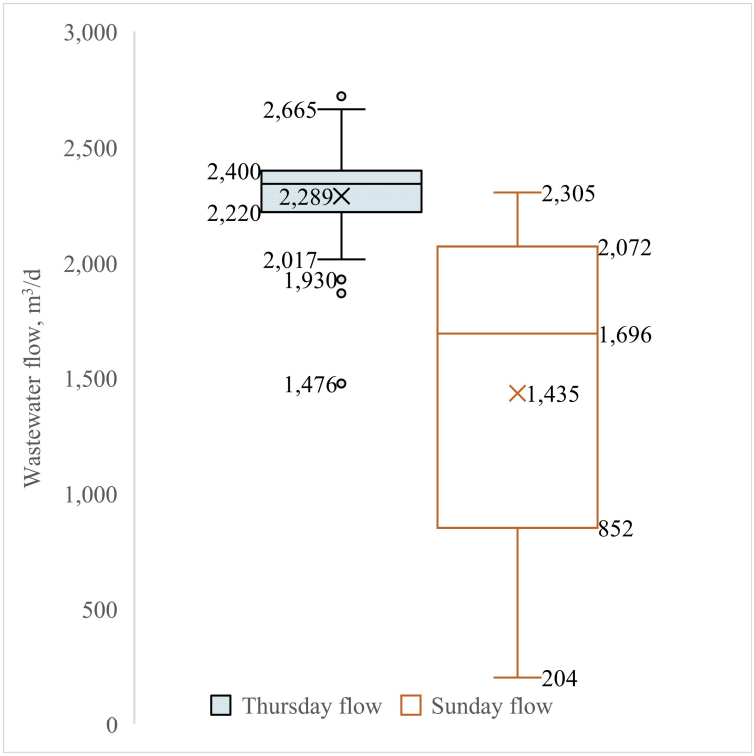


Figure 9 – Meat Packing Plant Wastewater Flow

On the other hand, the wastewater flow on Sundays was highly variable and generally lower. The plant did not have the capability to turn off the cooling water flow, so there was a baseline of continuous flow; it never dropped below 204 m^3/d. On top of that baseline flow, cleaning and processing flows were added. The highest flows tended to be on the last Sundays of the month, and perhaps represented extra work days to meet production quotas. The difference between Thursday and Sunday wastewater flows was statistically significant ($p < 0.001$).

The temperature data is summarized in Figs 10 and 11. Because the water supply was used for cooling plant equipment and for washing down cooking equipment, it was typically elevated above 20°C. It was not influenced by ambient air temperatures.

The weekday mean and standard deviation was 23.7°C and 3.0°C, respectively. This is significant because 20°C is the recommended minimum temperature for the use of an upflow anaerobic sludge blanket reactor, a preferred design according to the Water Environment Federation (2010) in their chapter on anaerobic treatment. Sunday temperatures were less consistent and lower at a statistically significant level ($p <$ 0.005).

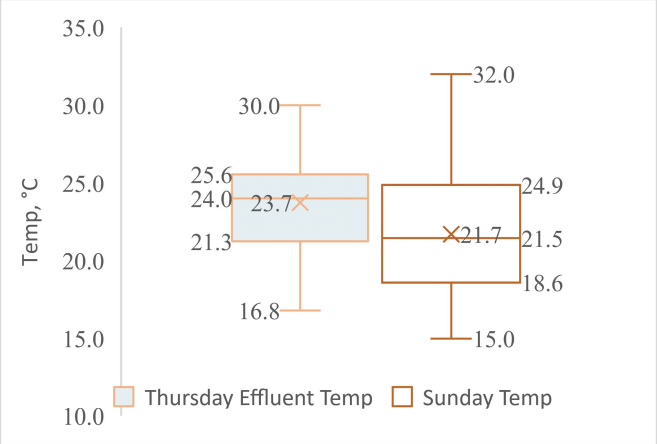


Figure 10 – Meat Packing Plant Wastewater Temperatures

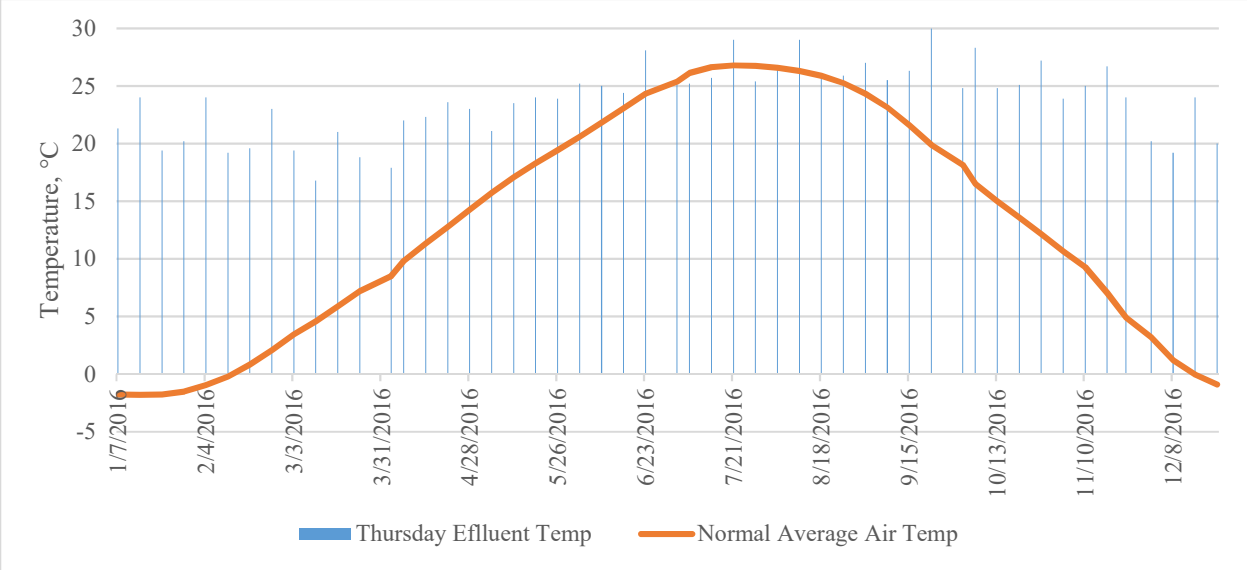


Figure 11 – Meat packing plant wastewater and ambient temperatures

The pH during plant operation (See Fig 12) was also highly consistent, with a mean and standard deviation of 7.7 and 0.6, respectively. This pH is within but at the upper range of that recommended for methanogenesis (Rittmann & McCarthy, 2001). The elevated pH was influenced primarily by the source of water supply for the meat packing plant. The 2014

consumer confidence report for the agency supplying the water to the plant reported pH and alkalinity of 8.7 and 110 mg/L, respectively (Veolia Corporation, 2015). The Sunday pH was higher at a statistically significant level ($p < 0.001$) and less consistent. This probably represents the use of caustic chemicals for cleaning and the washdown of ammonia-based products which are used for cooling and sanitation.

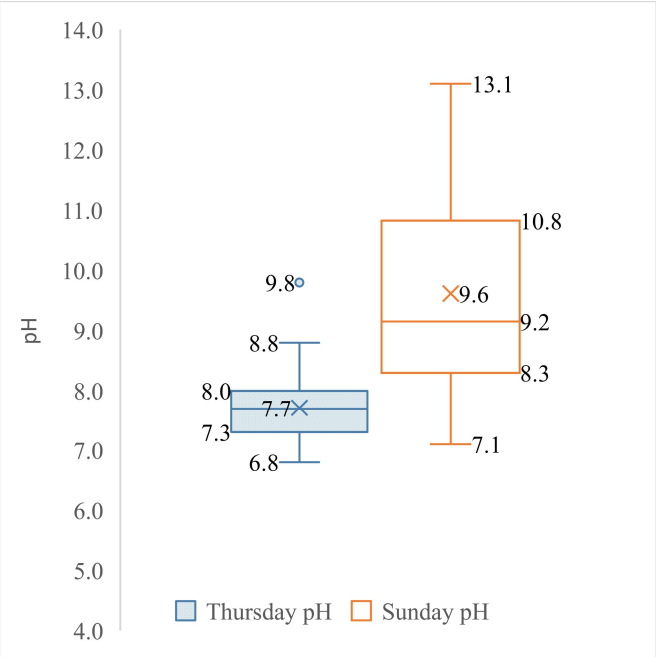


Figure 12 – Meat packing plant pH

These pH levels are above those recommended for methanogenesis, which presents an issue which would need to be addressed during preliminary design.

4.6.3 Constituent loading

Table 9 summarizes the constituent loading for the Thursday samples. Because all of these data sets had skew, a geometric mean and geometric standard deviation were used to estimate the 95% confidence interval, per Tchobanoglous et al. (2003). It is assumed that the TKN is reported as N and that the Total P is reported as P.

Table 9 – Meat packing plant organic loading

Constituent (mg/L)	Geometric mean	Geometric standard deviation, Sg (dimensionless)	Lower boundary of 95% confidence interval	Upper boundary of 95% confidence interval
BOD_5	485	1.25	0	1,700
COD	876	1.24	0	3,040
TSS	348	2.01	0	1,752
TKN	19.3	2.01	0	72.8
Total P	2.98	1.44	0	23.2
Oil & Grease	73.8	2.07	0	379
Chlorides	484	1.25	0	1700

Tchobanoglous et al. (2003) states that below COD levels of 1,300 mg/L, aerobic treatment may be preferable to anaerobic treatment. However, J. B. van Lier (2008) states that COD levels as low as 100-200 mg/L can be successfully treated using anaerobic biotechnologies, and a review article by Chan, Chong, Law, & Hassell (2009) lists 11 studies in which anaerobic treatment was successfully used on wastewater with COD levels less than 1,300 mg/L. In Chernicharo, van Lier, Noyola, & Bressani Ribeiro (2015), all of the studies representing state-of-the-art anaerobic treatment biotechnologies had influent COD levels less than 1,300 mg/L.

The ratio of TSS to COD is appropriate for the formation of sludge granules (Rittmann & McCarthy, 2001; Water Environment Federation, 1998).

The level of TSS is relatively low, which would reduce biogas generation rate, but not the effectiveness of anaerobic pre-treatment. No minimum TSS level is established in the literature.

N and P levels are sufficient for growth and not at inhibitory levels (Tchobanoglous et al., 2003).

The elevated chloride levels are due to the sodium salts used in the food processing operation. The geometric mean is at a level which could be stimulatory to anaerobic digestion, and the upper end of the 95% confidence interval is below moderately inhibitory concentrations (McCarty, 1964).

Correlations between organic wastewater constituents and COD were analyzed for the purpose of understanding the relationships between them, as shown in Table 10. Skew was observed in the upper quartile of the data set. These intermittent higher loadings could have been due to processing upsets, cleaning, or other factors. Table 10 shows the relationship of these constituents, excluding the upper quartile.

It is interesting that TSS increased at a nearly 1:1 linear rate with COD but was about 580 mg/L lower. This could have been caused by high chloride levels, which are known to consume dichromate in the COD test. The fact that chlorides and COD also have strong relationship supports this inference. In fact, there are a number of possible interferences with BOD_5 and COD analysis, especially for industrial wastewaters (Tchobanoglous et al., 2003), which supports the use of TSS as a parameter for estimating biogas yield on a regional basis.

Table 10 – Meat packing plant organic loading relationships

Constituent	As a function of COD	R^2
BOD_5	0.584·COD – 25.5	0.96
TSS	1.05·COD – 580	0.92
TKN	0.0233·COD – 1.96	0.95
Total P	0.010·COD – 2.78	0.92
Oil & Grease	0.213·COD – 114	0.97
Chlorides	0.626·COD – 59.4	0.98

It would be interesting to see if the same kind of correlations are found in other agro-industrial wastewaters. If so, that would open up more avenues for developing pre-treatment reactor designs. In this case, a simple reactor design based on TSS will be developed, as discussed in Section 4.6.4.

4.6.4 Reactor design for meat packing plant

A conceptual design was prepared to pre-treat the plant's wastewater. An upflow anaerobic sludge blanket (UASB) design was selected based on the guidance in Water

Environment Federation (2010). Example 10-3 from Tchobanoglous et al. (2003) was used as a guide for the design (See Appendix B). Table 11 provides the estimated reactor characteristics.

Table 11 – Conceptual UASB reactor for meat packing plant

Design characteristic	Estimate
Diameter	11 m
Height:	
Liquid	3.6 m
Gas collection	2.5 m
Total height	6.1 m
Liquid volume	359 m^3
Hydraulic retention time	3.6 h
Solids retention time	27.5 d
Effluent COD	130 mg/L
COD removal efficiency	85%
Average biomass concentration, X_{TSS}	27.3 mg/L
Methane biogas production	543 m^3/d
Alkalinity requirements	6,200 kg/d $CaCO_3$ equivalents

An unused portion of the case study site, which is adjacent to the existing wastewater discharge line, is large enough to accommodate the dimensions of the reactor (Fig 13).

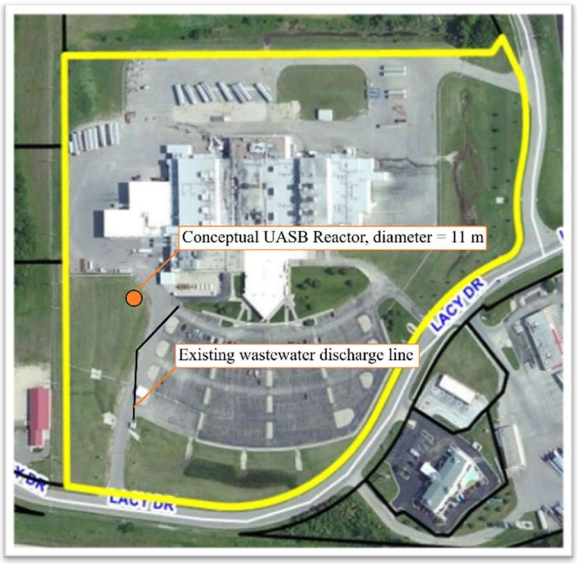


Figure 13 – Potential UASB reactor location on meat packing plant site

When the median value of the parameter-based model (Section 4.1), based on 0.9 m^3 CH_4/kg VSS destroyed, was applied to this case study, the estimated biogas yield was 272 m^3/day, when converted to 25°C. The higher value for biogas production resulting from the conceptual reactor design, 543 m^3/day, indicates that the parameter-based model is conservative, which is desirable.

The meat packing plant weekday flow rate, 2,297 m^3/d, is about ten times the median flowrate for agro-industry in Kansas, 276 m^3/d. This indicates that, in general, the typical agro-industry anaerobic pre-treatment system in the region would be fairly small.

The large alkalinity requirements, 6,200 kg/day of lime, represent a potentially unacceptable operating cost. Tchobanoglous et al. (2003) indicate that alkalinity can be produced from anaerobic treatment of meat-packing waste. This would result from the ammonia released during anaerobic treatment of the nitrogen-rich protein material. The topic of large alkalinity requirements for anaerobic treatment of agro-industrial wastes is not addressed in the literature, which may indicate that the waste itself does provide alkalinity in practice. However, several authors (Babaee, Shayegan, & Roshani, 2013; Kumari, Suresh, Arisutha, & Sudhakar, 2018; Parameswaran & Rittmann, 2012; Carlos Rico, Muñoz, Fernández, & Rico, 2015) recommend co-digestion of manure, paper waste, or other materials in order to balance alkalinity. The meat packing plant has several solid waste streams which would lend themselves to co-digestion, including cellulose-based spent sausage casings. This issue would need to be evaluated during preliminary design.

4.6.5 Economic evaluation of meat packing plant reactor

Based on the cost range of \$300 - \$500 per m^3 of reactor volume per Deublein & Steinhauser (2011), the capital cost for the 359 m^3 UASB treatment reactor, excluding ancillary equipment such as combined heat and power (CHP) or biogas conditioning equipment, would be on the order of \$100,000 - \$180,000. A cross-check was made using the following cost-estimating equation for a gravity sludge thickener, provided by McGivney & Kawamura (2008):

$$y = 2798.7 \cdot x^{1.305} \qquad \text{Equation (1)}$$

where y = cost in $US and X = diameter in feet. The gravity sludge thickener was chosen because its design and complexity are comparable to a UASB reactor. Equation (1) results in an estimated cost of $300,000 for the 11 m diameter UASB reactor. Thus, a conservative capital cost estimate for this case study is $200,000 - $300,000.

Operating costs are estimated at 3.5% of capital costs per year plus $10,000 in labor plus $5,000 for electrical costs, based on Deublein & Steinhauser (2011). This equates to $22,000 - $26,000 per year.

The economic value of the biogas, based on the commonly reported current market price of $3/MMBtu for natural gas, would be $17,000 per year. Thus, the cost savings from biogas generation would be somewhat lower than operating costs in the best case. The meat packing plant corporation requires its capital projects, including those of environmental benefit, to have an economic return, according to Drew Manker, Smithfield Corporation (personal communication, May 31, 2017). The cost savings should be substantially higher than the operating costs, such that the capital costs of the project are recovered in 2-5 years. Accordingly, the estimated biogas yield for the meat packing plant case study does not reach the tipping point of economic viability.

