DOE Bioenergy Technologies Office (BETO) 2021 Project Peer Review

PRODUCTION OF METHANE FROM ORGANIC WASTE STREAMS WITH NOVEL BIOFILM ENHANCED ANAEROBIC MEMBRANE BIOREACTORS (WBS 5.1.3.105 ANL; 5.1.3.106 LANL)

March 10, 2021

Waste-to-Energy Area Review

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PROJECT OVERVIEW

Current Status:

- High volume of wet organic waste streams in the US (63.13 Mtons of food waste/yr, EPA 2019)
- Bio-power production for scales <1 ton/day is not economically feasible
- Slow degradation rate and incomplete degradation of organic waste streams

Objective: Develop two-phase biofilm AnMBR to solve AD challenges

- Increase hydrolysis and methanogenesis reaction rates
- Improve process stability
- Develop resilient, robust, and productive microbial consortium
- Small AD footprint

Specific Project Goals:

- Develop scalable, high performance, low-cost, two-phase modular AnMBR (30 liter)
- Develop new process modelling tools for AD of organic waste streams
- Improve reaction kinetics (reduce digestion time from 5-10 days to 12-48 h), increase methane yield (0.45 L/g VS_{fed})
- Reduce footprint and operating cost
  - CAPEX > 1 fold less than conventional MF/UF membranes
  - > 2 fold reduction in AD footprint

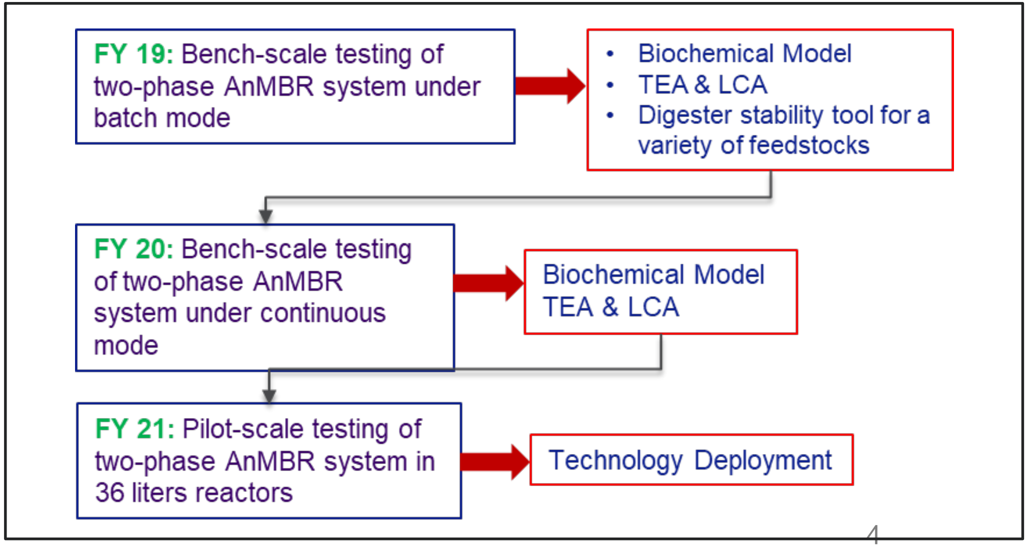
1 – MANAGEMENT

- Project consists of 5 tasks:
  - *Task 1:* Develop a flexible feedstock-blending plan for organic waste streams produced in the US - ANL and U. Michigan
  - *Task 2:* Develop a first-phase AnMBR inspired by the rumen that enhances hydrolysis and acidogenesis to maximize volatile fatty acid (VFA) production. U. Michigan and ANL
  - *Task 3:* Develop a second-phase biofilm AnMBR to enhance methanogenesis and optimize the conversion of VFAs to methane. U. Michigan and ANL.
  - *Task 4:* Perform process simulation and analysis to model full-scale performance of the proposed technology. U Michigan, LANL and ANL
  - *Task 5:* Conduct techno-economic analysis (TEA) and life cycle analysis (LCA) to assess economic and environmental viability of our novel technology and further facilitate its implementation at the full-scale. U Michigan and ANL
- Industry Partners: Gray Brothers, RAE and MWRD
- Project management: Monthly team meetings and biweekly task meetings
- Progress measurement: Milestones, industry partners guidance, BETO TMs feedback and TEA/LCA
- Risk mitigation: Increasing membrane surface area to increase biodegradation of recalcitrant materials, such as lignin and reduce volume of the bioreactors

PROJECT OVERVIEW

Why AnMBR based technology development?

