An Aeroponic Greenhouse and Anaerobic Digester: Linking sustainability with research and education on Clarkson University’s campus

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• Students:
  – Shaun Jones, Daniel Hilderbrandt, Marta Kinnunen, Venessa Brabant, Bradley Kelsey, Brendan Lennox, Taylor Lenney, Maria DeMuri
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The Problem

- About 36.39 million tons on food waste is buried in U.S. landfill each year¹
  - With limited oxygen, water, sunlight, and organisms food waste decomposes very slowly
- The older landfill are not set up to capture methane

Total Municipal Solid Waste Generation by Material, 2012
251 Million Tons (before recycling)
Source: EPA

William Rathje, An American Archaeologist with a PhD in anthropology from Harvard University
System Overview

- Vertical aeroponic greenhouse.
- Wood pellet and passive solar boiler.
- Anaerobic digester for food waste.
Food waste collection

Food

Energy Cabin

Food Waste

Solar panel

Greenhouse

Electricity

Biogas

Fertilizer

Anaerobic digester

Heat

Engine/generator
Vision for Year-round Sustainable Food in Cold Climates

• Controlled environment
• Continuous production
• Low land footprint
• Local production
• Technical Innovations
  – Aeroponic growth
  – LED lighting
  – Passive solar design w/ renewable energy inputs
  – Sensors and controls
  – Materials and energy recycling

(Summer 2008)
Pilot Scale Green House Structure

Daylighting – transmissive south wall

Insulated - Structural insulated panels (SIPs) elsewhere

Slightly sloping roof – gutter along north edge

Three rooms for experimental variables

Lettuce and tomatoes
System Components

- CEHRF structure
- Aeroponics/plants
- Water quality, recovery, treatment, nutrification and distribution
- Heating and ventilation
- Electricity and lighting
- Sensors, controls, data acquisition (for all other systems)
Aeroponic System

Aeroponic growing system with LED lights in Room 1 and Room 3
Lighting

- Daylight necessary ??% through south wall
- LEDs - Surexi™ Horticulture LED Series by Illumitex
- Controlled to provide sufficient photosynthetic photon flux density (PPFD)
• Material grinding and feeding system
• Three 1,400 gallon reactors operated as two-stage digester
• Biogas generated in the anaerobic environment
• ENI 20kW co-generation combustion engine → CHP
• Instrumentation for independent operation and remote control
Anaerobic digester
Up to 300 kg food waste/day
Transformed into biogas
Savings - $190/ton food waste diverted from landfill
Current Digester Food:

- Cheel kitchen (pre-consumer) ~100-150 lb/d
- Apartment collection ~100-150 lb/wk
- Student Center kitchen (pre-consumer) ~100-150 lb/d
- On-going – efforts to increase feeding rate → increase the biogas production
Heating System

- Energy Cabin
- European designed and built

- Solar thermal hot water (2 kW)
- Wood pellet boiler (20 kW)
• Hot water/glycol (T ~80°C) Pumped from Energy Cabin

• Digester
  • heat exchanger to transfer heat to internal AD heating loop
  • Supplemental electric HW heater
  • Eventually – additional heat recovered from engine loss

• Greenhouse
  • Solar gain substantial
  • 3 supplemental pumps in GH distribute HW to rooms
  • T independently controlled in each room

Heating System

Energy Cabin
Control System

- Program logic controller (PLC) connected to all 3 rooms
- Frequency of spraying
- Lights on/off
- Temperature
- Other possibilities
  - Water tank volume
  - pH
Learners access and control CLICS through the Internet.

Weather station integrated from Internet.

Other on-campus facilities...