Other potential economic benefits from an anaerobic pre-treatment system in this case could include renewable energy credits, a reduction in wastewater treatment fees, and a reduction in solid waste costs.

The most widely used renewable energy incentive is available from the USEPA's Renewable Fuel Standard (RFS) program (Gasper & Searchinger, 2018). In fact, this program has led to a significant increase in renewable natural gas production in the US (Fig 14) (USEPA, 2018c). However, an analysis of the cost curve (Cooley & Lee, 2013) for biogas conditioning equipment (Fig 15) indicates that the scale of this case study is well below the cost/capacity inflection point, indicating that the investment necessary to earn RIN credits would likely not be cost effective.

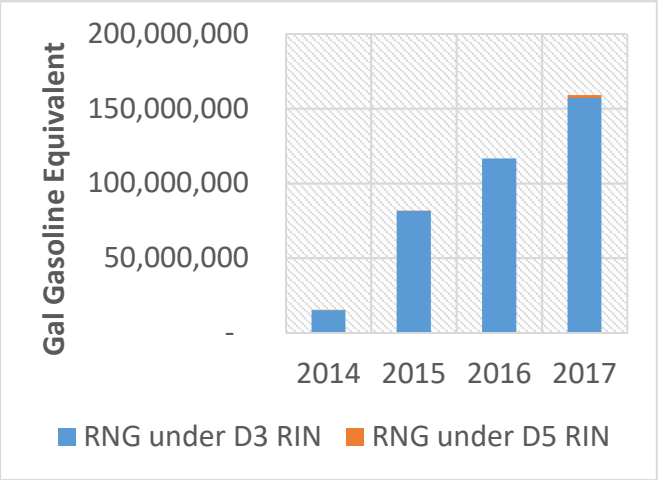


Figure 14 – Renewable gas production in US

Notes: D3 = cellulosic biofuels and D5 = advanced biofuels) renewable identification numbers (RINs)

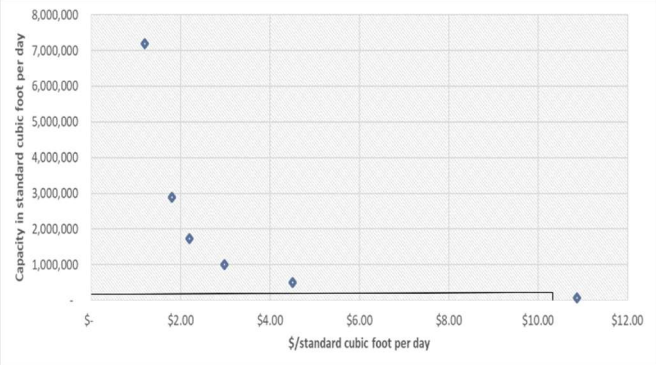


Figure 15 – Cost curve for biogas conditioning equipment

Notes: solid line meat packing plant case study)

A reduction in wastewater fees, based on reduced organic loading, would need to be negotiated with the municipality, and thus the savings are unknown at this time.

4.6.6 Alternative strategy for the combined disposal of wastewater and solid waste

Given the modest economic returns from the biogas which could be generated from anaerobic pre-treatment of meat packing plant wastewater, an alternative strategy was

considered. It became evident during the pollution prevention internship (Weil, 2017) that solid waste disposal costs (See Table 12) and corporate solid waste reduction goals were pressing issues for the meat packing plant environmental staff.

Table 12 – Potential of co-digestion of meat packing plant solid wastes.

Solid waste source	Approximate annual disposal costs	Current disposal method	Potential for anaerobic co-digestion
Spent cellulose casings	$77,000	Composting	• Low biogas yield • May require pre-treatment to hydrolyze solids • Could stabilize process
Inedible meat product	$300,000	Chemical denaturing, offsite rendering, then landfill	• High biogas potential • May requirement pre-treatment • High solids loading
Paper and cardboard	-	Baled and recycled	• Low biogas yield • Lower beneficial use than recycling
Plastics	$105,000	Landfill (recycling not possible due to contamination)	• If petrochemical plastics were replaced with biopolymers, could be co-digested (Hottle, Bilec, & Landis, 2017)
Total	**$482,000**		

Table 12 presents the cost data for current methods of disposing of solid waste with high organic content, which are thus potentially digestible. Fig 16 summarizes the 2016 utility and environmental costs for the meat packing plant.

It can be seen that the cost of current disposal methods for potentially digestible solid waste, $482,000, is on the same order of magnitude as wastewater disposal costs, $534,000. This fact prompted a research question: “Is there potential to co-digest portions of the solid waste stream with the wastewater flows in a dry anaerobic digester?” A review of the literature found little evidence of this approach. This may be due to the fact that dry, or solid-state, co-digestion of agro-industry solid waste with wastewater would cross two different engineering specialties.

However, a recent review article (André, Pauss, & Ribeiro, 2018) points out an increasing interest in solid-state anaerobic digestion as well as the potential to co-digest industrial solid waste and wastewater. Numerous scientific and biotechnological hurdles were identified. This would seem to be a subject worthy of future research, as the economics would be more favorable than for anaerobic pre-treatment of wastewater alone.

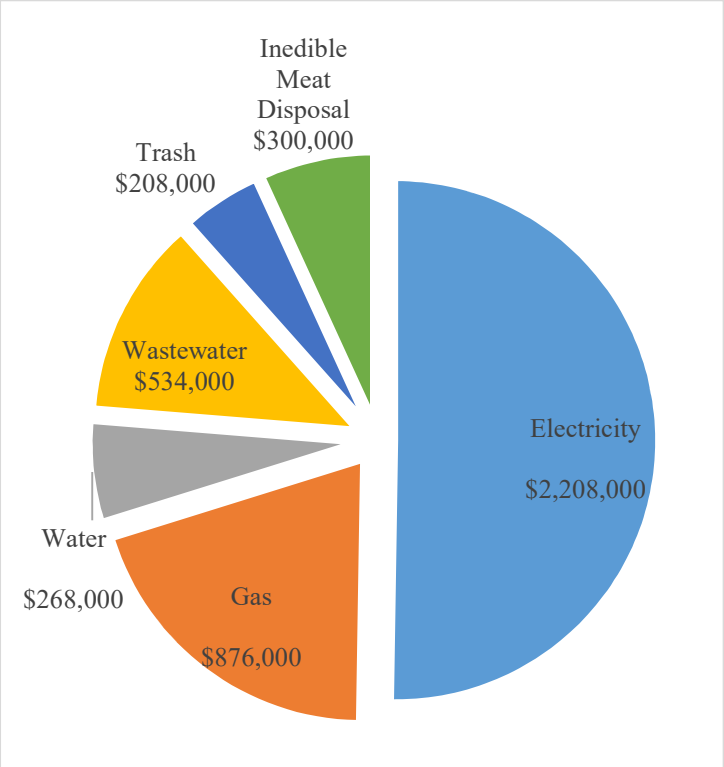


Figure 16 – 2016 utility and environmental costs for case study #1: meat packing plant

4.6.7 Biogas economics

Murray, Galik, & Vegh (2017) provide a helpful overview of biogas economics. Their model indicates that, if the price of natural gas were to increase to $5/MMBtu from the current average of $3/MMBtu, generating biogas from wastewater would be economically viable. However, they estimate the gross biogas potential from POTWs in the US would represent only 0.1% of natural gas demand. Milbrandt (2013) estimated the biogas potential from wastewater treatment at about four times this amount, but that is still a small percentage of the need. Both authors appear to have focused on anaerobic digestion of sludge rather than anaerobic treatment of wastewater. McCarty et al. (2011) found a higher energy potential if wastewater treatment plants were to convert from aerobic to anaerobic treatment. All the same, the view that emerges

from these models, as well as the regional model results, is that the biogas generated from anaerobic pre-treatment of agro-industrial wastewater is to be seen as a way of attaining environmental goals in a sustainable and cost-effective way rather than as a major new energy source. Pre-treating the high organic content of industrial wastewaters anaerobically would help to attain clean water goals by reducing loads on POTWs. Case study #2 also supports this point.

The non-monetary environmental gains that could result from adding anaerobic pre-treatment to existing agro-industrial wastewater treatment methods are difficult to account for, as one can't put a price on environmental impacts (e.g greenhouse gas emissions, ecosystem deterioration, eutrophication) in the same way as one can estimate the cost of an engineering project. Yet, there is a value to the environmental benefits that needs to be accounted for in policy decisions.

4.7 Case Study #2: Kansas State University dairy cow ranch

4.7.1 Ranch description

The Kansas State University Department of Animal Sciences and Industry operates a dairy teaching and research center on a ranch located on Animal Sciences Road north of Marlatt Avenue in Manhattan, KS (Scheffel, 2018). The facility houses approximately 300 lactating cows and 300 replacement heifers being raised for dairy use. Milking is performed on site.

Most of the raw milk is sold and processed into food products off-campus. A small percentage is retained by the university for processing as part of its food science program, which occurs at a different facility on campus according to Dr. Joel DeRouchey, Department of Animal Sciences and Industry (personal communication, October 12, 2018) and is thus not included in the case study.

4.7.2 Ranch wastewater characteristics

The wastewater resulting from the dairy ranch consists of a mix of the manure, which has relatively low moisture content, and the water used to wash down the cattle stalls, as well as stormwater runoff from the feed lots and pasture areas. Thus, a slurry is formed which is very high in solids and organic content.

As a ruminant, the digestive system of cows is capable of hydrolyzing cellulose and hemicellulose in the first two chambers of their four-chambered stomachs. Cellulose and hemicellulose are not normally favored for anaerobic treatment/digestion and biogas generation because of their slow hydrolysis rates (Rittmann & McCarthy, 2001). Thus, cows could be considered to be part of an efficient biomass utilization process in which plant-based material is converted to valuable dairy-based foods and the wastes are more readily converted to energy than would otherwise be possible. Of course, the ecosystem benefits are somewhat offset by the greenhouse gas effects of the methane emission resulting from cow digestion.

Literature on treatment of dairy cattle manure typically provides wastewater characteristics after screening of the manure or from samples of wastewater lagoons. Screening includes, at a minimum, sieving to remove most of the solids from the liquid fraction. C. Rico, García, & Rico (2011) detailed a novel screening method involving a four-week holding period to induce the initial stages of fermentation: hydrolysis and acidogenesis; followed by flocculation and sieving before treating the centrate with a lab-scale UASB reactor. The experimental results included measurement of biogas yield and treatment efficiencies. The values provided in Table 13 for the estimated wastewater characteristics for the Kansas State University dairy ranch are based largely on the values provided by these authors. Other authors (Dias, Fragoso, & Duarte, 2014) had higher values for dairy cattle manure wastewater because they used a less

comprehensive screening approach. The values provided by C. Rico et al. (2011) were used for this thesis because that study provided excellent detail on experimental methods and comprehensive data on experimental results, allowing for a comparison with calculated biogas yield.

Table 13 – Estimated wastewater parameters for dairy ranch

Wastewater parameter	Estimated value	Source/derivation
Flow	36 m^3/d	Redman (2010), based on 60 l/d per cow
Temperature	Ambient	C. Rico et al. (2011)
pH	7.2	ibid
BOD_5	6,140 g/m^3	Assumed to be 50% of TCOD, near midpoint of range given by Tchobanoglous et al. (2003)
TCOD	14,280 g/m^3	C. Rico et al. (2011)
COD_{VFA}	10,220 g/m^3	ibid
TS	14,680 g/m^3	ibid
VS	8,650 g/m^3	ibid
$NH_4 – N$	892 g/m^3	ibid
TKN	1,140 g/m^3	ibid
Total P	89 g/m^3	ibid

4.7.3 Reactor design for ranch

The design procedure set forth in Tchobanoglous et al. (2003) was again used to estimate the dimensions and performance characteristics of a conceptual UASB reactor to partially treat the liquid fraction of the manure from the dairy ranch and is summarized in Table 14. See Appendix B for hand calculations.

Unusual dimensions resulted from applying textbook (Tchobanoglous et al., 2003) UASB design procedures to this type of low volume, highly concentrated wastewater. The tall, narrow design had a diameter and height of 1.4 m and 12.5 m, respectively. However, the literature confirmed that pilot-scale reactors has similar dimensions. The 20 L and 40 L reactors used by Montoya, Da Mazareli, Da Silva, De Oliveira, & Leite (2017) had similar proportions; the first having diameter and height of 10 cm and 250 cm, respectively, and the second 15 cm and 232 cm respectively. These dimensions derive from the(Water Environment Federation, 1998)(ASCE, 1998)(ASCE, 1998) design method because the required cross-sectional area is relatively small due to low flow volumes, yet the height is relatively high due to the maximum

upflow velocity of 1 m/h. Although unconventional, it could be an efficient reactor, as it provides a long SRT in a small volume.

Table 14 – Conceptual UASB reactor for dairy ranch

Design characteristic	Estimate
Diameter	1.4 m
Height:	
Liquid	10.0 m
Gas collection	2.5 m
Total height	12.5 m
Liquid volume	15 m^3
Hydraulic retention time	10 h
Solids retention time	96 d
Effluent COD	40.5 mg/L
COD removal efficiency	99%
Average biomass concentration, X_{TSS}	852 mg/L
Methane biogas production	148 m^3/d

The high organic loading rate (OLR) used by C. Rico et al. (2011), 40.8 kg COD/m^3·d, was used to minimize reactor volume and height. To attain this OLR, it was necessary to base the design on mesophilic operating temperature, 35°C, as used by the earlier authors. Additional capital and operating costs would be needed to maintain thermophilic conditions.

The calculated biogas yield from the UASB reactor design was 148 m^3/d. This accords well with the biogas yield calculated from the VS conversion rate reported by C. Rico et al. (2011), which equals 122 m^3/d.

To compare with the parameter-based model for estimating biogas yield, TSS had to be estimated. Pettygrove (2010) reported mean TS and TSS values of 8.5 g/L and 4.7 g/L, respectively, in samples taken from seven dairy ranch manure lagoons. Applying this 0.55 ratio to the given TS value, then calculating biogas yield based on TSS, resulted in an estimate of 140 m^3 CH_4/d, which is comparable to the value calculated from the conceptual UASB reactor design.

In comparison with the median values for agro-industry in Kansas, the dairy ranch wastewater reactor has a smaller average flow, 36 m^3/d *vs.* 276 m^3/d. But because the organic loads from the dairy ranch wastewater are more highly concentrated, 4,700 mg/L *vs.* 378 mg/L, the potential yield of biogas, about 140 m^3 CH_4/d, is higher than that of a median Kansas agro-industry, 50 m^3 CH_4/d.

4.7.4 Comparison of results with AgSTAR spreadsheets

One of the reasons why the dairy ranch was chosen as a second case study for the thesis is that free online tools are available to model biogas yield from dairies. These tools are not available for meat packing plants or other, more highly capitalized, industries. Apparently, the intended audience of many of these tools are farmers and dairy operators.

In cooperation with the US Department of Agriculture, the US Environmental Protection Agency (USEPA) has made available the free Microsoft Excel calculation tools for estimating biogas yield, cost, environmental benefits and economic viability for agriculture-based anaerobic digestion systems (USEPA, 2018a). Three spreadsheets that apply to dairy ranch manure were downloaded. The USEPA has also developed the FarmWare model, reviewed by Brouwer, Grimberg, & Powers (2012) and Kythreotou, Florides, & Tassou (2014), but that model is not free and was not downloaded. The input to all of the models was based on herd size. The average body mass for lactating cows and heifers provided by Milbrandt (2005) was used to calculate input parameters where necessary. Table 15 summarizes the results, which were not very consistent, differing by an order of magnitude from the low estimate, 128 m^3 CH_4/d to the high estimate, 1,296 m^3 CH_4/d.

Only the Astill et al. (2016) spreadsheet allows the user to modify the estimated VS characteristics of the wastewater, which is likely the reason that it was closest to the biogas yield

calculated from the reactor design in Section 4.7.3, 148 m^3/d. It also allows the user to adjust volume of animal wastewater generated per wet-cow equivalents (WCE), the effect of co-digesting other organics, HRT, and VS conversion rate. Additionally, this author's workbook provides worksheets to estimate revenue and operating costs as well as the costs and benefits of fiber separation, nutrient separation, water recovery, combined heat and power generation, and biogas conditioning.

Table 15 – Biogas yield results from AgSTAR spreadsheets

Source	Estimated biogas yield m^3 CH_4/d	Methodology	Other information assumed/provided
Anaerobic digester system enterprise budget calculator (Astill et al., 2016)	128	Vol CH_4/mass VS fed	• Flow = 65 m^3/d • Volume fed = 23,700 tonnes/y • Solids reduction = 33% • Digester volume = 1,287 m^3 • Capital cost = $1,750,000
Anaerobic digestion financial decision tool (Gloy, 2008)	670	Vol CH_4/mass VS converted	• Solids fed = 11,600 tonnes/y • VS content = 11.33% • Solids reduction = 30%
Biogas economic model and toolkit (Baker Tilly, 2012)	1,296	Vol CH_4/mass COD converted	• Solids fed = 12,810 tonnes/y • COD destruction = 70% • TSS reduction = 5%

One observation from the wide range of results is that the use of free online calculators for a policy-level analysis of potential biogas yield does not appear to be advisable. If used, a model such as that of Astill et al. (2016), which allows the wastewater parameters to be accurately characterized, would be a good choice. The approach taken in this thesis, to design conceptual reactors based on median wastewater characteristics, is more credible, as the inputs, calculations, and outputs are all stated clearly.