High organic loading rate	Short reactor hydraulic retention times (HRTs)
Long solids retention times (SRTs)	Less space requirement
Less sludge production, hence less sludge handling and disposal costs	Short start up period
Process stability under peak hydraulic and organic loading conditions	High-quality effluent (low turbidity, solids, COD)



Target:

Produce methane at a yield of 0.45 L/gVS$_{fed}$ in two-phase AnMBR (36 liter) on a sustainable basis at TRL 4

3 – IMPACT

- Development of an economical and sustainable biofuel production technology by implementing novel strategies for renewable biopower generation.

- A novel scalable AnMBR technology enhances degradation kinetics and facilitates high methane yields and small AD footprints

- Tech transfer/Marketability: New AnMBR technology at TRL 4 allows use of poorly valorized food waste and other organic waste generated in the US
  - More than 4 Quad BTU energy potential for biogas derived methane (NREL report)
  - Encourage development of new AD industry

4 – PROGRESS AND OUTCOMES

- Task 2 – Volatile acid production stage: Higher VFA yield at low HRT and organic loading rate

Acid production stage	HRT (d)	SRT (d)	OLR (g VS/L reactor/day)	Temperature (°C)	VFA yield (g VFA/g VS fed)	Literature
	0.5	5	18	39	0.41	This project
	5 (batch)	NA	1.68	30	0.42	Wang et al 2014
	5	5	11	35	0.32	Jiang et al. 2013

- Task 3 – Methane production stage: Higher methane yield at low HRT

Methane production stage	HRT (d)	SRT (d)	OLR (g/L reactor/day)	Temperature (°C)	Removal	methane yield (L/g VS fed)	Literature
	4.7	>500	0.5	20	84% (COD)	0.55	This project
	15	15	2.9	35	79% (TS)	0.45	Fonoll et al 2016
	15	15	0.68	37	NA	0.43	Kawai et al 2014
	10 - 30	10 - 30	0.4-6	mesophilic - thermophilic		0.35-0.41	Komilis 2017 Review

- Task 4 – Developed a fastADM1 model to describe the two-phase system paired with a digester stability tool and accurately captured the VFA production, methane production rate, and digester stability
- Task 5 – Completed development of a techno-economic model for two-stage AnDMBR and conducted life cycle assessment on the two-phase system to compare its environmental impact to other food waste handling methods including incineration, composting, and landfilling
- The pilot-scale experiments started in February 2021.
- The operation of individual reactors helped us identify risk points, improve reactor design, and determine the optimal operating conditions.

PROJECT OVERVIEW- TASKS

(1) Develop a flexible feedstock-blending plan for organic waste streams produced by a typical U.S. city that meets treatment requirements and maximizes energy recovery. ANL and U. Michigan

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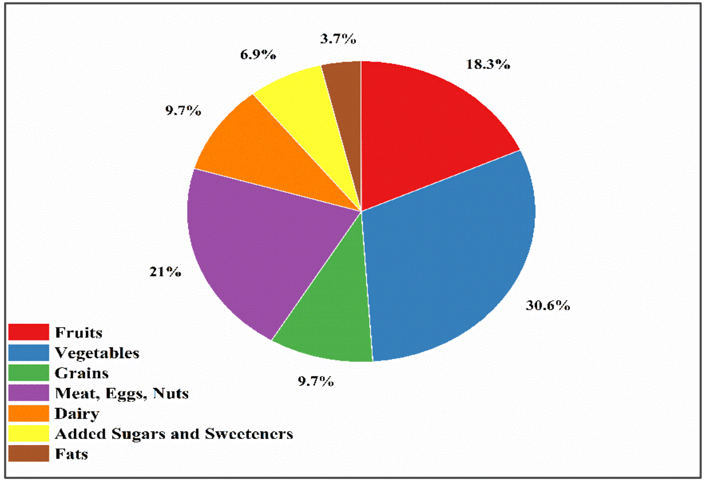
(4) Perform process simulation and analysis to model full-scale performance of the proposed technology. U Michigan, LANL and ANL, and RAE and MWRD