Local Area Network

Server running MANGO M2M

RS-485

Low Area Network

Modbus IP

Modbus IP

Modbus IP

Light intensity

Temperature

Humidity

PLC

Greenhouse

Light on/off

Pumps on/off

PLC

Digester

PLC

Energy Cabin

Internet
Mango Database for Data Acquisition

• Graphical interface to select datasets
• Pre-defined “reports” with sensor/data required for your project
• Virtual data available to clean up the database
  – All 30 min. intervals
  – Missing data recorded as blanks
  – Calculated variables derived from original data (e.g., heat content)
• Graphical output with student selected variables
  – Time series
  – X-Y scatter
  – Dual Y-axis graph
• Data download to MS Excel
Data Acquisition and Archiving

http://greenhouse.wlan.clarkson.edu:8080/watch_list.shtml
Improved GUI for student access to data
Greenhouse
- Heating system
- Lighting system
- Electricity consumption
- Water/nutrient flows*
- Lettuce yields*

Energy Cabin
- Wood pellets consumed
- Hot water/glycol
  - Temperatures
  - Flowrates
  - Both in and out of
    - Solar thermal*
    - Boiler
    - Hot water tank

Digester
- Food weight into system
- COD analysis
- Biogas generation
  - (flowrate, composition)
- Electricity consumption*
- Heating system
Example
Digester Research
Basic Digestion Process

1. Hydrolysis
2. Fermentation
3. Acetogenesis
4. Methanogenesis

- Complex organic matter (carbohydrates, proteins, fats) → Soluble organic molecules (sugars, amino acids, fatty acids)
- Volatile fatty acids
- Acetic acid
- $\text{H}_2$, $\text{CO}_2$
- $\text{CH}_4 + \text{CO}_2$
Food Waste Potential

- Food waste has higher biogas potential than other sources like agriculture and wastewater sludge.

[Image showing potential biogas yield compared to other sources like corn silage, grass, and manure.]
Food Waste Success Stories

• East Bay Municipal Utility District, Oakland, CA
  – First wastewater treatment plant in the nation to convert post-consumer food scraps to energy via anaerobic digestion.
  – Methane powers plant and produces natural fertilizer.

• University Wisconsin, Oshkosh
  – Use dry fermentation technology to digest university food waste scraps and city yard waste to produce enough electricity to power up to 15% of institution’s electricity.
University of Wisconsin - Oshkosh Biodigester
Oshkosh System

• Dry AD technology
  – High solids content (25% and above)
  – Material stays stationary within chamber
  – HRT = 28 days
  – No additional liquid input
  – Liquid is recirculated
  – Feedstock can be composted after AD

• Power generation 370 kW treating 8,000 tons of waste annually (22 ton/day)

  16.8 kW per ton of Feedstock
So Can We Do Any Better?
Clarkson’s Mixed Food Waste Composition

- Chemical Oxygen Demand (COD) = 268,264 ± 181,549 mg/L
- Total Solids (TS) = 19.66 ± 12.88%
- Volatile Solids (VS) = 18.74 ± 12.60%
Phases of Anaerobic Digestion

1st Stage

Hydrolysis

Acidogenesis

Volatile Fatty Acid (VFA)

Acetogenesis

1st Stage Effluent

Methanogenesis

2nd Stage

Digested Effluent

Bio-gas (CH$_4$ & CO$_2$)

H$_2$ & CO$_2$

Influent

Conventional Single Stage Digestion

*K. Venkiteshwaran “Two-Stage Anaerobic Co-Digestion using crude glycerol or cheese whey with dairy manure to improve methane production”
Single vs. Two Phase Comparison

- **Single Stage**
  - Easier to maintain.
  - Simpler to operate.

- **Two-Phase**
  - Environmental control of each phase (temp, pH).
  - Control of hydraulic retention time (HRT).
  - Optimization of process by increased volatile fatty acid (VFA) production.
  - Smaller overall reactor volume due to smaller HRT.
Clarkson’s Digester Operation

- Ability to run single stage and two-phase digestion.
- Separate mixing cycles for each stage.
Given the variable loading what process will be most reliable and efficient?

• Single stage system could result in overloading at high loading conditions, or
• Fermentation stage of 2-stage system may be difficult to maintain during low loading conditions
Approach

• Operate system first as single stage system at higher loading rates
• Followed by 2-stage operation at low loading
Methane Content

http://greenhouse.wlan.clarkson.edu:8080/mango/login.htm
Biogas Production

Approximately 500 ft$^3$/d feeding an average of 113 lbs/d at 12±8 % VS
Approximately 1,362±544 L CH4/kg VS added
Or 272 m$^3$ biogas per ton of foodwaste or 21 kW per ton of FW

http://greenhouse.wlan.clarkson.edu:8080/mango/login.htm
Average Chemical Characterization

![Bar chart showing solids percentage and COD (mg/L) for different stages.](image-url)
Acidogenesis HRT Affecting pH in Reactor

Acid Reactor 15-day Average HRT

Acid Reactor pH
Recent pH condition's

![Graph showing pH condition over time for Stage 1 and Stage 2.]