4.7.5 Economic evaluation of dairy ranch reactor

Similar methodology was used for capital and operating cost estimates for the dairy ranch bioreactor as was used in Section 4.6.5 for the meat packing plant, except that the unit costs for construction were doubled to account for the smaller scale and the higher strength materials and

insulation needed for the reactor. This resulted in a range of $19,000 - $23,000 for capital costs and $5,700 – $7,800 per year for operating costs. The economic value of the biogas at $3/MMBtu would be $5,800 per year. The use of biogas to heat the reactor was not accounted for. Again, the cost savings are about equal to the low end of operating costs.

The cost estimate is an order of magnitude less than that calculated by the Astill et al., (2016) spreadsheet. The reason for this difference is that the conceptual reactor design in this case is based only on the liquid fraction of the manure waste, as the conceptual solid/liquid separation scheme set forth by C. Rico et al. (2011) was assumed. In contrast, Astill et al. (2016) based their reactor stream on the entire waste stream to be digested. A side-by-side cost comparison could only be made if the cost of the dry anaerobic digestion system assumed by C. Rico et al. (2011) were accounted for.

While the cost savings from generating biogas from anaerobic pre-treatment of dairy ranch wastewater do not meet the tipping point of recovering capital costs, the overall capital cost is modest. It would be interesting to see if a prototype could be built on the Kansas State University site as a student project using common building materials and simple construction methods. If such a system were able to effectively treat dairy wastewater as expected, it could serve as a model for agricultural extension agents in the state.

4.8 Case study comparison

While the meat packing plant case study had detailed wastewater data and the dairy ranch case study was based on typical values from literature, the results were similar in both cases. In both cases, an UASB reactor could effectively pre-treat the wastewater, significantly reducing the loads on downstream POTWs. In both cases, the estimated biogas yield was on the same order of magnitude as estimates based on a parameter-based model. For case study #1, biogas

yield from the proposed model and the conceptual reactor design were 272 and 543 m^3 CH_4/d, respectively. For case study #2, biogas yield from the proposed model and the conceptual reactor design were 122 and 140 m^3 CH_4/d, respectively. A further source of validation was attained for case study #2 results, in that the best available online spreadsheet (Astill et al., 2016) produced a biogas yield estimate of 148 m^3 CH_4/d.

Both cases were similar in that the economic benefits of potential biogas generation did not reach the tipping point of economic viability.

4.9 Attitudes regarding anaerobic treatment biotechnologies

The number of respondents to the opinion part of the survey was too small for the results to have statistical significance. At least 30 complete responses would have been needed for the survey to have statistically validity, according to a common rule of thumb (Hoggs, Tanis, & Zimmerman, 2015), and only four complete responses were received to this portion of the survey as discussed in Section 4.2. However, they serve as a tentative indication of what the awareness and attitudes may be in the sample population, i.e. personnel responsible for industrial pre-treatment at agencies with POTWs > 1.0 MGD in Kansas.

The reasons for the low participation rate in this part of the survey may have to do with the values of the survey population, which are oriented towards compliance with wastewater discharge standards. As the survey was asking for information about problems with existing pre-treatment methods and ways to improve those methods, there may have been a reluctance on the part of the survey population to respond, even to an anonymous survey. One comment written in on the survey supports this inference: it said that “We used to have a problem with our agro-industrial user, but now we don’t.” A more personal method of obtaining information would

probably be needed to glean information about problems with existing methods of agro-industrial pre-treatment.

Fig 17 indicates that there is a moderate amount of awareness of and experience with anaerobic digestion biotechnology, as applied to wastewater treatment.

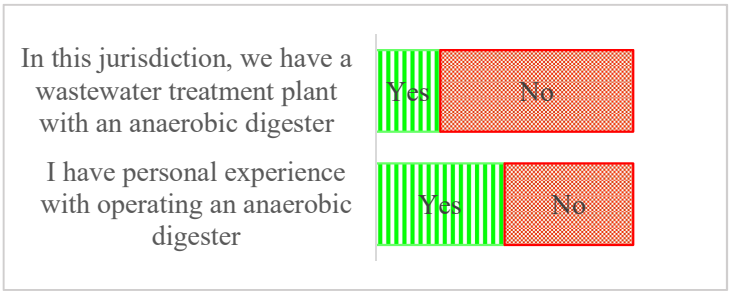


Figure 17 - Awareness of anaerobic digestion yes/no questions

Fig 18 indicates that, whereas there is a slightly positive attitude towards the use of anaerobic digestion as a sludge management solution, attitudes were somewhat negative towards the potential use of anaerobic digestion for pre-treatment of agro-industrial wastewater. A comment on the survey indicated that there had been problems with an agro-industrial discharger in the past, but these problems had since been resolved. It is not surprising that, in an industry where compliance is typically the highest goal, the survey respondents would not be inclined to report any problems with attaining compliance, even in an anonymous survey. Another qualitative form of inquiry, such as focus groups, would probably be helpful to identify the most serious issues of concern (Colucci, 2007).

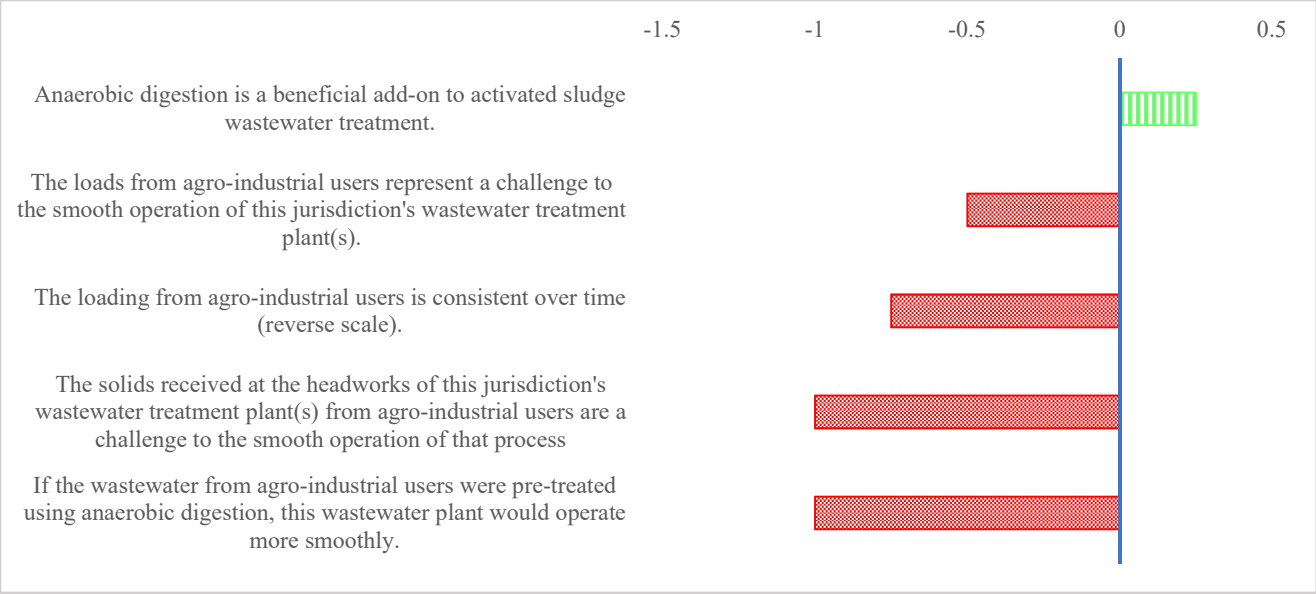


Figure 19 - Attitudes towards the technology

Notes: responses converted from a 1 to 7 Likert scale to a -3 to +3 mean favorability in which 0 = neither agree nor disagree. The responses to the reverse scale question were inversed.

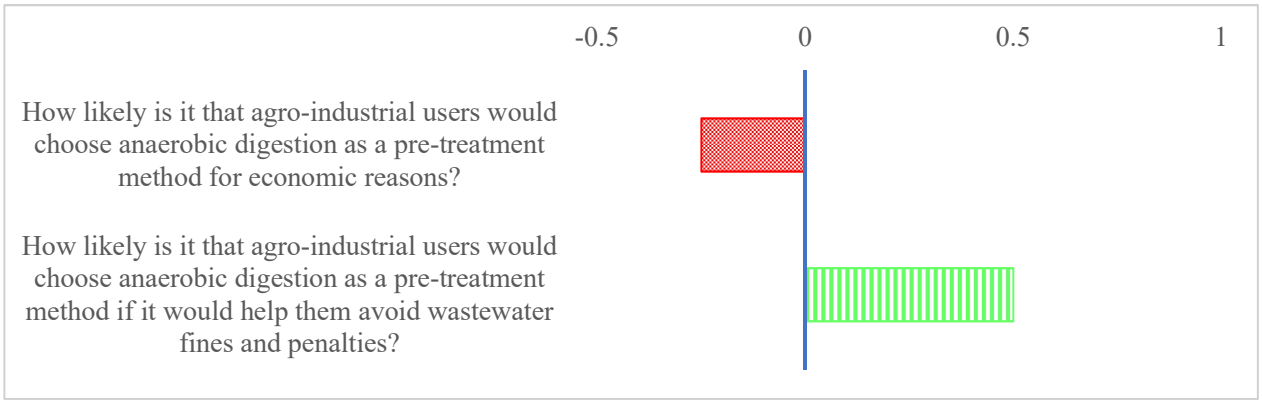


Figure 18 – Likelihood of adopting technology for common reasons

Note: responses converted from a 1 to 7 Likert scale to a -3 to +3 mean favorability in which 0 = neither likely nor unlikely.

For the responses summarized in Figs 19 and 20, the respondents were asked to put themselves in the place of their agro-industrial users and consider what would motivate them to use anaerobic digestion as a pre-treatment biotechnology. The responses were as expected, that avoidance of potential wastewater fines and penalties would be a likely motive for adopting the biotechnology. A comment was offered: "The user would use the system if it helped them avoid fines and penalties." This aligns with the information gleaned from two personal interviews with

agro-industrial users who adopted the biotechnology: Stephen Bugle, wastewater pre-treatment superintendent for the Archers Daniel Midland plant in Decatur, IL (personal communication, October 6, 2017) and Dr. Shawn Veltman, H&V Consulting Company (personal communication, November 2, 2017).

Fig 20 summarizes potential barriers to adopting the biotechnology. Given the results of the economic analysis for the two case studies, it is not surprising that capital and operating costs were identified as barriers. The lack of incentive to change from current methods of wastewater treatment is also somewhat intuitive, as wastewater treatment is not a profit center for the agro-industrial plants.

Fig 21 serves to validate the responses summarized in Fig 19, in that avoidance of fines and penalties would be primary motivators. The other primary motivation, expansion of plant capacity, is related. The same types of motivations served as an impetus in the examples where anaerobic biotechnologies are currently being applied to agro-industrial pre-treatment (See Section 2.7)

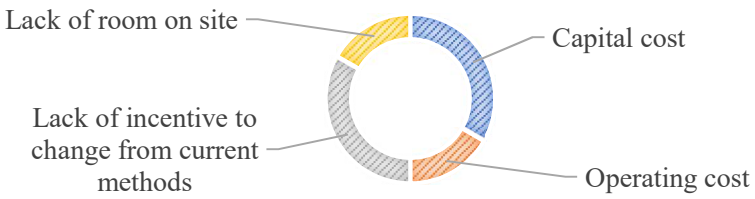


Figure 20 – Barriers to adopting the technology

Note: The question asked was, "What are the primary barriers that would prevent an agro-industrial user from implementing anaerobic digestion as a pretreatment method?" Potential responses that were not chosen were: "operational complexity" and "lack of awareness of anaerobic digestion". The response "lack of room on site" was written in.

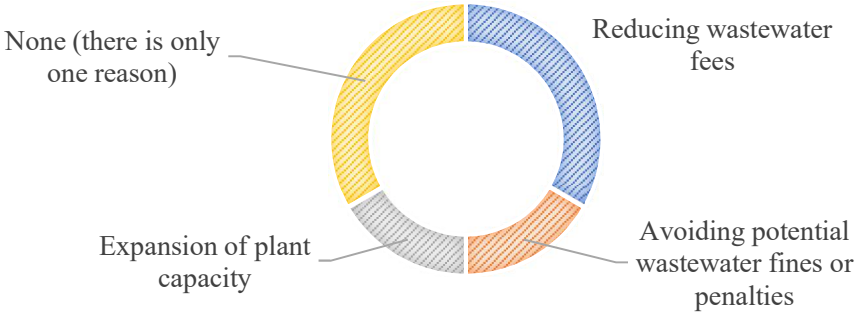


Figure 21 – Motivations for adopting the technology

Note: The question asked was, "Why would an agro-industrial user be motivated to choose anaerobic digestion as a pretreatment method?" Potential responses that were not chosen were: "reducing costs by recovering resources such as biogas from wastewater" and "improving corporate sustainability profile". The responses "none" were written in.

Chapter 5 - Conclusions

The proposed model to estimate potential biogas yield from anaerobic pre-treatment of agro-industrial wastes on a regional basis, using the required reporting parameters of flow and TSS, would appear to provide a reasonable estimate, as evidenced by comparable yield values obtained from conceptual reactor designs for two case studies.

If anaerobic wastewater pre-treatment were fully adopted in Kansas agro-industry, a median estimate of 19,800 MMBtu of biogas (methane) could be generated, equivalent to the natural gas demand of about 500 homes. The quantity of biosolids diverted from publicly owned treatment works would be 1,000 – 1,200 tonnes/year. The median BOD_5 received from agro-industrial users would be reduced from 1,500 to 420 mg/L, which would bring loading near the range that municipal wastewater treatment plants are designed to treat. Greenhouse gas emissions would likely be reduced, if leakage were controlled and dissolved methane were captured.

The upflow anaerobic sludge blanket (UASB) reactor is a viable design for situations where the temperature of the agro-industrial wastewater discharge is above 15°C. Although less ideal, this reactor design could also be used to treat the liquid fraction of diary manure wastewater in a small reactor volume.

The economics of using anaerobic biotechnology to pre-treat agro-industrial wastewater are not favorable, when the value of biogas alone is considered. Notwithstanding the economics, significant water quality benefits in terms of reduced organics and solids loading would be attained through this approach.

There appears to be a measure of awareness of anaerobic biotechnology in the wastewater treatment profession, but there is little motivation to adopt the biotechnology for pre-

treatment of agro-industrial wastewater. Agencies either do not perceive an issue with the wastewater they receive from agro-industrial users or they are not inclined to report problems to an unknown survey-taker. Cost is perceived as a primary barrier to adopting the biotechnology. However, if the agro-industrial users were forced to consider changing from current methods due to fines, penalties, increased fees, or the need to expand their plants, they might be motivated to consider anaerobic biotechnologies.

Chapter 6 - Policy and Research Recommendations

The results indicate that additional economic incentives would be required if the State of Kansas sought to reap the environmental benefits of anaerobic pre-treatment of agro-industrial wastes. Initially, it would be appropriate to continue funding research and extension activities related to this biotechnology. The research could estimate the anticipated costs and benefits of the biotechnology with more accuracy and precision than was possible in this thesis, which would then guide policy decisions.

One logical first step would be to more fully evaluate the accuracy of the proposed parameter-based model, which uses TSS and flow to estimate biogas potential. Data regarding the actual biogas yield from Kansas State University AnMBR plant and the Dodge City anaerobic lagoons could be compared against the estimated yield from the model, for example.

Additionally, it would be appropriate to perform BMP tests and lab-scale reactor experiments on representative agro-industrial flows in Kansas. Kansas State University's Biosecurity Research Institute has expressed an interest in participating in such a research effort. The Kansas State University dairy ranch and other units of the Department of Agriculture might also be willing to provide wastewater samples for analysis. If BMP tests are performed, the results should be interpreted in the light of literature which states that the results for k_h, the hydrolysis coefficient, may be artificially low.

As to barriers which might be preventing adoption of the biotechnology, a larger survey effort would be needed understand the issues more clearly. Including wastewater professionals from neighboring states with similar agro-industries would enlarge the survey pool. It would be interesting to include engineering and university professionals in the survey, as well as environmental coordinators working at agro-industry plants, and compare the attitudes between

the different groups. Focus groups should also be used, as they are known to elicit more nuanced information and also more complete disclosure on complex issues than can be attained in a number-based survey. Also, continued outreach could encourage agro-industrial users to consider anaerobic biotechnology in situations where they are forced to make a change from current methods of pre-treatment.

It would be interesting to gather information about countries where anaerobic biotechnology to pre-treat agro-industrial wastes is widely implemented, such as Thailand. What is different in the realms of policy, economics and attitudes that led to adoption of the biotechnology?

Continued research into the best available biotechnology would be appropriate. In particular, conceptual design and lab-scale experiments on dry anaerobic digestion systems to co-digest agro-industrial solid waste and wastewater should be pursued.

All of the above would be appropriate research efforts for the National Science Foundation integrated food energy and waste traineeship program, for which Kansas State University has received funding in the years 2019 – 2021. Anaerobic pre-treatment of agro-industrial wastes is specifically addressed in the program proposal. As this thesis has demonstrated, anaerobic pre-treatment of agro-industrial wastes has the potential to improve the resiliency of rural areas in Kansas.