(5) Conduct techno-economic analysis (TEA) and life cycle analysis (LCA) using the newly developed performance model to assess economic and environmental viability of our novel technology and further facilitate its implementation at the full-scale. U Michigan and ANL, and NREL, RAE and MWRD

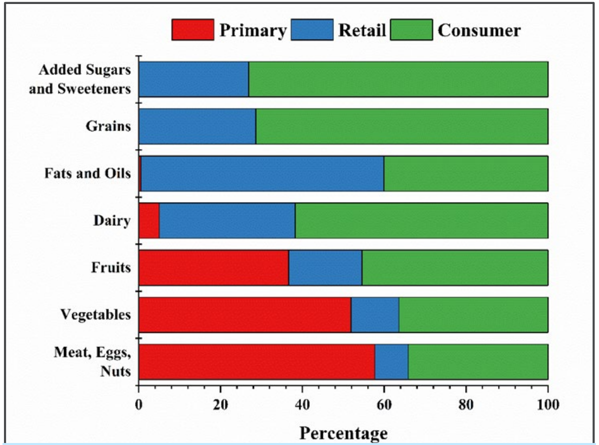
Flexible Feedstock-blending Plan

Estimates on FLW from commonly cited US agencies and organizations. Adapted from Further With Food's Food Loss Waste Comparisons.

Organization	FLW Estimate (million tons)	Year Reported	Data Collection Methodology
USDA	66.5	2010	Nationally representative surveys (retail inventories/shipments and household purchases/stated consumption).
US EPA	40.7	2017	FLW Generated: existing studies of the food generation rate applied to updated Census estimates of businesses and households. FLW Disposed: (Total FLW generated-FLW going to composting).
National Resources Defense Council (NRDC)	86	2003	Percent difference between the number of calories in the U.S. food supply and the number of calories consumed by end consumers.
Rethink FLW Through Economics and Data (ReFED)	62.5	2015	Estimates of commercial and residential FLW (in 2015) applied to 2015 Census data on manufacturing, retail, food service and households. On-farm estimates are based on extrapolation from agricultural case studies.



Distribution of FW by food group in the United States in 2017



Food losses across supply chain

Water Research 112 (2017) 19–28

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

ELSEVIER

A stability assessment tool for anaerobic codigestion

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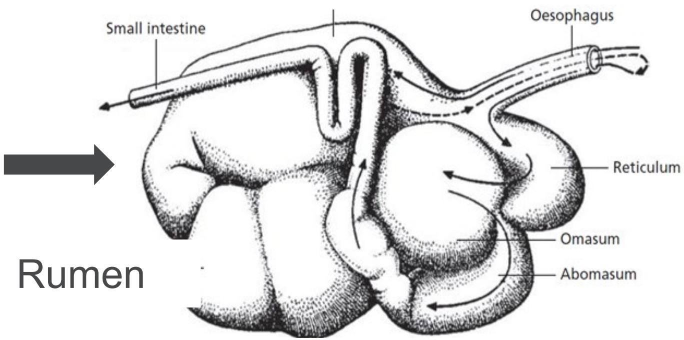
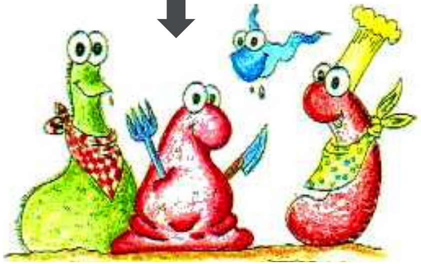
The rumen is a natural ecosystem with efficient lignocellulose hydrolysis → promote hydrolysis and acidegonesis