- **Stage 1**
  - 5/11/2014: Reactor pH 8.5
  - 5/16/2014: Reactor pH 7.8
  - 5/21/2014: Reactor pH 8.2
  - 5/26/2014: Reactor pH 7.9
  - 5/31/2014: Reactor pH 8.0
  - 6/5/2014: Reactor pH 7.7
  - 6/10/2014: Reactor pH 7.5

- **Stage 2**
  - 5/11/2014: Reactor pH 9.2
  - 5/16/2014: Reactor pH 8.8
  - 5/21/2014: Reactor pH 8.6
  - 5/26/2014: Reactor pH 8.3
  - 5/31/2014: Reactor pH 8.1
  - 6/5/2014: Reactor pH 7.9
  - 6/10/2014: Reactor pH 7.7
## Biogas Production Comparison

<table>
<thead>
<tr>
<th></th>
<th>One-stage</th>
<th>Two-stage</th>
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<tbody>
<tr>
<td><strong>Substrates</strong></td>
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<tr>
<td>COD (mg·L⁻¹)</td>
<td>273400</td>
<td>267000±149900</td>
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<tr>
<td>TS (%)</td>
<td>19.62</td>
<td>23.62±7.85%</td>
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<tr>
<td>VS (%)</td>
<td>18.69</td>
<td>22.88±8.53%</td>
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<td><strong>Digester operation</strong></td>
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<tr>
<td>VS loading rate (kg·m⁻³ d⁻¹)</td>
<td>3.79</td>
<td>0.78±0.42</td>
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<tr>
<td>COD loading rate (kg·m⁻³ d⁻¹)</td>
<td>3.87±1.93</td>
<td>0.79±0.16</td>
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<td><strong>Digester characteristics</strong></td>
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<tr>
<td>pH</td>
<td>7.32</td>
<td>5.2±0.4</td>
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<tr>
<td></td>
<td>8.4±0.1</td>
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<td>COD (mg·L⁻¹)</td>
<td>19730</td>
<td>162700±60900</td>
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<tr>
<td></td>
<td>22900±8800</td>
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<tr>
<td>VS (%)</td>
<td>0.84</td>
<td>6.01±3.31%</td>
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<td></td>
<td>1.60±1.00%</td>
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<tr>
<td>TS (%)</td>
<td>1.54</td>
<td>7.32±3.37%</td>
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<td></td>
<td>2.84±1.58%</td>
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<td>VFA (mg·L⁻¹ as HAc)</td>
<td>38900±4800</td>
<td>6300±3600</td>
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<td><strong>Digester performances</strong></td>
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<tr>
<td>Temperature (°C)</td>
<td>37.32</td>
<td>37.32</td>
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<tr>
<td>VS removal (%)</td>
<td>96</td>
<td>93</td>
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<tr>
<td>COD removal (%)</td>
<td>93</td>
<td>91</td>
</tr>
<tr>
<td>Methane concentration (%)</td>
<td>58.60</td>
<td>58.98</td>
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<tr>
<td>Methane yield (L·CH₄·kg VS⁻¹)</td>
<td>380</td>
<td>446</td>
</tr>
<tr>
<td>Methane yield (L·CH₄·kg COD⁻¹ removed)</td>
<td>359</td>
<td>481</td>
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</tbody>
</table>
CLICS in Classes

Senior Design Engineering & Management
Senior Design Environmental Engineering
Summer Undergraduate Research on Ammonia Inhibition
Mechanical Engineering Senior Design
Industrial Ecology
Applied Statistics
Calculus 2
Numerical Methods
Introduction of Environmental Engineering
Biological Processes
EM456: Digester Heating

• Three sources of heat energy for digester reactors.
Energy Balance

- **Energy production**
  \[ E_A = (M_p) \cdot (\text{L.H.V. of methane}) \]
  Where \( M_p \) is the daily methane production rate.