As a guide to those who may take this research forward, here are a few retrospective observations to be aware of. First, the hyperbole used in the industry regarding biogas can be unhelpful. The reality of modest economic returns, especially given the historically low price of natural gas, needs to be kept in mind. That said, there are potentially significant environmental benefits to adopting anaerobic pre-treatment of agro-industry wastewater to the existing activated

sludge treatment at POTWs. The overall system can operate more efficiently and produce cleaner water more reliably and at less cost, which is a tangible benefit. To demonstrate the potential in a credible way, the plan of research needs to be thought through carefully and laid out in advance. It would make sense to broaden the regional focus to include neighboring states so that a larger sample can be obtained. Agro-industrial wastewater data could be more easily obtained through open-records act requests rather than an on-line survey, given enough time and resources. That would then allow for representative sampling methods to be applied. For example, actual wastewater samples could be collected from a statistically significant sample set and BMP tests performed on that set. Also, a representative sample of agencies and industries could be interviewed in person to get more accurate and nuanced responses to the awareness and attitude questions.

The TSS-based model for estimating biogas potential from pre-treatment of agro-industrial waste on a regional basis has the potential to be a valuable contribution to the literature. It would facilitate policy making about how to incentivize and promote this form of biotechnology. It is the author's hope that future research will, in fact, validate this model and make it available for general use.

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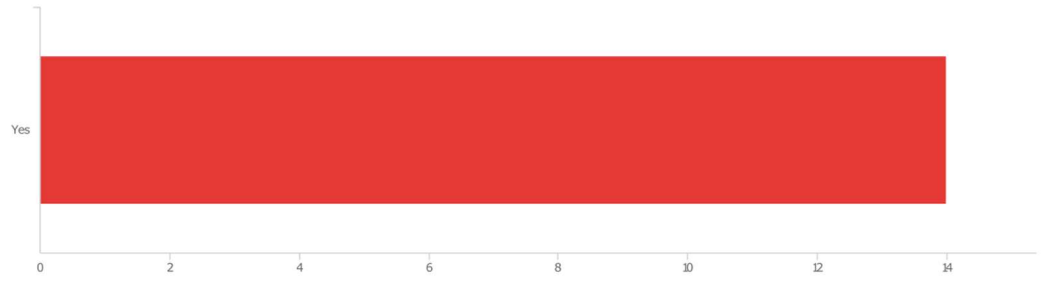
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Appendix A - Survey Report

Default Report

KS Industrial Pretreatment Survey
September 5, 2018 10:41 AM CDT

Q1.1 - The purpose of this short survey is to assess a potentially beneficial technology to pre-treat industrial wastes. About 50 POTWs in Kansas are receiving the survey. It should take less than 10 minutes to complete, and your thoughtful and accurate participation would be much appreciated. The results will be presented on August 28th, 2018 at the KWEA/Ks AWWA conference. First, please indicate your willingness to participate: "I understand this project is research, and that my participation is voluntary. I also understand that if I decide to participate in this study, I may withdraw my consent at any time, and stop participating at any time without explanation, penalty, or loss of benefits to which I may otherwise be entitled." "I verify that by clicking Yes below that I have read and understand this consent form, and willingly agree to participate in this study under the terms described."



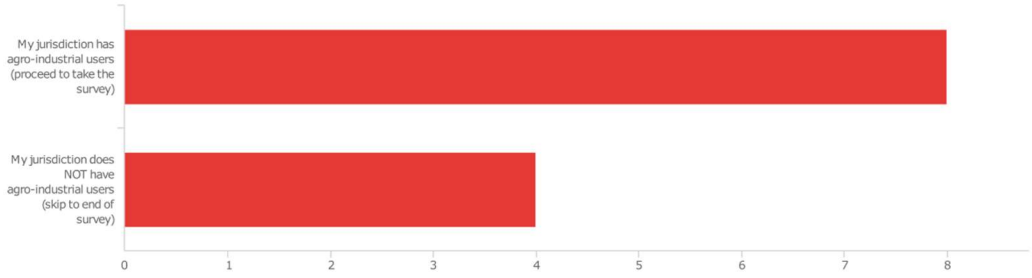
#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count

1	The purpose of this short survey is to assess a potentially beneficial technology to pre-treat industrial wastes. About 50 POTWs in Kansas are receiving the survey. It should take less than 10 minutes to complete, and your thoughtful and accurate participation would be much appreciated. The results will be presented on August 28th, 2018 at the KWEA/Ks AWWA conference. First, please indicate your willingness to participate: "I understand this project is research, and that my participation is voluntary. I also understand that if I decide to participate in this study, I may withdraw my consent at any time, and stop participating at any time without explanation, penalty, or loss of benefits to which I may otherwise be entitled." "I verify that by clicking Yes below that I have read and understand this consent form, and willingly agree to participate in this study under the terms described."	31.00	31.00	31.00	0.00	0.00	14

#	Field		Choice Count
1	Yes	100.00%	14

Showing Rows: 1 - 1 Of 1

Q1.2 - Please think about the industries that discharge heavy organic loads, either in terms of flow or concentration, to your wastewater treatment plant(s). In this survey, these dischargers are referred to as agro-industrial users. The survey will ask you to enter data for each agro-industrial user. If you have more than one in your jurisdiction, you will have the option to add more data until you are done. If you don't have all the data requested, please provide as much information as you do have.



#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Please think about the industries that discharge heavy organic loads, either in terms of flow or concentration, to your wastewater treatment plant(s). In this survey, these dischargers are referred to as agro-industrial users. The survey will ask you to enter data for each agro-industrial user. If you have more than one in your jurisdiction, you will have the option to add more data until you are done. If you don't have all the data requested, please provide as much information as you do have.	4.00	5.00	4.33	0.47	0.22	12

#	Field		Choice Count
1	My jurisdiction has agro-industrial users (proceed to take the survey)	66.67%	8
2	My jurisdiction does NOT have agro-industrial users (skip to end of survey)	33.33%	4
			12

Showing Rows: 1- 3 Of 3

1_Q2.2 - Average BOD5 (mg/L):

Yes - Average BOD5 (mg/L):
150
200
3998

Showing records 1- 3 of 3

1_Q2.3 - Average Total Suspended Solids (TSS) (mg/L):

Yes - Average Total Suspended Solids (TSS) (mg/L):
100
100
2985

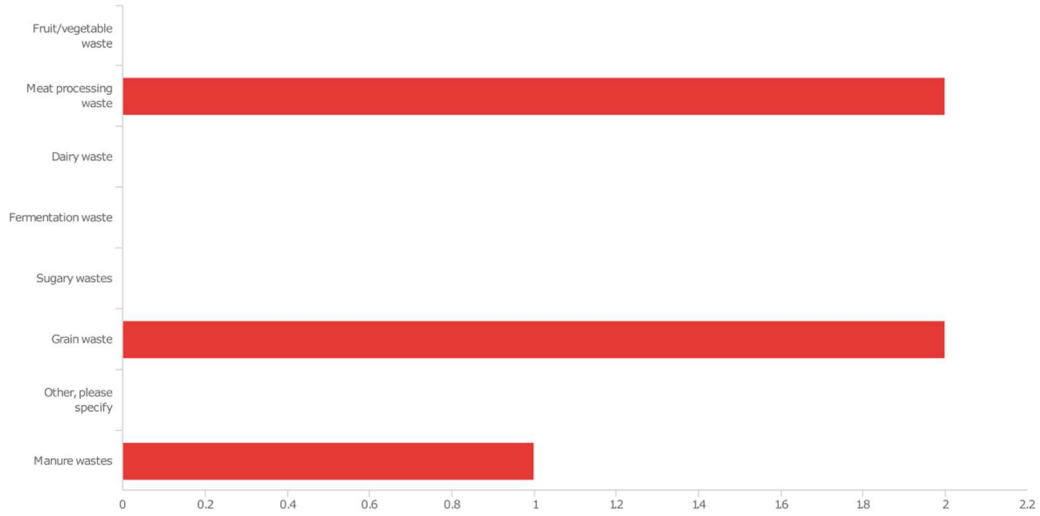
Showing records 1- 3 of 3

1_Q2.4 - Average flow (MGD):

Yes - Average flow (MGD):
0.05
0.025
103.15

Showing records 1- 3 of 3

1_Q2.5 - What is the nature of the agro-industrial loading from this user? (select all that apply)



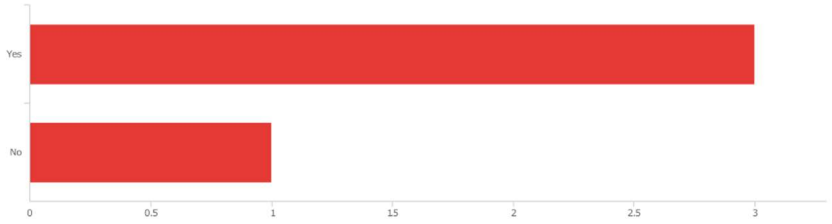
#	Field	Choice Count	
1	Fruit/vegetable waste	0.00%	0
2	Meat processing waste	40.00%	2
3	Dairy waste	0.00%	0
4	Fermentation waste	0.00%	0
5	Sugary wastes	0.00%	0
6	Grain waste	40.00%	2
7	Other, please specify	0.00%	0
8	Manure wastes	20.00%	1
			5

Showing Rows: 1 - 9 Of 9

Other, please specify

No Data

1_Q34 - Are these industrial wastewater loads currently pre-treated at the user's facility?

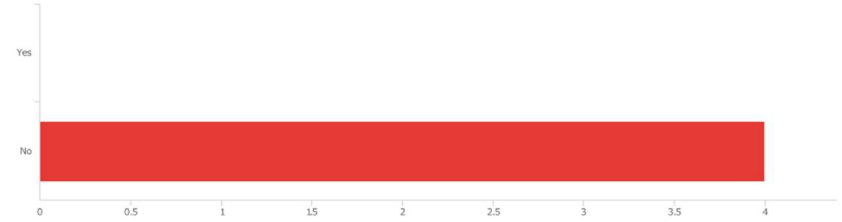


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Yes - Are these industrial wastewater loads currently pre-treated at the user's facility?	23.00	24.00	23.25	0.43	0.19	4

#	Field		Choice Count
1	Yes	75.00%	3
2	No	25.00%	1
			4

Showing Rows: 1 - 3 Of 3

1_Q2.6 - Would you like to add data for another agro-industrial user?

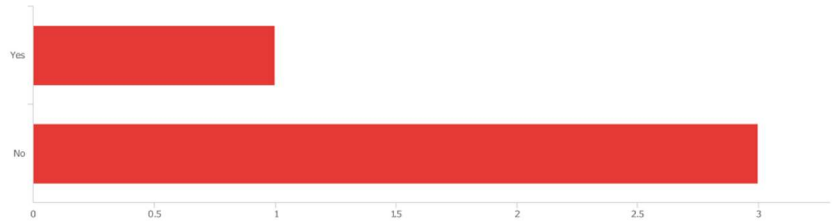


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Yes - Would you like to add data for another agro-industrial user?	2.00	2.00	2.00	0.00	0.00	4

#	Field		Choice Count
1	Yes	0.00%	0
2	No	100.00%	4
			4

Showing Rows: 1 - 3 Of 3

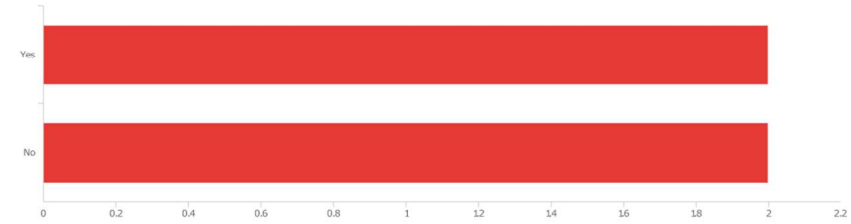
Q3.2 - In this jurisdiction, we have a wastewater treatment plant with an anaerobic digester.



#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	In this jurisdiction, we have a wastewater treatment plant with an anaerobic digester.	1.00	2.00	1.75	0.43	0.19	4

#	Field	Choice Count

Q3.3 - I have personal experience with operating an anaerobic digester.

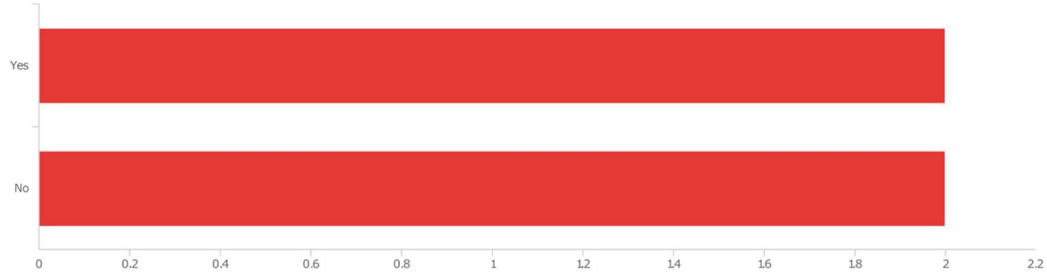


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	I have personal experience with operating an anaerobic digester.	1.00	2.00	1.50	0.50	0.25	4

#	Field		Choice Count
1	Yes	50.00%	2
2	No	50.00%	2
			4

Showing Rows: 1 - 3 Of 3

Q3.3 - I have personal experience with operating an anaerobic digester.

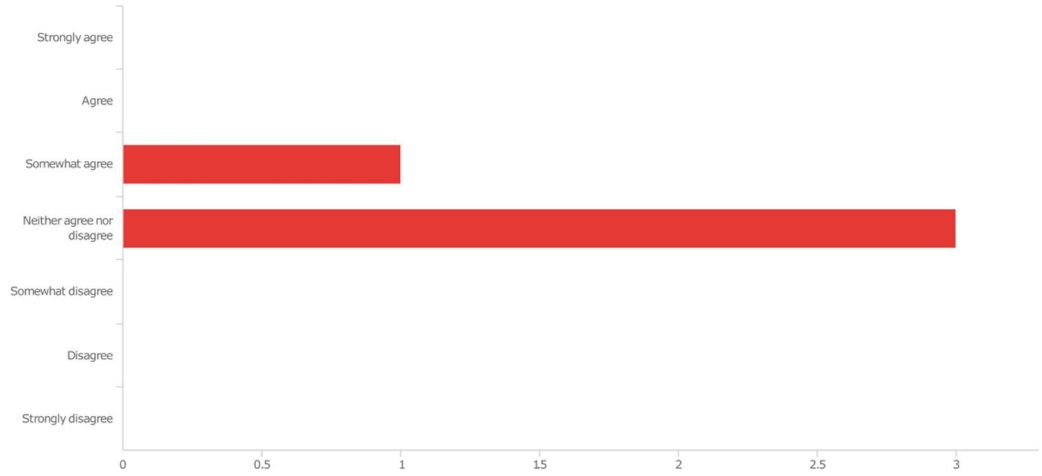


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	I have personal experience with operating an anaerobic digester.	1.00	2.00	1.50	0.50	0.25	4

#	Field		Choice Count
1	Yes	50.00%	2
2	No	50.00%	2
			4

Showing Rows: 1- 3 Of 3

Q3.4 - Anaerobic digestion is a beneficial add-on to activated sludge wastewater treatment.



#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Anaerobic digestion is a beneficial add-on to activated sludge wastewater treatment.	10.00	11.00	10.75	0.43	0.19	4

#	Field		Choice Count
1	Strongly agree	0.00%	0
2	Agree	0.00%	0
3	Somewhat agree	25.00%	1
4	Neither agree nor disagree	75.00%	3
5	Somewhat disagree	0.00%	0
6	Disagree	0.00%	0
7	Strongly disagree	0.00%	0
			4

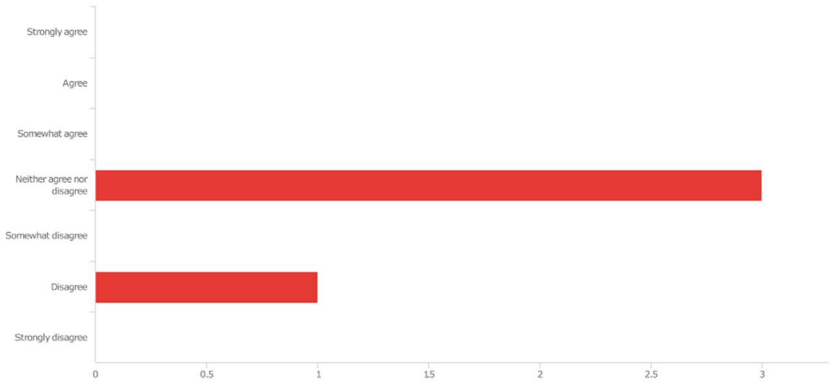
Showing Rows: 1- 8 Of 8

Q3.5 - Comments (optional):

Comments (optional):
In our system we have an anaerobic lagoons

Showing records 1- 1of 1

Q3.6 - The loads from agro-industrial users represent a challenge to the smooth operation of this jurisdiction's wastewater treatment plant(s).