http://www.drgregsymko.com/eat-that-cow/



Hydrolytic and fermentative bacteria



Solid retention time = 40–90 h

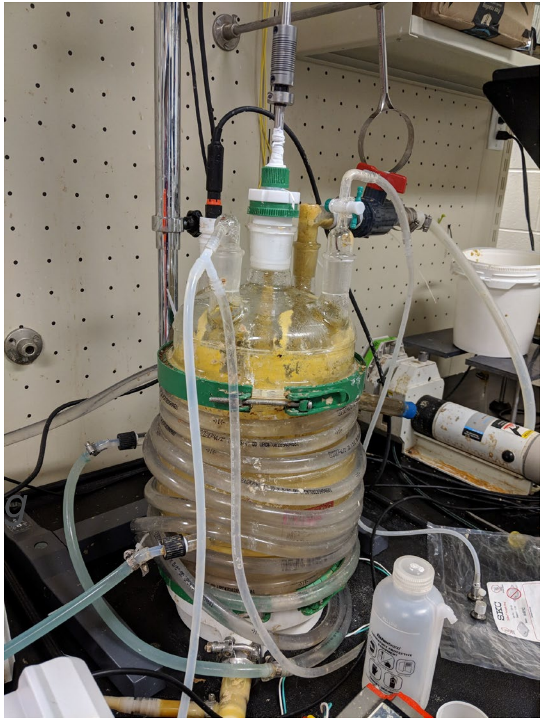
Hydraulic retention time = 8-16 h

Organic loading rate > 15 g VS L_R^{-1} day^{-1}

Rumen inspired dynamic membrane bioreactor

Operating conditions:

1st Phase Rumen Reactor



- Sludge Retention Time = 128 h (*compared to ≥5 days*)
- Hydraulic Retention Time = 12 h (*compared to ≥1 day*)
- pH = 6.3
- Temperature = 39^{o}C
- Cafeteria food waste:
  - 75 g Volatile Solid (VS) kg^{-1}
  - 16.7% of VS are lignocellulosic
- Organic Loading Rate= 18 ± 3 gVS $L_R^{-1}day^{-1}$ (*compared to 2-12 g VS $L_R^{-1}day^{-1}$*)
- Inoculum: Rumen content

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Second-stage bioreactor for methane production

Conventional AnMBRs are not cost- and environmentally-competitive with existing technologies → novel design with dynamic membranes → MagnaTree Bioreactor

Dynamic membrane: Filtering biofilm formed on support structure with pore size of 10 – 100 microns

- Membrane cleaning is energy intensive (High OPEX)
  - Less pore blocking
  - Lower transmembrane pressures
- Membrane material cost is expensive (High CAPEX)
  - Cheaper material (e.g. nylon, polyester, SS mesh)
  - Higher fluxes – less membrane area required

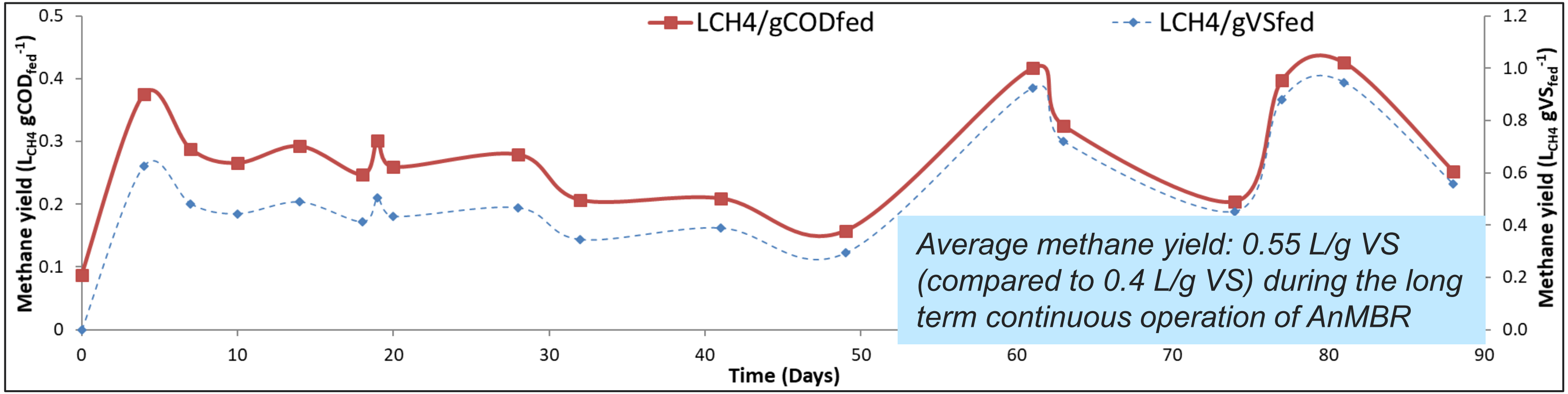
Rumen inspired dynamic membrane bioreactor