- **Heat required to heat feedstock**
  \[ E_B = Q \cdot C_p \cdot \delta(T_i - T_0) \]
  Where \( Q \) (m\(^3\) per day) is the load flow rate, \( C_p \) (kJ/kg °C) is the specific heat of feed, \( \delta \) (kg/m\(^3\)) is the specific weight of feed and \( T_i - T_0 \) (°C) is the difference between these two temperatures.

- **Heat loss through reactor walls**
  \[ E_C = k \cdot S(T_i - T_e) \]
  Where \( k \) (Wm\(^2\)/°C) is the global heat transfer coefficient and \( S \) (m\(^2\)) the heat surface exchange. Temperature difference between digester reactor (\( T_i \)) and the pervading environmental temperature \( T_e \).

- **Mechanical energy requirements**
  \[ E_D = P \cdot T_{ps} \]
  Where \( P \) is the power (W) and \( T_{ps} \) its daily functioning duration.

- **Net energy production**
  \[ E_P = E_A - (E_B + E_C + E_D) \]
2-phase system with CHP

Energy (MJ)

- Heat Energy Demand
- Excess Heat Energy
- Electricity Generation
Economically viable?
CE491: Current focus – increase food throughput

- Evaluate pre-processing to reduce particle size
- Disposer vs pulping
Improve Waste Handling

• So we can increase waste production reliably
• E.g. pulping
Pulping results

Particle Size Relative to %TS

- D60
- D30
- D10

Particle Diameter (in)

%Total Solids
Lighting Needs in GH

CE486/586 – Industrial Ecology
Assignment

- Evaluate the use of electricity and associated emissions required to grow lettuce in our pilot greenhouse. Use both Mango to create reports for lighting and the excel spreadsheet included on Moodle (Sept 30-Oct 4).
  - Create reports for “GH Rm 3 Light” to compare lighting requirements for seasons. (copy required graph images to paste into a word document)
    - Sept 30 – Oct 7, 2013
    - June 14 – June 22, 2013
    - Dec 1 – Dec 8, 2012
  - Using graphs included for each of these reports -
    - compare the amount of light received by the green house (hours and intensity) and the resulting general change in the number of lights on during sunny periods.
  - Using the Excel spreadsheet (on Moodle),
    - determine the number of lights on for each time step.
    - estimate the electric energy required for each time step for the actual number of lights that were on (note- each strip requires 72 W power)
    - estimate the electric energy required if all of the light strips were on during that same time period
    - Calculate the savings in daily electric energy for each day included in the excel spreadsheet.
  - Calculate the daily CO\textsubscript{2}, NOx and SO\textsubscript{2} emissions for the total electricity and savings due to our use of daylight
  - Discuss the value of using day light for supplementing electric light in the greenhouse and the application of sensors and controls to automate lighting.
Lighting Efficiency Efforts

• Timers – on/off 12 hours/day
• LED bulbs (72W/strip)
• Only red & blue light generated
• Daylight sensors – some lights off when sufficient daylight entering

What is the value of day lighting to reduce electric energy use?
1. Click on Greenhouse to access data

http://greenhouse.wlan.clarkson.edu:8080/mango
2. Click on Lighting System to access data
4. Change Dates for each report you run

5. Run report

---

Note:
Due to change in Sensor placement within the GH:

1. For incoming solar intensity, “Light_window intensity” correct sensor until Sept. 2013. Use “Light intensity South” for access to these data after.

2. Electric power sensor was switched. Electric power data and sensor labeled “Rm 1” provides data until Oct. 7, then “Rm 3” sensor correct thereafter.