#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	The loads from agro-industrial users represent a challenge to the smooth operation of this jurisdiction's wastewater treatment plant(s).	11.00	13.00	11.50	0.87	0.75	4

#	Field		Choice Count
1	Strongly agree	0.00%	0
2	Agree	0.00%	0
3	Somewhat agree	0.00%	0
4	Neither agree nor disagree	75.00%	3
5	Somewhat disagree	0.00%	0
6	Disagree	25.00%	1
7	Strongly disagree	0.00%	0
			4

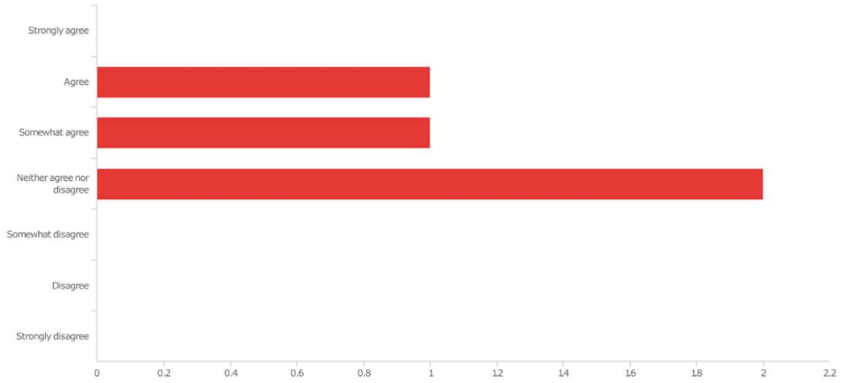
Showing Rows: 1- 8 Of 8

Q3.7 - Comments (optional):

Comments (optional):
In the past this was the case. But now due to good communications and pre-treament the operation runs alot smoother.

Showing records 1- 1of 1

Q3.8 - The loading from agro-industrial users is consistent over time.



#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	The loading from agro-industrial users is consistent over time.	9.00	11.00	10.25	0.83	0.69	4

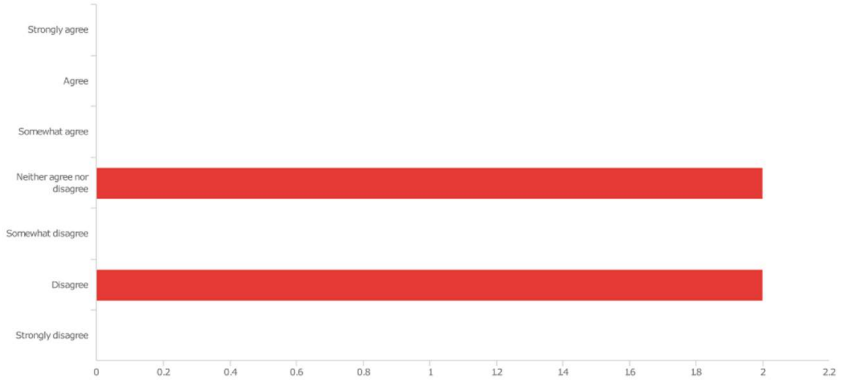
#	Field		Choice Count
1	Strongly agree	0.00%	0
2	Agree	25.00%	1
3	Somewhat agree	25.00%	1
4	Neither agree nor disagree	50.00%	2
5	Somewhat disagree	0.00%	0
6	Disagree	0.00%	0
7	Strongly disagree	0.00%	0
			4

Showing Rows: 1- 8 Of 8

Q3.9 - Comments (optional):

No Data

Q3.10 - The solids received at the headworks of this jurisdiction's wastewater treatment plant(s) from agro-industrial users are a challenge to the smooth operation of that process.



#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	The solids received at the headworks of this jurisdiction's wastewater treatment plant(s) from agro-industrial users are a challenge to the smooth operation of that process.	11.00	13.00	12.00	1.00	1.00	4

#	Field		Choice Count
1	Strongly agree	0.00%	0
2	Agree	0.00%	0
3	Somewhat agree	0.00%	0
4	Neither agree nor disagree	50.00%	2
5	Somewhat disagree	0.00%	0
6	Disagree	50.00%	2
7	Strongly disagree	0.00%	0
			4

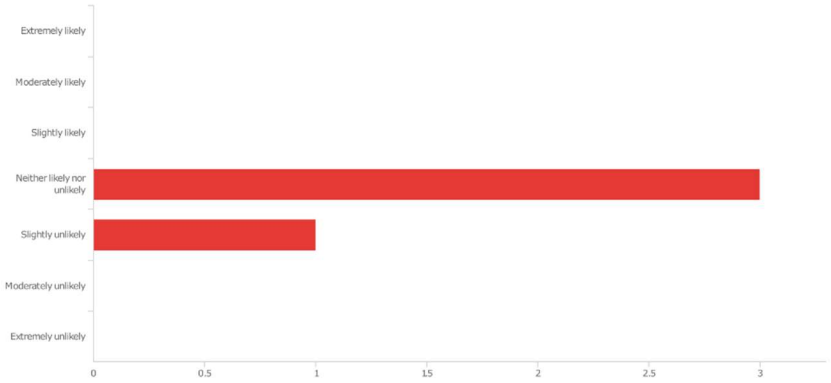
Showing Rows: 1 - 8 Of 8

Q3.13 - Comments (optional):

Comments (optional):
We do not want the user to use anaerobic pretreatment

Showing records 1- 1of 1

Q3.15 - How likely is it that agro-industrial users would choose anaerobic digestion as a pre-treatment method for economic reasons?



#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	How likely is it that agro-industrial users would choose anaerobic digestion as a pre-treatment method for economic reasons?	11.00	12.00	11.25	0.43	0.19	4

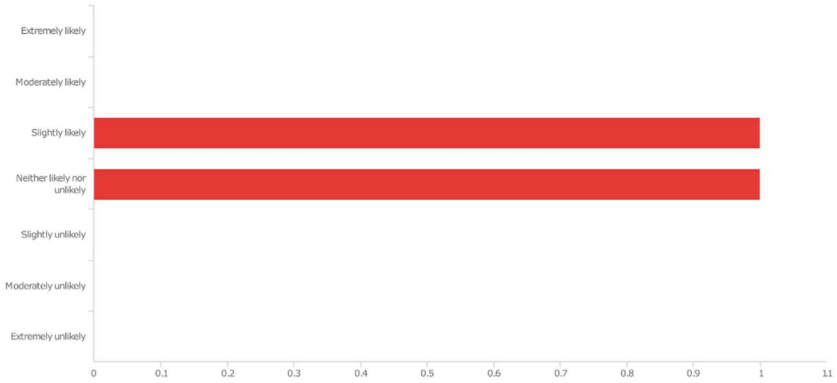
#	Field		Choice Count
1	Extremely likely	0.00%	0
2	Moderately likely	0.00%	0
3	Slightly likely	0.00%	0
4	Neither likely nor unlikely	75.00%	3
5	Slightly unlikely	25.00%	1
6	Moderately unlikely	0.00%	0
7	Extremely unlikely	0.00%	0
			4

Showing Rows: 1- 8 Of 8

Q3.16 - Comments (optional):

No Data

Q3.17 - How likely is it that agro-industrial users would choose anaerobic digestion as a pre-treatment method if it would help them avoid wastewater fines and penalties?



#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	How likely is it that agro-industrial users would choose anaerobic digestion as a pre-treatment method if it would help them avoid wastewater fines and penalties?	10.00	11.00	10.50	0.50	0.25	2

#	Field		Choice Count
1	Extremely likely	0.00%	0
2	Moderately likely	0.00%	0
3	Slightly likely	50.00%	1
4	Neither likely nor unlikely	50.00%	1
5	Slightly unlikely	0.00%	0
6	Moderately unlikely	0.00%	0
7	Extremely unlikely	0.00%	0
			2

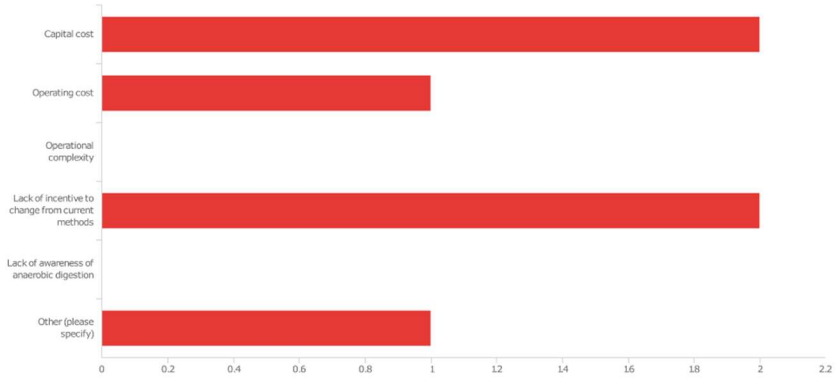
Showing Rows: 1 - 8 Of 8

Q3.18 - Comments (optional):

Comments (optional):
the user would use the system if it helped them avoid fines or penalties.

Showing records 1- 1of 1

Q3.19 - What are the primary barriers that would prevent an agro-industrial user from implementing anaerobic digestion as a pre-treatment method (select two)?



#	Field		Choice Count
1	Capital cost	33.33%	2
2	Operating cost	16.67%	1
3	Operational complexity	0.00%	0
4	Lack of incentive to change from current methods	33.33%	2
5	Lack of awareness of anaerobic digestion	0.00%	0
6	Other (please specify)	16.67%	1
			6

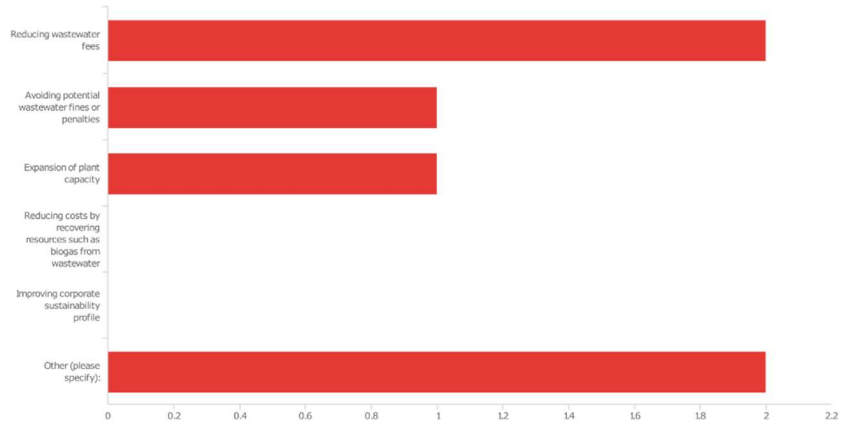
Showing Rows: 1- 7 Of 7

Other (please specify)

Other (please specify)
room

Showing records 1- 1of 1

Q3.20 - Why would an agro-industrial user be motivated to choose anaerobic digestion as a pre-treatment method? (select two)



#	Field		Choice Count
1	Reducing wastewater fees	33.33%	2
2	Avoiding potential wastewater fines or penalties	16.67%	1
3	Expansion of plant capacity	16.67%	1
4	Reducing costs by recovering resources such as biogas from wastewater	0.00%	0
5	Improving corporate sustainability profile	0.00%	0
6	Other (please specify):	33.33%	2
			6

Showing Rows: 1 - 7 Of 7

Other (please specify):

Other (please specify):
none
N/A

Showing records 1 - 2 of 2

Q3.21 - Please add any other thoughts you have about using anaerobic digestion as a pre-treatment method for agro-industrial users.

Please add any other thoughts you have about using anaerobic digestion as a...
with our WWTP, we want the loading to stay consistent, since we have our own Bio-Gas Facility that uses the loading from our industrial user for the generation of bio-gas.

Showing records 1 - 1of 1

End of Report

Appendix B - Hand Calculations

9/26/18

Calculation of biogas potential from agro-industrial users in Kansas.

Objective Given data that the median agro-industrial user has

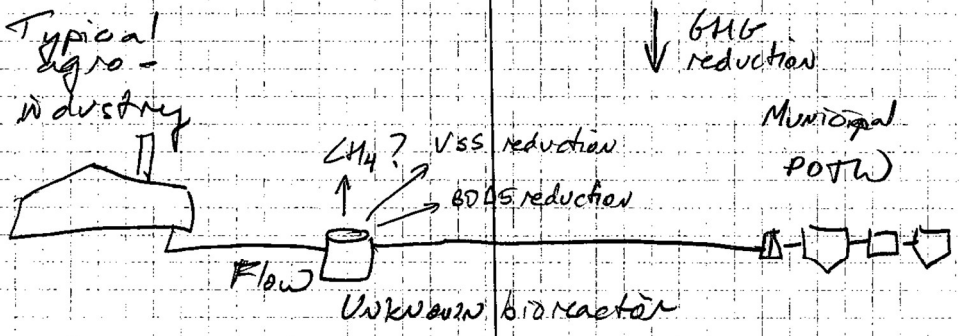
flow = 330 m^3/d

BOD5 = 1,470 mg/L

TSS = 455 mg/L

estimate methane generation potential using MOP-8 sludge digestion methodology.

Physical Setting



Solution

a. CH_4 yield

MOP-8 Sludge digestion model

TSS mg/L · 80% VSS/TSS · 50% destruction of VSS · Flow, L/d / 10^6 mg/kg · Gas production, $m^3 CH_4$/kg VSS destroyed

CH_4 gas production should range from 0.8 - 1.0 $m^3 CH_4$ / kg VSS destroyed

$= 455\ mg/L \cdot 80\% \cdot 56\% \cdot \frac{330{,}000\ L/d}{1e6} \cdot 0.8$ low

$= 48\ m^3/d$ low

$=$ " $\cdot 1.0$ high

$= 60\ m^3/d$ high

$\times 21 =$

1,010 m^3/d low
1,260 m^3/d high. } CH_4 potential

b. VSS reduction

$= TSS\ mg/L \cdot 80\% \frac{VSS}{TSS} \cdot 50\%$ reduction $\cdot \frac{Flow,\ L/d}{1e6}$

$= 60\ kg/d$

$\times 21 = 1{,}260\ kg/d$

c. BOD5 reduction

MOP-8 Anaerobic treatment section reports BOD5 reduction of 72% from anaerobic pretreatment

$BOD5\ (S) = So \frac{(100 - Removal\ rate)}{100}$

$= 1{,}260 \left(\frac{100-72}{100} \right) = 353$

Note that this value falls between the medium & high strength values for BOD_5 discussed by Tchobanoglous, 2003. Thus, anaerobic pretreatment would bring the agro-industrial flows within the range of BOD_5 for which treatment plants are typically designed.

d. Energy offset

Mean CH_4 potential = 1,130 m^3/d

Assume 5.5 days/week production

Yearly CH_4 = 1,130 m^3/d · 5.5 · 52

= 323,000 m^3/y.

US residential natural gas consumption

(USEIA) 4.6 million million cubic feet/year average for 2010–2017

US number of households

(Statista) 123 million

Average natural gas consumption per residence

$$= \frac{4.6 \times 10^{12}}{123 \times 10^{6}}$$

= 37,000 cf/residence/year

= 1,100. m^3/yr

Volume of methane equal to

$$\frac{323{,}000 \ m^3/yr}{1{,}100 \ m^3/yr \cdot \text{residence}}$$

= 290 residences.

e. Solids reduction

VSS reduction = 60 kg/d. of production

VSS/TSS ratio = 80%

$$TSS = \frac{1}{0.8} VSS$$

= 75 kg/d

5.5 days/wk production

Yearly load reduction

$$= 75 \frac{kg}{d} \cdot 5.5 \ d \cdot 52$$

= 21,000 kg/yr × 21 = 441,000 kg/yr

Tchobanoglous reports typical TSS = 95 g/d

Equivalent population $= \frac{441{,}000 \ kg/yr}{95 \ g/d \cdot \frac{1 \ kg}{1000 \ g} \cdot \frac{365 \ d}{1 \ yr}}$

= 13,000

f. Inputs to EPA WARM calculator.

Tons of food waste anaerobically digested

1,260 kg/d · 5.5 · 52 =

360,000 kg/y

= 794,000 lb/y

= 397 T/yr

GHG reduction from landfill to anaerobic digestion of 397 T/yr of food waste = (611)

g. Check EPA WARM calculator for Smithfield (No solid waste co-digestion)

VSS reduction =

$$445\ mg/L \cdot 80\% \cdot 50\% \cdot \frac{2,300,000}{1e6}$$

= 411 kg/d

= 117 kg/yr

= 129 T/yr

179 landfill

-19 AD

U.S. Energy Information Administration

NATURAL GAS

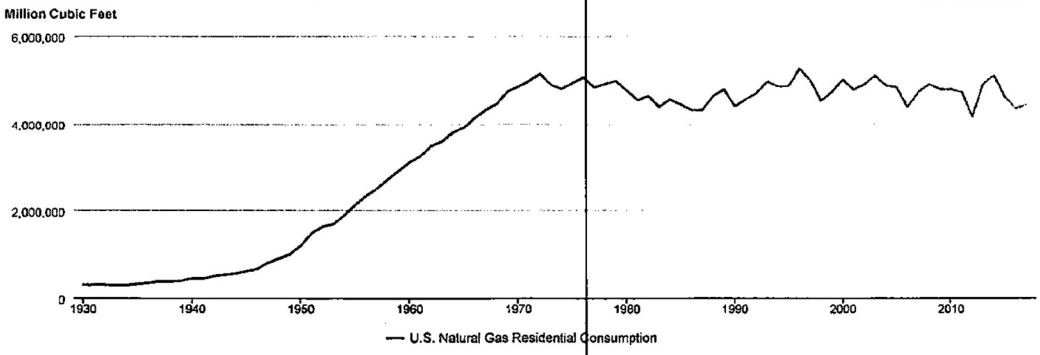
OVERVIEW | DATA | ANALYSIS & PROJECTIONS GLOSSARY FAQS

Referring Pages:
- Natural Gas Delivered to Residential Consumers
- U.S. Natural Gas Consumption by End Use
- Residential Consumption of Natural Gas (Summary)

View History: ○ Monthly ◉ Annual Download Data (XLS File)

U.S. Natural Gas Residential Consumption

DOWNLOAD



Source: U.S. Energy Information Administration

This series is available through the EIA open data API and can be downloaded to Excel or embedded as an interactive chart or map on your website.