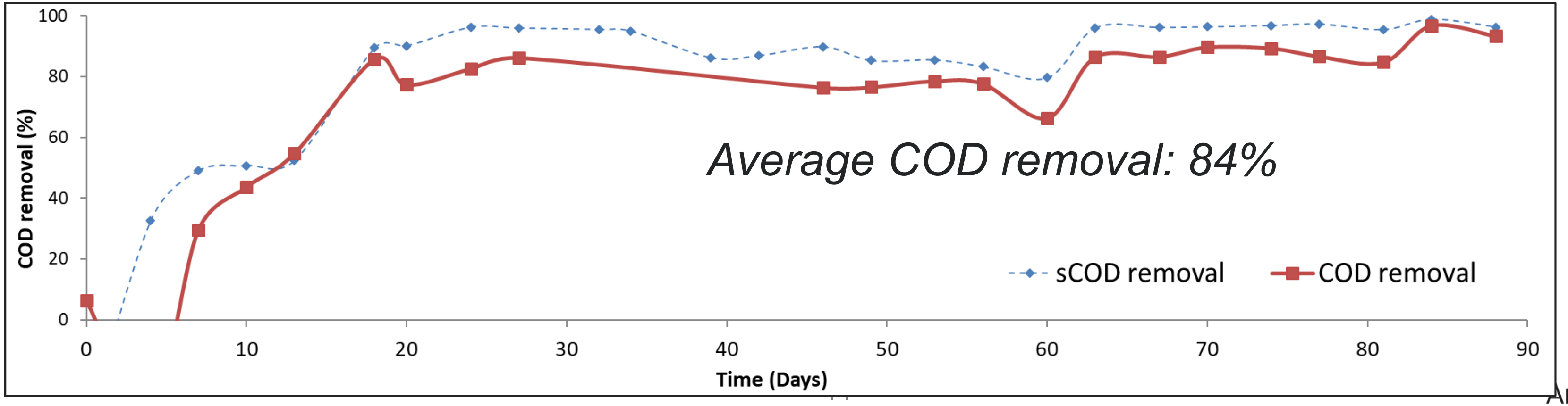
Operating conditions:

2nd Stage MagnaTree Reactor

- SRT = **>500 d** *(compared to 15 d)*
- HRT= **5.5 d** *(compared to 15 d)*
- pH = 7.5
- Temperature = **20^{o}C** *(compared to 35 – 55^{o}C)*
- Inoculum: 2nd phase digester effluent
- Feed: 1st phase rumen reactor effluent

The MagnaTree reactor achieves high methane yield and high COD removal rate during the long-term operation





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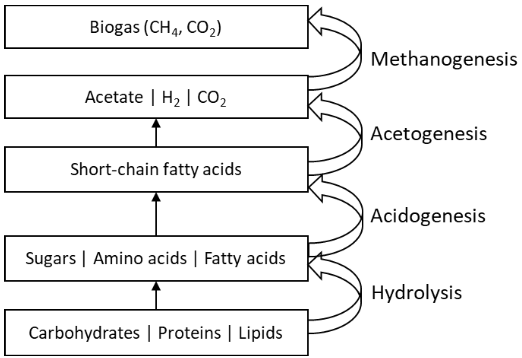
Modelling AnMBR performance

- Previous models have been developed to model **one stage AD.**
- A model is needed that evaluates the feasibility of different waste stream combinations and the process performance from the lens of **two stage AD.**
- **Why?** Hydrolysis step is rate limiting and varies with biodegradability of waste.



Substrate	Hydrolysis constant (d^{-1})	Reference
Coffee waste	0.04	Neves et al. 2004
Barley and sewage sludge	0.08	Neves et al. 2004
Pork neutral fat	0.63	Garcia-Gen et al. 2013
Waste activated sludge	0.16	Shimizu et al. 1993
Grass	0.26	Veeken et al. 1999
Municipal solid waste	0.21	Trzcinski et al. 2012

Parameter	ADM1 Model	New Model
Application	One stage	One and Two stage
Configuration	Widely used conventional AD processes	Both conventional and new AD processes including AnMBR
AD Operating Conditions Specification	Limited	Customizable
Data Processing Time	Long	Short (× 40 times faster)