---
6. Mango requires you to refresh the page before the report is completed (~1 min after report button clicked)

7. Review the report graphics

8. Download report values for use in Excel for further analysis
Light strips On or OFF

# light strips on $ \times 72 \text{ W/strip} = \text{electric power for each time step (W)}$

$\sum \text{power each time interval} \times \Delta t = \text{daily energy consumed (Wh)}$
GH - Light-Intensity-South

Data type: Numeric
Start: 0.0
Minimum: 0.0 @ 2013/09/30 00:00
Maximum: 875.05283333333332 @ 2013/09/30 12:32
Average: 70.96014205523628
Sum: 715298.1286712629
Count: 10081

GH - 3_Light_LLPPF

Data type: Numeric
Start: 0.0
Minimum: 0.0 @ 2013/09/30 00:00
Maximum: 1060.0453333333332 @ 2013/10/03 12:45
Average: 119.20196666216295
Sum: 1201536.9549302722
Count: 10080
Rm 3 data – Power (W)

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<tr>
<td>Start</td>
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<tr>
<td>Minimum</td>
<td>31.0 @ 2013/10/05 19:00</td>
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<td>Maximum</td>
<td>772.0 @ 2013/10/05 07:03</td>
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<tr>
<td>Average</td>
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<td>Sum</td>
<td>1.6911529E7</td>
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<td>Count</td>
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Graph showing power consumption from 30-Sep to 7-Oct.
Data collected from Mango describing light system in the Greenhouse Sept 30 - Oct 4, 2013 (not - data file too large to collect an entire week)
downloaded and "massaged" 10/21/13, S. Powers

<table>
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<tr>
<th>Date</th>
<th>Time</th>
<th>GH - 3_Light_1 IND</th>
<th>GH - 3_Light_2 IND</th>
<th>GH - 3_Light_LINT (W/m²)</th>
<th>GH - 3_Light_LLPP F (umol/m²/s)</th>
<th>GH - Light-Intensity-South (W/m²)</th>
<th>GH - Power - Rm3 (W)</th>
<th>day-time</th>
<th># lights on</th>
<th>time step (h)</th>
<th>electric energy - lights (Wh)</th>
<th>total electric energy (Wh)</th>
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Downloaded data (w/more columns)

Calculations

65,541 rows of data
Turning off lights in daytime could save $127 for each room in the greenhouse (if extrapolation to the year is reasonable). This is approximately 33% savings of the light energy/cost versus if all lights on for 12 h/d

\[ 33\% = \frac{\text{electricity used if all on for 12 hours} - \text{actual electricity used}}{\text{electricity used if all on for 12 hours}} \]
So Far

• CLICS project has been integrated into 12 classes reaching 660 students over the past three semesters
  – Introduction to Statistics class accounts for 37% of the total student number
• Nearly 75% of all students strongly agreed/agreed that the overall experience of using campus data was positive and recommended that CLICS should be used in other classes.
Instruments/Methodology

**Student Questionnaire**
- **Measures:**
  - Sustainability Literacy (pre vs. post)
  - STEM Self-efficacy (pre vs. post)
  - Overall satisfaction with use of real-world data in assignments/projects (post-only)
- **Administration:**
  - Anonymous via SurveyMonkey
  - Coded to match pre and post responses

**Rubric Review of Selected Projects/Assignment**
- **Measures:**
  - Critical Thinking
  - Communication Administration:
  - Random selection (10 or 10% of projects)
  - 2 reviewer team

**Faculty Questionnaire**
- **Measures:**
  - Efficacy of the interface
  - Student engagement in course content
  - Impact on content mastery
  - Instructor support
- **Administration:**
  - Anonymous via SurveyMonkey
  - Post only

**Focus Group Discussion**
- Direct input
- Open ended
- Critical to process
Highlights from 2014 Administration

• Sustainability Literacy- 69 questions
  – Knowledge (46), Affect (12), Behavior (9), level of concern (12)
  – Overall, students had higher scores on affect and self-efficacy subscales than on knowledge or behavior
  – Students scored highest on knowledge questions about systems concepts, which are highly ‘affective’ in character (understanding the impact of our actions on other people and the environment)
  – In general, students do NOT feel they know a lot about sustainability (11.6% agree/strongly agree)

• STEM- related Self-Efficacy – 8 questions
  – increased skills at data retrieval (64% agree/strongly agree)
  – stimulated my thinking (65% agree/strongly agree)
  – made me better able to visually present data effectively (58% agree/strongly agree)
  – enhanced my understanding of course content/concepts (58% agree/strongly agree)
- Overall Satisfaction 19 questions +1 open ended
  - 72% agreed/strongly agreed that “Using data made the assignment more relevant for me”
  - 76% of the students agreed/strongly agreed that the data were overall useful

- Faculty Survey- 24 questions +1 open ended

- Focus Group Discussion
  - Consensus that use of real world data had value
  - Consensus was that faculty would use real world data again
Conclusions

Campus digester/greenhouse/energy cabin system

– Provides research platform to study individual systems and integrated system

– Diverts food waste from solid waste stream saving revenue

– Provides real-life data for class room instruction improving students appreciation of sustainability efforts and engagement in STEM subjects.