U.S. Natural Gas Residential Consumption (Million Cubic Feet)

Decade	Year-0	Year-1	Year-2	Year-3	Year-4	Year-5	Year-6	Year-7	Year-8	Year-9
1930's	295,700	294,406	298,520	283,197	288,236	313,498	343,346	371,843	367,772	391,153
1940's	443,646	442,067	498,537	529,444	562,183	607,400	660,820	802,150	896,348	992,544
1950's	1,198,369	1,474,725	1,621,966	1,685,503	1,894,248	2,123,952	2,327,564	2,500,269	2,714,251	2,912,601
1960's	3,103,167	3,248,578	3,478,563	3,589,021	3,787,292	3,902,802	4,138,259	4,313,303	4,450,354	4,728,281
1970's	4,837,432	4,971,690	5,125,982	4,879,387	4,786,128	4,924,124	5,051,360	4,821,485	4,903,006	4,965,365
1980's	4,752,082	4,546,450	4,633,035	4,380,599	4,555,465	4,433,377	4,313,969	4,314,833	4,630,330	4,780,638
1990's	4,391,324	4,555,659	4,690,065	4,956,445	4,847,702	4,850,318	5,241,414	4,983,772	4,520,276	4,725,672
2000's	4,996,179	4,771,340	4,888,818	5,079,351	4,868,797	4,826,775	4,368,466	4,722,358	4,892,277	4,778,907
2010's	4,782,412	4,713,777	4,149,519	4,897,372	5,087,471	4,612,888	4,345,031	4,422,523		

- = No Data Reported; -- = Not Applicable; NA = Not Available; W = Withheld to avoid disclosure of individual company data.

Release Date: 8/31/2018
Next Release Date: 9/28/2018

Referring Pages:
- Natural Gas Delivered to Residential Consumers
- U.S. Natural Gas Consumption by End Use
- Residential Consumption of Natural Gas (Summary)

Tchobanoglous Ch 7-12 regional biogas yield estimate

Objective: Given data that the median agro-industrial user has

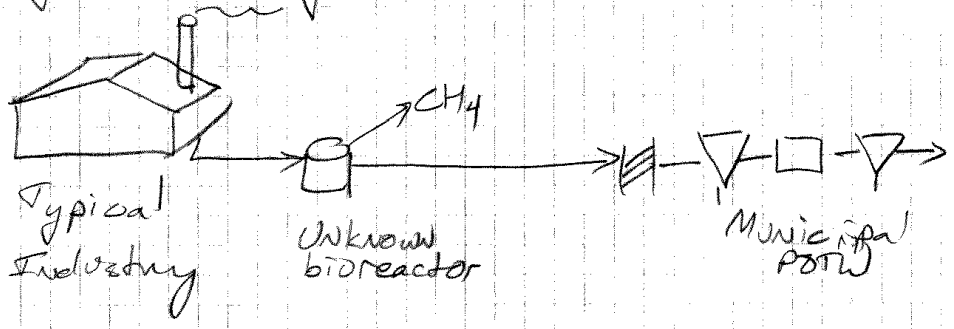
$Flow = 330\ m^3/d$

$BOD_5 = 1,470\ mg/L$

$TSS = 455\ mg/L$

Estimate methane generation potential using Tchobanoglous (2003) methodology

Physical Setting



Solution

Convert BOD_5 to bs COD.

Ch. 8-2 state bCOD/BOD ratio typically 1.64

Correlation between BOD_5 & COD for Smithfield data is also 1.65

Little non-soluble COD expected in this effluent

$\therefore$ bs COD $= 1.65 \cdot BOD_5$

$= 1.65 \cdot 1,470\ mg/L$

$= 2430\ mg/L$

$COD_{in} = COD_{eff} + COD_{VSS} + COD_{methane}$

Find each term

$COD_{in} = Q \cdot S_o$

$= 320\ m^3/d \cdot 1000\ L/m^3 \cdot 2{,}430\ mg/L \cdot g/1000\ mg$

$= 802{,}000\ g/d$

$COD_{eff} = (1 - 0.67) \cdot Q \cdot S_o$

$= 264{,}000\ g/d$

$COD_{VSS} = 1.42\ g\ COD/g\ VSS \cdot 0.04\ g\ VSS/g\ COD \cdot 0.67 \cdot 802{,}000\ g/d$

$= 30{,}500\ g/d$

$COD_{methane} = 802{,}000 - 264{,}000 - 30{,}500$

$= 507{,}500\ g/d$

Find CH_4 production at STP

$CH_4 = 0.35\ L\ CH_4/g\ COD$

$CH_4 = 507{,}500\ g/d\ COD \cdot 0.35\ L\ CH_4/g\ COD \cdot 1\ m^3/1{,}000\ L$

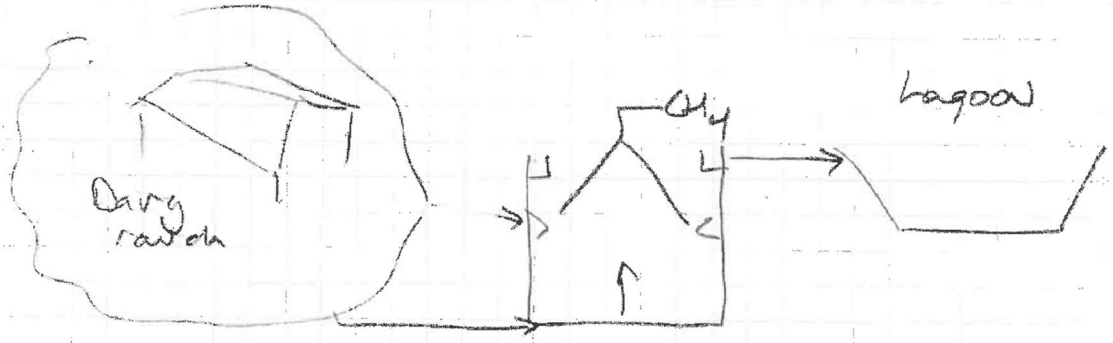
$= 177\ m^3/d$

10/31/18 Robert Weil

Hand calcs for Masters' thesis

Design UASB reactor for KSU dairy ranch manure slurry following the example of Tchobanoglous (2003), Example 10-3

Physical setting



$Q = 36\ m^3/d$

Temp = 25°C

pH = 7.0

BOD_5 = 20,300 g/m3

TCOD = 40,700 g/m3

TS = 33,700 g/m3

TKN = 1,200 g/m3

Total P = 2,100 g/m3

VS = 24,000 g/m3

sCOD assumed to be 87% of COD = 35,000 g/m3

pCOD assumed to be 115% of COD = 47,000 g/m3

Effluent VSS = 67% reduction from influent = 11,000 g/m3

Alk assumed to be 110 g/m3

SO_4 assumed to be 200 g/m3

3. Reactor dimensions

a $A = \frac{Q}{V} = \frac{36\ m^3/d}{1\ m/h \cdot 24\ h/d} = 3 = 1.5\ m^2$

$A = \frac{\pi D^2}{4} \Rightarrow D = 1.4\ m.$

b Reactor liquid height

$H_L = \frac{V_L}{A} = \frac{3.71\ m^3}{1.5} = 2.47\ m$

Not realistic. Adjust OLR↑ and upflow↓

At OLR = 8, upflow = 0.8

$V_N = 158$, $V_L = 185$, $A = 1.9\ m$, $D = 1.5\ m$

$H_L = 97\ m.$

Looks like I need a different approach

What if the digester were heated to 35°C and OLR ↑ to 40 kg/m³ (Montoya)

Rico (2011) used hydrolysis, flocculation & screening to separate the solid fraction from the liquid fraction. The parameters of the UASB influent were

Well below the Tchobanoglous range but he does say that volumetric COD loading will determine reactor size for strong waste waters

c. $H_T = H_L + H_G = 11.5\,m$.

d. Overall dimensions Dia = 1 m
Ht = 11.5 m.

3. HRT

$$V_L/Q = 891\,m^3 / 36\,m^3/d \cdot 24\,h/d = 594\,h = 24\,d!$$

This is much higher than Rico - theirs was in range of 1 d

Their article doesn't give enough information to resolve the inconsistency

Try Rico's approach

1. $$V_N = \frac{36\,m^3/d \cdot 14.28\,kg/m^3\,COD}{40.8\,kg\,COD/m^3 \cdot d}$$

$= 12.8\,m^3$ better

2. $V_L = 15.0\,m^3$

3. Reactor dimensions

a. $$A = \frac{36\,m^3/d}{1.0\,m/h \cdot 24\,h/d} = 1.5\,m^2$$

Dia = 1.4 m.

4. Substitute parameter values & solve for θ_x (SRT)

Assume X_e = effluent sCOD + 300 g/m^3

= 2,856 + 300

= 3,156 g/m3

$Q X_e$ = 36 3,156 = 113,616 g/d

$$= \frac{36 \cdot 0.08 (13,230 - 2,856)}{1 + 0.03\theta_x} \left[\frac{29,877}{1 + 0.03\theta_x}\right]$$

$$+ \frac{0.15 \cdot 0.03 \cdot 36 \cdot 0.08 (13,230 - 2,856) \cdot \theta_x}{1 + 0.03\theta_x} \left[\frac{137 \cdot \theta_x}{1 + 0.03\theta_x}\right]$$

$$+ 36 \cdot 2,850 \left[102,600\right]$$

SRT = 96 days per iteration. Sheet 10

5. Estimate effluent COD at SRT = 96 d, 35°C

$$K = \frac{0.20}{0.08} = 2.5 \text{ g COD/g VSS·d}$$

$$S = \frac{160([1 + (0.03 \cdot 96)]}{96(0.08 \cdot 2.5 - 0.03) - 1} = \frac{620}{15.32} = 40.5 \text{ mg/L}$$

SRT OK

We would attain

$36 m^3/d \cdot 8.65 g/L\ VS \cdot \frac{1 kg}{1000 g} \cdot 0.392 m^3 CH_4/kg\ VS\ fed$

122 m^3/d

Fairly close

Parameter-based model

TS = 14.68 g/L

TSS % of TS = (Retty grave) $4.7/8.5 = 55\%$

TSS = 8.12 g/L

VSS 80% of TSS = 6.49 g/L or kg/m^3

$6.49 kg/m^3 \cdot 36 m^3/d \div 67\% = 156 kg$ TSS

$156 \cdot 0.8 = 125$

$156 \cdot 1.0 = 156$

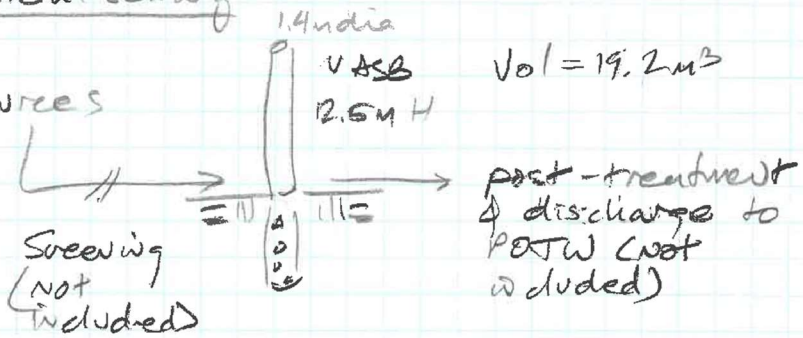
11/2/18 Robert Weil Masters Thesis Calculations

Capital and operating costs of an UASB system for K State's dairy research

Objective

Rough order of magnitude cost estimate based on conceptual reactor design

Physical setting



Solution

Previous estimate (9/25/18) priced at a unit cost of $485 - $580 / m³.

Adjust upward by 100% due to greater complexity of one design & smaller scale

19.2 x 485 x 2.0 = $19,000 Low

19.2 x 580 x 2.0 = $23,000 High

Operating costs

3.5% of capital costs + 100 hrs + $5,000
× $20/hr electricity

$5,700 – $7,800

Economic return

@ $3/MMBTU

148 m^3/d · 365 * 0.036 MMBtu/m^3 CH_4

= 1,940 MMBTU/yr

@ $3/MMBTU = $5,820/yr

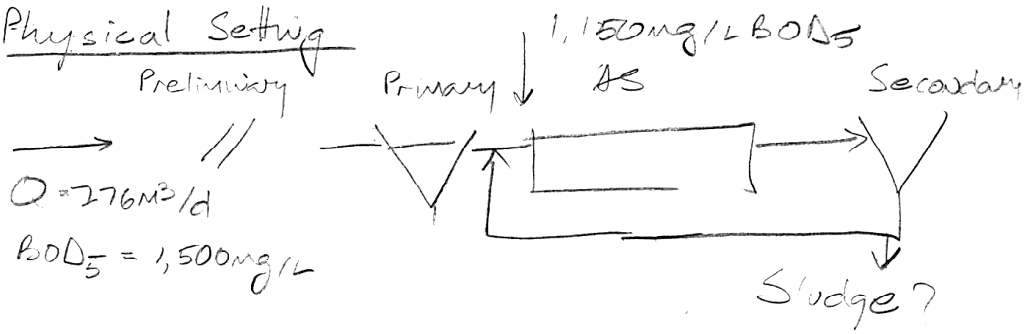
Again, about equal to operating costs on the low end

October 19, 2018 Robert Weil

Hand calculations of solids production from activated sludge process from agro-industrial wastes

Objective Given median wastewater parameters for agro-industrial wastewater in Kansas, find the solids resulting from activated sludge treatment of one flow. Assume 30% BOD_5 reduction in primary clarifier.

Physical Setting



Ref: Tchobanoglous, Ch. 8

$$P_{X,VSS} = Y_{obs}(Q)(S_o - S)\left(1\ kg/10^3\ g\right)$$

Y_{obs} typically 0.4

Assume $S = 5$ mg/L

$$P_{x,vss} = 0.4 \cdot 276\ M^3/d \cdot 1{,}000\ L/M^3 \cdot (1{,}150 - 5)\ mg/L \cdot 1\ kg/10^6\ mg$$

= 126 kg/d.

× 30 × 365

= 1,384,167

= 1,380 metric tonnes/yr

1/6 = 230

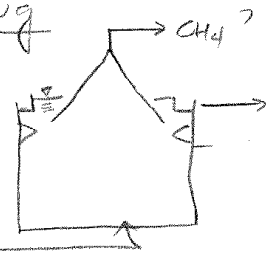
1/8 = 170

10/29/13 Robert Weil

Hand calcs for Masters' thesis

Design UASB reactor for meat packing plant case study, following the example of Tchobanoglous (2003), Example 6-3

Physical setting



Goal = 85% removal

Assume effluent VSS = 126 g/m³ (nbVSS + 35)

COD = 876 g/m³

TSS = 348 g/m³

VSS = 80% of VSS = 278 g/m³

Alk = 110 g/m³

SO_4 assumed to be 200 g/m³

Temp = 25°C

sCOD assumed to be 87% of COD = 762 g/m³

pCOD assumed to be 115% of COD = 1007 g/m³

Effluent VSS = 67% reduction from Influent = 92 g/m³

Design parameters and assumptions

1. From Table 10-10

$Y = 0.08\ g\ VSS/g\ COD$

$k_d = 0.08\ g\ VSS/g\ VSS \cdot d$

$\mu_M = 0.25\ g\ VSS/g\ VSS \cdot d$

2. f_d = 0.15 g VSS cell debris / g VSS biomass decay
3. CH_4 production at 35°C = 0.40 L CH_4 / g COD
4. Reactor volume effectiveness factor = 85%
5. Height for gas collection = 2.5 M

Solution

A volumetric loading of 6 kg sCOD / m^3 · d chosen because ≥ 85% sCOD removal ok if organic loads high in volatile FA.

1. Reactor volume

$$V_N = \frac{Q\ S_o}{L_{org}} = \frac{2{,}400\ m^3/d \cdot 0.762\ kg/m^3}{6\ kg\ sCOD/m^3 \cdot d}$$

$$= 305\ m^3$$

2. Total reactor liquid volume

$$V_L = \frac{V_N}{E} = \frac{305\ m^3}{0.85} = 359\ m^3$$

upflow velocity of 1 m/h selected bas on COD partially soluble

3. Reactor dimensions

a. $$A = \frac{Q}{v} = \frac{2{,}400\ m^3/d}{1\ m/h \cdot 24\ h/d}$$

$$= 100\ m^2$$

$$A = \frac{\pi D^2}{4} \qquad D = 11.\ m.$$

b. Reactor liquid height

$$H_L = \frac{V_L}{A} = \frac{359\ m^3}{100\ m^2} = 3.6 M$$

c. Reactor total height

$H_T = H_L + H_F = 3.6M + 2.5M = 6.1M$

d Reactor dimensions

Diameter = 11M

Height = 6.1 M.