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Modelling AnMBR performance

Sensitivity Analyses

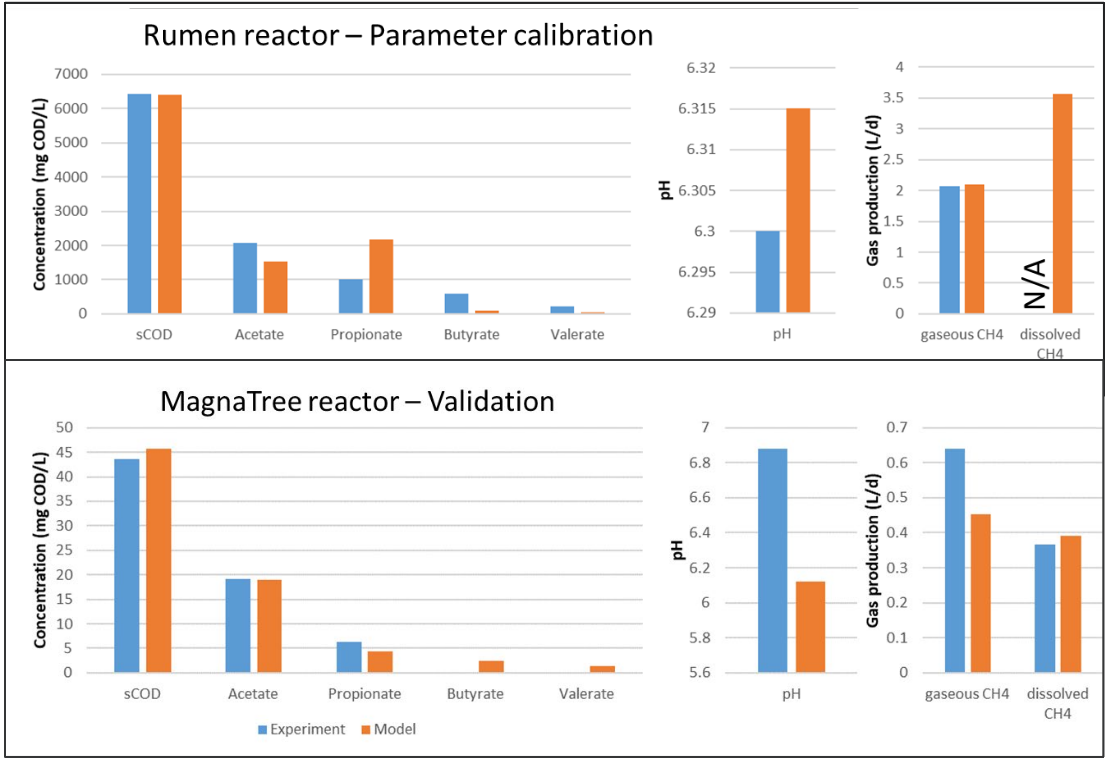
→Linking existing sensitivity analysis software to ADM1

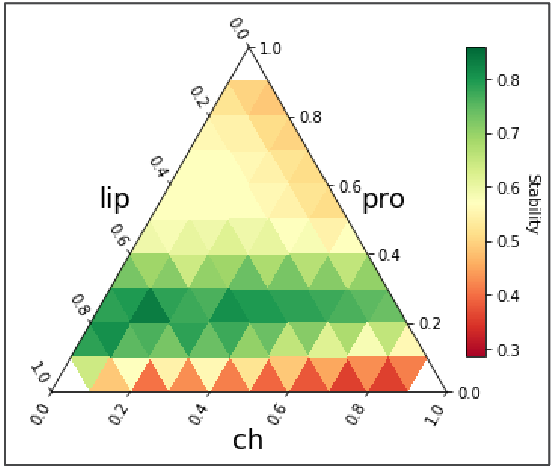
MADS (Model Analysis & Decision Support)

- Sensitivity Analysis
- Parameter Estimation
- Model Inversion and Calibration
- Uncertainty Quantification
- Model Selection and Model Averaging
- Model Reduction and Surrogate Modeling
- Machine Learning (e.g., Blind Source Separation, Source Identification, Feature Extraction, Matrix / Tensor Factorization, etc.)
- Decision Analysis and Support
- Open source: https://github.com/madsjulia/Mads.jl

New model: iPython interface for system configuration, operation model setup, and post-simulation analyses with tool developed under various programming environments

Model calibration and validation





- Kinetic parameters were calibrated with the experimental data from the rumen reactor
- Model performance was validated with the MagnaTree reactor
- A modified stability tool is interfaced with the model output
  – feed composition on digester stability