– Significantly contributes to sustainability effort of the university.
COMING SOON:
Separate your food waste from your trash to feed the anaerobic digester!
Questions/Comments?

Thank you for listening!
Student research on Ammonia Inhibition of AD
More nutrient data on dropbox: Dropbox\Green House Data\Digester\Nutrient Data
Toxicity: Ammonia

• Major toxicant in full-scale anaerobic digesters
• Produced through the biological breakdown of nitrogenous matter
  ➢ Beneficial at <200 mg/L$^6$
• Free Ammonia (NH$_3$) is known to be the most toxic form$^6,7,8$
• FA increases with increasing pH
  \[ \text{NH}_4^+ \rightarrow \text{NH}_3 + \text{H}^+ \]
• Concentration at which ammonia is inhibitory remains uncertain
  0.088 g/L to 14g/L
The Project: Methods

Experimental Set Up
• 500 mL reactors operated under mesophilic conditions (35-37 °C) at varying ammonia levels
• Ammonia added in the form of NH4Cl
• Methane measured using the AMPTS II Bio Methane Potential Instrument
• VS/TS, COD, and NH3-N
• pH ≈ 7.0-8.0
• Inhibition determined by methane production rate and biogas volume
• Ammonia Inhibition Constant determined graphically using Monod Kinetics
Monod Kinetics

• Common microbiological model to evaluate the biodegradation process\(^9\)
• Describes microbial growth kinetics\(^{10}\)
• Equation adapted from Monod Kinetic Growth Model

\[ q_{CH_4} = -\frac{1}{C} \cdot \frac{k_m S X}{K_s + S} \cdot \frac{1}{1 + \frac{S_I}{K_I}} \]

- \( S_I \) - ammonia concentration
- \( K_I \) - inhibition parameter of ammonia

\[ q_{CH_4} = -A \cdot \frac{1}{1 + \frac{S_I}{K_I}} \]
Results

Inhibition Parameter for Varying Ammonia Concentrations Normalized by COD of FW

\[
\frac{1}{q_{CH_4}} = \frac{1}{A} + \frac{1}{K_I \cdot A} \cdot S_I
\]

Experimentally Determined

\[K_I = 341.7 \text{ mg/L}\]

\[y = 207.78x + 0.071 \]

\[R^2 = 0.5057\]
Model of the Inhibitory Effects of Ammonia

Rate of Methane Production/COD as a Function of Ammonia Concentration

The 95th percentile of $K_I$ is between 206 mg/L and 993 mg/L

$$q_{CH_4} = -A \cdot \frac{1}{1 + \frac{S}{K_I}}$$
Literature Comparison

$K_I$ Values
Manure/Animal Waste

- 4 mg/L NH$_3$-N
- 213.3 mg/L NH$_3$-N
- 1600 mg/L NH$_3$-N
- 1450 mg/L NH$_3$-N

$K_I$ Values
OFMSW

- 215 mg/L NH$_3$-N
- 98.7 mg/L NH$_3$-N
- 88.0 mg/L NH$_3$-N
- 180.9 - 230.3 mg/L NH$_3$-N
- 158.4 - 395.4 mg/L NH$_3$-N
- 161.9 - 219.8 mg/L NH$_3$-N
- 237.6 mg/L NH$_3$-N

$K_I$ Value
Clarkson’s Kitchen Waste

- 341 mg/L NH$_3$-N

- Variance with linearizing the Monod model & the complexities of AD
- Research other mathematical models to better fit our data and more accurately determine the inhibition constant of ammonia

The 95th percentile of $K_I$ is between 206 mg/L and 993 mg/L