3. Hydraulic detention time, τ

$$\tau = \frac{V_L}{Q} = \frac{359\ m^3 \cdot 24\ h/d}{2,400\ m^3/d} = 3.6\ h.$$

4. Reactor SRT.

a $QX_e = P_{X,VSS}$ = solids wasted per day

$$P_{X,VSS} = \frac{Q(Y)(S_o - S)}{1 + k_d SRT} + \frac{f_d\ k_d\ Q\ Y\ (S_o - S)\ SRT}{1 + k_d SRT}$$

$$+ Q(NbVSS) - QX_e$$

b Data to solve equation

i. effluent sCOD = $0.15(876\ g/m^3) = 131\ g/m^3$

ii effluent NBVSS given 67% degraded

$= 0.33(278) = 92\ g/m^3$

iii pCOD = $0.5(1007 - 876) = 66\ g/m^3$

iv Total degradable influent COD, S_o =

$S_o = 762 + 66 = 828\ g/m^3$

Given		
Q	2400	m3/d
Xe	126	g/m3
Y	0.08	g VSS/g COD
kd	0.03	g VSS/g VSS d
um	0.25	g VSS/g VSS d
fd	0.15	g VSS/g FSS
S	131	g COD/m3
nbVSS	91	g VSS/m3
pCOD	66	g COD/m3
So	828	g COD/m3

Q-Xe		302400	302400	302400	302400	302400
SRT Trials (d)		40	30	20	28	27.5
Eq 7-52 components						
134,000/1+.03*SRT		60,909	70,526	83,750	72,826	73,425
(602*SRT)/(1+.03*SRT)		10,945	9,505	7,525	9,161	9,071
	220000	220,000	220,000	220,000	220,000	220,000
Sum of right side		291,855	300,032	311,275	301,987	302,496
Difference		10,545	2,368	(8,875)	413	(96)

5 of 8

c. Substitute parameter values & solve for Θ_x (SRT)

$Q X_e = 2,400 \cdot 131 = 360,000$ g/d.

$$= \frac{2,400 \cdot 0.08 \cdot (828-131)}{1+0.03\Theta_x}\left(\frac{134,000}{1+0.03\Theta_x}\right)$$

$$+ \frac{0.15 \cdot 003 \cdot 2400 \cdot 0.08 (828-131)\Theta_x}{1+0.03\Theta_x}\left(\frac{602\Theta_x}{1+0.03\Theta_x}\right)$$

$$+ 2,400 \cdot 92 \quad (220,000) \text{ g/d.}$$

SRT = 27.5 d based on iteration (sheet 4)

5. Estimate effluent COD at SRT = 27.5d, 25°C

$$S = \frac{K_s\,[1 + k_d\ SRT]}{SRT\,(Y_k - k_d) - 1}$$

$$k = \frac{\mu_M}{Y} = \frac{0.25}{0.08} = 3.125 \text{ g COD / g VSS-d}$$

If 900 used S = 325 mg/l

$$S = \frac{360\ [1+(0.03 \cdot 27.5)]}{[27.5(0.08 \cdot 3.125 - 0.03) - 1]}$$

$$= \frac{657}{5.05} = 130 \text{ mg/l.}$$

~~130~~ / 876 = 15 % OK, as expected

7. Determine average X_{TSS}

$$X_{TSS} \simeq \frac{Q X_e \, SRT}{2{,}400 \cdot 126 \cdot 27.5\,d \cdot 1\,kg/10^3\,g}{305\,m^3}$$

$= 27.3\ kg/m^3$

Within the range of 5-40 g/L for UASB
kg/m³

8 Methane production

a COD = $S_0 - S$ = 828 - 131 = 697

b COD sulfate reducing = 0.9 (200)(0.67 g COD/g SO_4)

= 120.6

c COD used by methane bacteria

= 697 - 120.6 · 2,400 m³/d = 1,380,000 g COD/d

d Methane production rate

at 25°C $(0.40\ L/g)\left(\frac{273.15+25}{273.15+35}\right) = 0.387\ L/g$

Amount of CH_4 produced/d = 0.387 · 1,380,000

= 534,000 L/d

= 534 m³/d

7 of 8

Total gas volume (65% methane)
$= 534 / 0.65 = 821\ m^3/d$

9 skip

10. Alkalinity required to maintain pH 7

$X_{H_2CO_3} = \frac{1 \text{ atm} - 0.35}{1,623} = 2.156 \times 10^{-4}$

$[H_2CO_3] = 2.156 \times 10^{-4} \cdot 55.6 \text{ mole/l} =$
1.20×10^{-2} mole/l

$[HCO_3^-] = \frac{4.467 \times 10^{-7} \text{ mole/l} \ (1.20 \times 10^{-2} \text{ mole/l}}{10^{-7} \text{ mol/l}}$

$= 0.0536$ mole/l

$HCO_3^- = 0.0536 \cdot 61 \cdot 10^3 = 3,270$ g/l

$Eq = \frac{3.26 \text{ g/l}}{61 \text{ g/eq}} = 0.0536$ eq/L

$= 2.68$ g/l as $CaCO_3$

Needed $= 2.68$ g/l $- 0.1$ g/l $= 2.58$ g/l

Daily alkalinity addition
$= 2.58$ g/l $\cdot$ 2,400 m³/d $\cdot$ 1000 l/m³ $\cdot$ 1 kg/1000 g
$= 2,200$ kg/d !

Comparison with parameter-based methane estimate.

CH_4 = 0.8 / M^3 of VSS destroyed (low)

= 0.8 · 278 = 222 at STP ⇒ 242 m^3 at 25°C

1.0 / m^3 of VSS destroyed (high)

= 1.0 · 278 = 278 ⇒ 303 m^3

1.12 · 278 = 311 ⇒ 339 m^3

≈ 534 m^3/d

Higher than parameter-based estimates, demonstrating them to be conservative.

AD Budget Calculator

Anaerobic Digester System Enterprise Budget Calculator

☑ Anaerobic Digester
☐ Codigest Organics
☐ Compressed Natural Gas
☐ Combined Heat & Power
☐ Environmental Credits

☐ Fiber Separation
☐ Nutrient Separation
☐ Water Recovery
Nutrient Balance

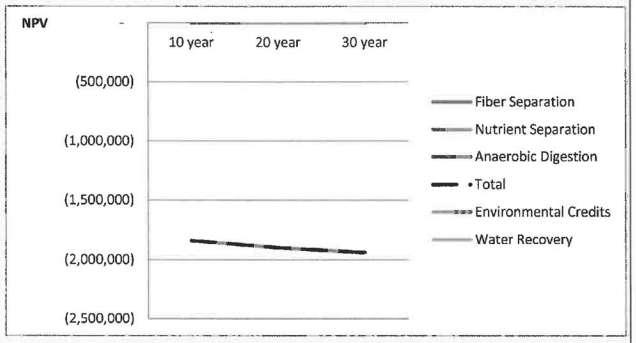
Herd Size, WCE 500
Neighbor's WCE -
Total WCE 500

☐ Flush Dairy; Scrape otherwise

Capital Costs
☐ Grants 25%
Discount Rate 4%

Revenue & Operating Cost

Technology Component	Net Present Value 10 year	20 year	30 year
Fiber Separation	-	-	-
Nutrient Separation	-	-	-
Water Recovery	-	-	-
Anaerobic Digestion choose CNG or CHP with Manure Only	(1,838,840)	(1,898,722)	(1,939,175)
Environmental Credits	-	-	-
Total	(1,838,840)	(1,898,722)	(1,939,175)



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The views expressed are the authors' and do not necessarily reflect those of the Economic Research Service or the USDA.

Last updated: June 7, 2016

$\frac{903}{1,345}$ * = 67% ⇒ 300 heifers ≈ 200 milking cows

⇒ Total herd size = 500

* Millbrandt (2005)

☑ **Anaerobic Digester** ☐ **Codigest Organics** **Control Panel** **Nutrient Balance**

PRODUCTION	QUANTITY	UNIT	QUANTITY	UNIT	QUANTITY	UNIT	SUBTOTAL	% TOTAL	TOTAL	Unit
Volume Input									65	m3/day
Animal Waste	500	WCE	0.13	m3/WCE/day	100%	% sent to AD	65	84%		m3/day
Other Organics	11	Ton/day	1.102	m3/Ton	100%	% sent to AD	-	16%		m3/day
Digester Volume	65	m3 flow/day	22	HRT in days					1,430	m3
Methane Output									46,928	m3 CH4
Animal Waste	23,725	m3/year	8.6	kg VS/ m3	0.23	m3 CH4/ kg VS ir	46,928	100%		m3 CH4
Other Organics	-	m3/year	163.4	kg VS/ m3	0.37	m3 CH4/ kg VS ir	-	0%		m3 CH4

Nutrient Balance	Volume (m3)	Tons	% System N	Tons N	% System P	Tons P	% System Solids	Tons Solids
In Flow								
Liquid Effluent		26,336	100%	58	100%	16	100%	1,831
Out Flow								
Liquid Effluent		25,730	100%	58	100%	16	67%	1,224

CAPITAL COSTS	QUANTITY	UNIT	PRICE	INDEX	SUBTOTAL	% TOTAL	TOTAL	% CAPITAL
Animal Waste Portion							1,750,201	100%
Pre digester Separati	500	WCE	572	Process Machine	-	0%		
Freight, Rentals,Mob	500	WCE	241	Freight Prod Pric	120,505	7%		
Excavation/Digester/	500	WCE	(342)	Construction Lab	(170,909)	-10%		
Vessel	500	WCE	1,088	Buildings	543,878	31%		
Insulation / Interior (	500	WCE	56	Buildings	28,128	2%		
Hollow Core Roof Pa	500	WCE	151	Buildings	75,523	4%		
Manure, Gas, & Wat	500	WCE	758	Pipe Valves And I	379,159	22%		
Equipment - Heat Ex	500	WCE	1,060	Heat Exchangers	529,955	30%		
Permitting, Engineeri	500	WCE	193	Engineering And	96,702	6%		
System Start-up & St	500	WCE	295	Engineering And	147,260	8%		
Sales Tax	0.0%	% ofAnimal '	1,750,201		-	0%		
Codigest Organics Portion							-	0%
Pre digester Collectic	500	WCE	73	Process Machine	36,637	0%		
Freight, Rentals,Mob	16%	% of Capital	120,505	Freight Prod Pric	19,281	0%		
Excavation/Digester/	16%	% of Capital	(170,909)	Construction Lab	(27,345)	0%		
Vessel	16%	% of Capital	543,878	Buildings	87,021	0%		
Insulation / Interior (	16%	% of Capital	28,128	Buildings	4,501	0%		
Hollow Core Roof Pa	16%	% of Capital	75,523	Buildings	12,084	0%		
Manure, Gas, & Wat	16%	% of Capital	379,159	Pipe Valves And I	60,665	0%		
Equipment - Heat Ex	16%	% of Capital	529,955	Heat Exchangers	84,793	0%		
Permitting, Engineeri	16%	% of Capital	96,702	Engineering And	15,472	0%		
System Start-up & St	16%	% of Capital	147,260	Engineering And	23,562	0%		
Sales Tax	0.0%	% of Capital	316,669		-	0%		
Combined Heat & Power (CHP)								
Compressed Natural Gas (CNG)								
Boiler								
Other								
CAPITAL COSTS TOTAL							1,750,201	

			CEPC Indice Current							
	Observation Year		2013	2018						
	WCE									
Tech	Revised Capital Item	Index Item	41456		Intercept1	Intercept2	Slope1	Slope2	Cost	Cost/WCE
AD	Pre digester Separation/Thickeni	Process Machinery	655		289512.259	205553.886	-6.5814117	27.0019375	286,222	572
AD	Freight, Rentals,Mobilization	Freight Prod Price	143.78		140551.875	39007.9282	-40.094297	0.52328187	120,505	241
AD	Excavation/Digester/Driveway/M	Construction Labor	320.2		-257375.37	68845.3716	172.933669	42.4453723	(170,909)	(342)
AD	Concrete Vessel	Buildings	531.1		514554.504	297598.448	58.6478101	145.430232	543,878	1,088
AD	Insulation / Interior Coating	Buildings	531.1		-22644.349	89094.747	101.545531	56.8498923	28,128	56
AD	Hollow Core Roof Panels	Buildings	531.1		57470.137	1682.09081	36.1059144	58.4211329	75,523	151
AD	Manure, Gas, & Water Piping, H2	Pipe Valves And Fittings	861.8		416764.243	90046.9643	-75.210964	55.4759471	379,159	758
AD	Equipment - Heat Exchangers, W	Heat Exchangers And Tanks	620.7		563612.549	43065.8711	-67.315031	140.903641	529,955	1,060
AD	Permitting, Engineering, & Testin	Engineering And Supervision	324.6		108189.534	-176291.38	-22.975646	90.8167182	96,702	193
AD	System Start-up & Support	Engineering And Supervision	324.6		170603.415	-1786.3161	-46.687134	22.2687582	147,260	295
Total, no pre										
Codigest	Pre-Digester Collection Pit	Buildings	531.1		28744.2922	61440.3021	15.7848174	2.70641342	36,637	73
Fiber	[illegible]	Process Machinery	[illegible]							
CHP	[illegible]	Buildings	[illegible]							
CHP	[illegible]	Electrical Equipment	[illegible]							
CHP	[illegible]	Electrical Equipment	[illegible]							
CHP	[illegible]	Inflation	[illegible]							
	Operating Cost									
AD	Manure Equip. & Digester				117938.883		16.6496289		120,080	0.00701041

			CEPC Indic	Current						
	Observation Year WCE		2013	2018						
Tech	Revised Capital Item	Index Item	41456		**Intercept1**	**Intercept2**	**Slope1**	**Slope2**	**Cost**	**Cost/WCE**
AD	Pre digester Separation/Thickeni	Process Machinery	655		289512.259	205553.886	-6.5814117	27.0019375	286,222	572
AD	Freight, Rentals,Mobilization	Freight Prod Price	143.78		140551.875	39007.9282	-40.094297	0.52328187	120,505	241
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AD	Equipment - Heat Exchangers, W	Heat Exchangers And Tanks	620.7		563612.549	43065.8711	-67.315031	140.903641	529,955	1,060
AD	Permitting, Engineering, & Testin	Engineering And Supervision	324.6		108189.534	-176291.38	-22.975646	90.8167182	96,702	193
AD	System Start-up & Support	Engineering And Supervision	324.6		170603.415	-1786.3161	-46.687134	22.2687582	147,260	295
Total, no pre										
Codigest	Pre-Digester Collection Pit	Buildings	531.1		28744.2922	61440.3021	15.7848174	2.70641342	36,637	73
Fiber	[illegible]	[illegible]	[illegible]							
CHP	[illegible]	[illegible]	[illegible]							
CHP	[illegible]	[illegible]	[illegible]							
CHP	[illegible]	[illegible]	[illegible]							
CHP	[illegible]	[illegible]	[illegible]							
	Operating Cost									
AD	Manure Equip. & Digester				117938.883		16.6496289		120,080	0.00701041

Anaerobic Digestion Financial Decision Tools

Lactating Cows	300
Dry Cows	300

Milking Animals	
pounds of manure per cow/day	150.00
volatile solids content %	11.33%
Solid conversion to biogas	30%
CF of biogas per lb VS converted	16
btu's per cf of biogas	625
btu's per cow per day	51,000
CF methane per cow per day	51
CF biogas per cow per day	81.60
Total BTU's/Year	5,584,500,000
Total Tons of Waste treated per year	8,213
Total Solids per year	1,095

18,615 CF/yr = 527 l/yr × 300 = 158,100 m³/y

Value of 1MMBTU ($'s)	6
Value per ton	$4.08

dry cows	
pounds of manure per cow/day	83.00
volatile solids content %	11.08%
Solid conversion to biogas	30%
CF of biogas per lb VS converted	16
btu's per cf of biogas	$ 625
btu's per cow per day	27,600
CF methane per cow per day	28
CF biogas per cow per day	44.16
Total BTU's/Year	3,022,200,000
Total Tons of Waste treated per year	4,544
Total Solids per year	602

10,220 = 28 l/yr × 300 = 86,800 m³/y

244,900 m³/yr

Value of 1MMBTU ($'s)	6
Value per ton	$3.99

Other Wastes	
Tipping Fees net of disposal costs per ton	$0.00
Tons per day	-
volatile solids content %	40%
Solid conversion to biogas	30%
CF of biogas per lb VS converted	16
btu's per cf of biogas	625
btu's per day	-
CF methane per day	-
CF biogas per day	-
Total BTU's/Year	-
Total Tons of Waste treated per year	-

Value of 1MMBTU ($'s)	6
Value per ton	#DIV/0!

Lactating Cows

Total Manure and Nutrients Generatad by Dairy Project

		per cow per day	per cow/year	daily operation	annual operation
Total Manure	lbs	150.00	54,750	45,000	16,425,000
	tons	0.08	27.38	23	8,213
	gallons	18.07	6,596	5,422	1,978,916
total solids	lbs	20	7,300	6,000	2,190,000
	tons	0.01	4	3	1,095

Dry Cows

Total Manure and Nutrients Generated by Dairy Project

		per cow pe	per cow/year	daily operation	annual operation
Total Manure	lbs	83.00	30,295	24,900	9,088,500
	tons	0.04	15.15	12	4,544
	gallons	10.00	3,650	3,000	1,095,000
total solids	lbs	11	4,015	3,300	1,204,500
	tons	0.0055	2	2	602

Enter assumptions below

Farm 1	
Anaerobic Digestion - Inputs	**Inputs**
Animal type	Dairy
Number of animal units (AU=1000lb)	674
Animal unit	1.4
Manure (lb/AU/day)	82.00
Total manure (lb/day)	77,375
Moisture content (%)	0%
TSS content (%)	100%
Total moisture (gal/day)	-
Total TSS (lb/day)	77,375
COD per lb/AU/d	11.00
Total COD (lb)	10,380
Anaerobic Digestion - Reductions	
Flow (%)	1%
TSS (%)	5%
COD destruction rate(%)	70%
Anaerobic Digestion - Outputs	
Flow (gal/day)	-
TSS(lb)	73,506
COD (lb)	3,114
Power generation potential	
Methane per lb of COD (ft^3)	6.30
Methane potential per day (ft^3/day)	45,774
Total farm's yearly methane potential CH4 (ft^3)	16,707,523

Farm 2	
Anaerobic Digestion - Inputs	**Inputs**
Animal type	Dairy
Number of animal units (AU=1000lb)	-
Animal unit	1.4
Manure (lb/AU/day)	82.00
Total manure (lb/day)	-
Moisture content (%)	0%
TSS content (%)	100%
Total moisture (gal/day)	-
Total TSS (lb/day)	-
COD per lb/AU/d	11.00
Total COD (lb)	-
Anaerobic Digestion - Reductions	
Flow (%)	1%
TSS (%)	5%
COD destruction rate(%)	70%
Anaerobic Digestion - Outputs	
Flow (gal/day)	-
TSS(lb)	-
COD (lb)	-
Power generation potential	
Methane per lb of COD (ft^3)	6.30
Methane potential per day (ft^3/day)	-
Total farm's yearly methane potential CH4 (ft^3)	-

6473 104 m^3

Farm 3	
Anaerobic Digestion - Inputs	**Inputs**
Animal type	Dairy
Number of animal units (AU=1000lb)	-
Animal unit	1.4
Manure (lb/AU/day)	82.00
Total manure (lb/day)	-
Moisture content (%)	0%
TSS content (%)	100%
Total moisture (gal/day)	-
Total TSS (lb/day)	-
COD per lb/AU/d	11.00
Total COD (lb)	-
Anaerobic Digestion - Reductions	
Flow (%)	1%
TSS (%)	5%
COD destruction rate(%)	70%
Anaerobic Digestion - Outputs	
Flow (gal/day)	-
TSS(lb)	-
COD (lb)	-
Power generation potential	
Methane per lb of COD (ft^3)	6.30
Methane potential per day (ft^3/day)	-
Total farm's yearly methane potential CH4 (ft^3)	-

Farm 4	
Anaerobic Digestion - Inputs	**Inputs**
Animal type	Dairy
Number of animal units (AU=1000lb)	-
Animal unit	1.4
Manure (lb/AU/day)	82.00
Total manure (lb/day)	-
Moisture content (%)	0%
TSS content (%)	100%
Total moisture (gal/day)	-
Total TSS (lb/day)	-
COD per lb/AU/d	11.00
Total COD (lb)	-
Anaerobic Digestion - Reductions	
Flow (%)	1%
TSS (%)	5%
COD destruction rate(%)	70%
Anaerobic Digestion - Outputs	
Flow (gal/day)	-
TSS(lb)	-
COD (lb)	-
Power generation potential	
Methane per lb of COD (ft^3)	6.30
Methane potential per day (ft^3/day)	-
Total farm's yearly methane potential CH4 (ft^3)	-

300 milking cows @ 1345 lbs/cow = 403,500
+300 heifers @ 903 lbs/cow = 270,900
674,000
÷ 1000
674 AU

} Milbrandt, 2005

Farm Sources

Appendix D - ADM Wastewater Pre-Treatment Site Visit Report

Site Visit Notes

Archers Daniel Midland, Decatur, IL. Stephen Bugle. July 12th, 2018.

See schematic.

They have two streams: high salt (9.5 mgd) and low salt (5.3 mgd). Biogas is recovered from both. Low salt is red on the schematic; it goes to reuse within the plant, then is discharged for municipal treatment. The high salt goes through DAF solids separation, then is discharged for municipal treatment. The anaerobic digesters are large rectangular units, 35 mgal each in volume. They are called bulk volume fermenters (BVF). This is a patented process of ADI, a Evoqua brand. (See attached). The organic wastewater flows up through a sludge blanket. There are two stages of digestion along the length of the units. The units are covered with a heavy layered membrane. Biogas collects in the void space along the edges and is withdrawn for treatment.

Both high salt and low salt go through aerobic polishing before being discharged for municipal treatment. Originally, the plant used only aerobic treatment, but implemented anaerobic treatment because it could not dispose of biosolids as it had been doing. The combination of anaerobic and aerobic treatment is very effective. Stephen said that his municipal treatment staff has had no complaints since they implemented the anaerobic process, but there were many complaints before that.

The first stage of biogas treatment is a chemical process to remove hydrogen sulfide chemically. It is called the Lo-Cat system (see attached), and it uses iron as a complexing agent. One of the results is elemental sulfur. Stephen was pleased with this technology.

The final stage of biogas upgrading is a Guild PSA process. When it was first started, it did not work as smoothly as Guild advertised, but it is working smoothly now. There is a fairly high level of maintenance on this unit.

The renewable natural gas goes through a pipeline about one mile in length and is injected into a natural gas transmission main. Stephen said that the corporate managers are cautious about the economic returns on RNG and are waiting to see how this project turns out before investing in another one.

Some gas is not upgraded to RNG standards and is used in the manufacturing plant. Stephen's opinion was that recovering biogas for plant usage was a viable approach.

One of the things I take from this project is that it is a very large scale facility. It indicates to me that the RNG upgrading equipment can really only be justified for industrial pretreatment when the flows are very large.

ADI® Systems
an EVOQUA brand

CONTACT PRODUCT EXPERT

Shannon Grant
President
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EMAIL

REQUEST PROPOSAL

ADI-BVF® REACTOR

Anaerobic digestion system that offers very stable, robust wastewater treatment and biogas generation under a wide range of operating conditions.

ADI Systems from Evoqua is the exclusive provider of the ADI-BVF® reactor, with 140 installed full-scale applications around the world. Our experience with low-rate anaerobic digestion is unmatched in the wastewater treatment industry.

The BVF® reactor treats wastewater streams with moderate to high concentrations of organics (COD/BOD), suspended solids, and fat, oil, and grease (FOG), typically without the need for primary treatment. The reactor can be configured as an in-ground earthen basin or an above-ground tank based on space availability. It is sized to work at low volumetric loading rate conditions, and designed to handle variations in wastewater flows and characteristics and maximize biogas production. This makes the BVF reactor an ideal choice for treating wastewater from a variety of industries.

DOCUMENTATION

CASE STUDIES

NEWS RELEASES

VIDEOS

COST SAVINGS

- Minimize sludge handling and disposal costs
- Save on energy costs:
  - Low energy consumption design
  - Significantly less energy-intensive than aerobic systems
  - Energy recovery from biogas can reduce use of fossil fuels
- Eliminate wastewater surcharges
- Reduce or eliminate chemical usage

PROCESS ADVANTAGES

- Stability during peak flows and loads
- No up-front solids and FOG removal required
- Operates at a wide temperature range
- Offers ability to store waste sludge
- Custom-designed geomembrane cover:
  - Collects valuable biogas
  - Provides insulation and odor control

ENVIRONMENTAL BENEFITS

- Continuously meet discharge requirements
  - Consistent effluent quality
- Convert organic waste to recoverable green energy (heat and power)
- Waste sludge suitable for land application as liquid fertilizer (high nutrient content)
- Improve local and global water security

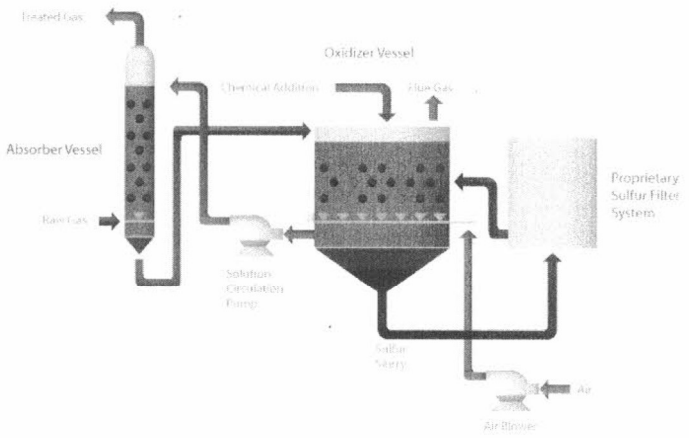
SIMPLIFIED OPERATION & MAINTENANCE

- Minimal equipment and moving parts results in low maintenance requirements
- Requires less operator attention
- Flexible sludge wasting program
- Data trending for process control
- Geomembrane cover provides easy access for sampling and maintenance

APPLICABLE TECHNOLOGIES

- LO-CAT
- AMINEX
- THIOLEX
- REGEN
- REGEN ULS

LO-CAT® H_2S REMOVAL TECHNOLOGY



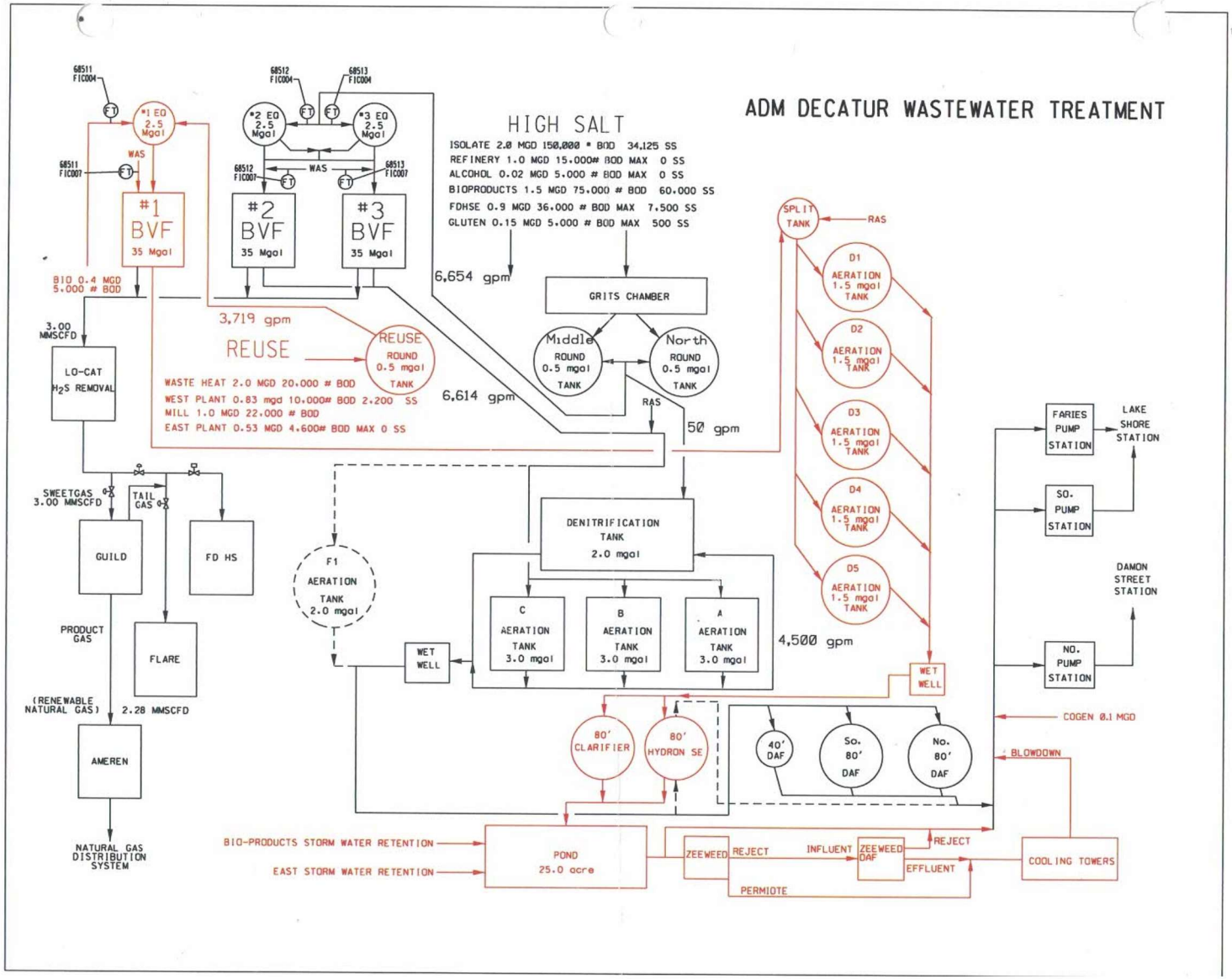
VIEW APPLICATION

The Environmentally Friendly Way To Remove Hydrogen Sulfide From Natural Gas

The LO-CAT® process is a patented, wet scrubbing, liquid redox system that uses a chelated iron solution to convert H2S to innocuous, elemental sulfur. It does not use any toxic chemicals and does not produce any hazardous waste byproducts. The catalyst is readily available and since it's continuously regenerated in the process, less catalyst is used, more money is saved.

The LO-CAT® process is applicable to all types of gas streams including air, natural gas, CO2, amine acid gas, biogas, landfill gas, refinery fuel gas, etc. The liquid catalyst adapts easily to variations in flow and concentration. Flexible operation allows 100% turndown in gas flow and H2S concentrations. Units require minimal operator attention.

More than 200 installations around the world depend on the LO-CAT® process to remove hydrogen sulfide from gas streams. The LO-CAT® process is reliable, efficient, and economical and is licensed with guarantees of: H2S removal efficiency, sulfur removal capacity and chemical consumption rates.


ADM DECATUR WASTEWATER TREATMENT
HIGH SALT
ISOLATE 2.0 MGD 150,000 * BOD 34,125 SS
REFINERY 1.0 MGD 15.000# BOD MAX 0 SS
ALCOHOL 0.02 MGD 5.000 # BOD MAX 0 SS
BIOPRODUCTS 1.5 MGD 75.000 # BOD 60.000 SS
FDHSE 0.9 MGD 36.000 # BOD MAX 7.500 SS
GLUTEN 0.15 MGD 5.000 # BOD MAX 500 SS
6,654 gpm
GRITS CHAMBER
Middle ROUND 0.5 mgal TANK
North ROUND 0.5 mgal TANK
RAS
50 gpm
SPLIT TANK
D1 AERATION 1.5 mgal TANK
D2 AERATION 1.5 mgal TANK
D3 AERATION 1.5 mgal TANK
D4 AERATION 1.5 mgal TANK
D5 AERATION 1.5 mgal TANK
#1 BVF 35 Mgal
#2 BVF 35 Mgal
#3 BVF 35 Mgal
#1 EQ 2.5 Mgal
#2 EQ 2.5 Mgal
#3 EQ 2.5 Mgal
WAS
BIO 0.4 MGD 5.000 # BOD
3.00 MMSCFD
LO-CAT H2S REMOVAL
3,719 gpm
REUSE
REUSE ROUND 0.5 mgal TANK
WASTE HEAT 2.0 MGD 20.000 # BOD
WEST PLANT 0.83 mgd 10.000# BOD 2.200 SS
MILL 1.0 MGD 22.000 # BOD
EAST PLANT 0.53 MGD 4.600# BOD MAX 0 SS
6,614 gpm
SWEETGAS 3.00 MMSCFD
TAIL GAS
GUILD
FD HS
PRODUCT GAS
FLARE
(RENEWABLE NATURAL GAS)
2.28 MMSCFD
AMEREN
NATURAL GAS DISTRIBUTION SYSTEM
F1 AERATION TANK 2.0 mgal
DENITRIFICATION TANK 2.0 mgal
C AERATION TANK 3.0 mgal
B AERATION TANK 3.0 mgal
A AERATION TANK 3.0 mgal
4,500 gpm
WET WELL
WET WELL
80' CLARIFIER
80' HYDRON SE
40' DAF
So. 80' DAF
No. 80' DAF
FARIES PUMP STATION
LAKE SHORE STATION
SO. PUMP STATION
DAMON STREET STATION
NO. PUMP STATION
COGEN 0.1 MGD
BLOWDOWN
BIO-PRODUCTS STORM WATER RETENTION
EAST STORM WATER RETENTION
POND 25.0 acre
ZEEWEED
REJECT
INFLUENT
ZEEWEED DAF
REJECT
EFFLUENT
PERMIOTE
COOLING TOWERS