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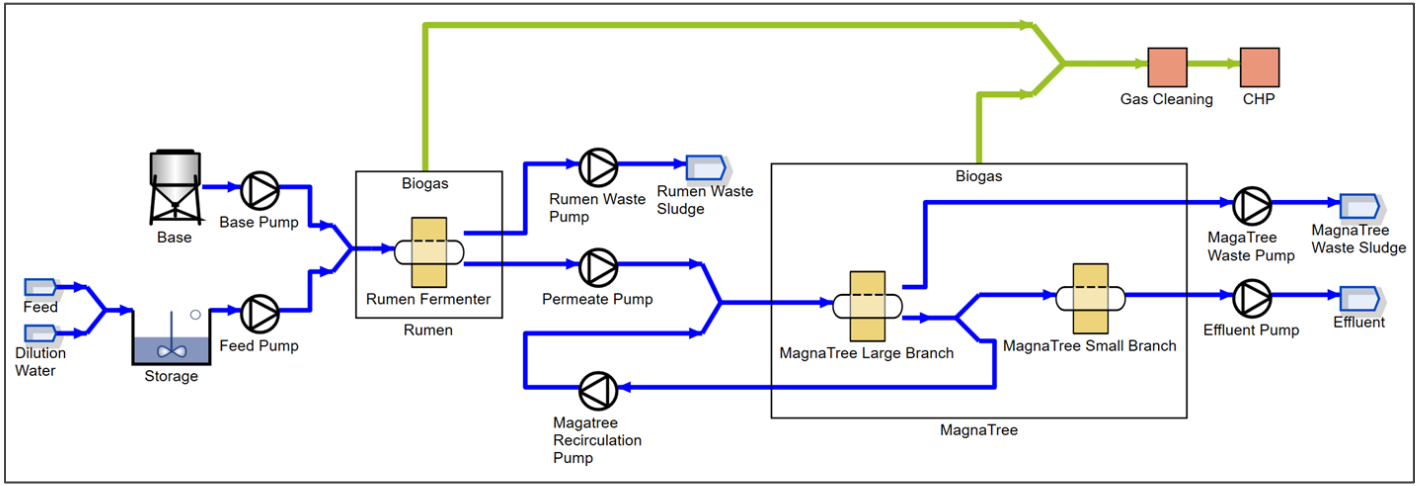
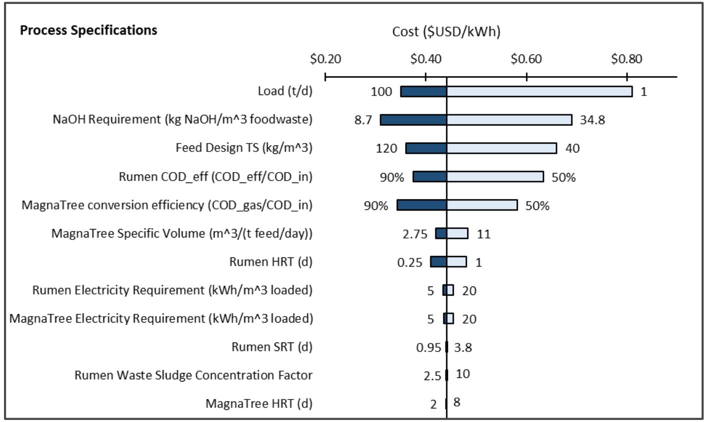
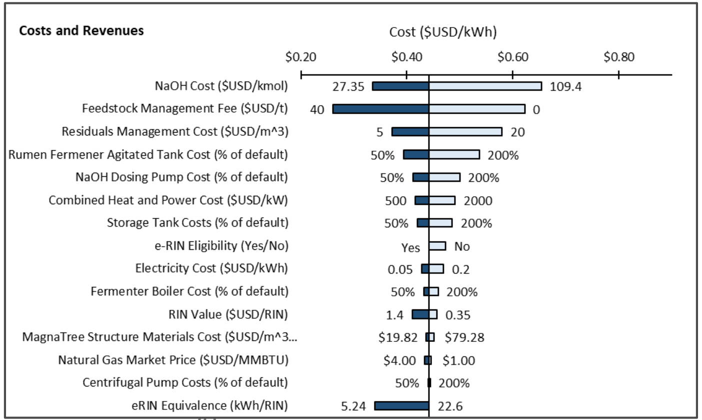
TEA of AnMBR



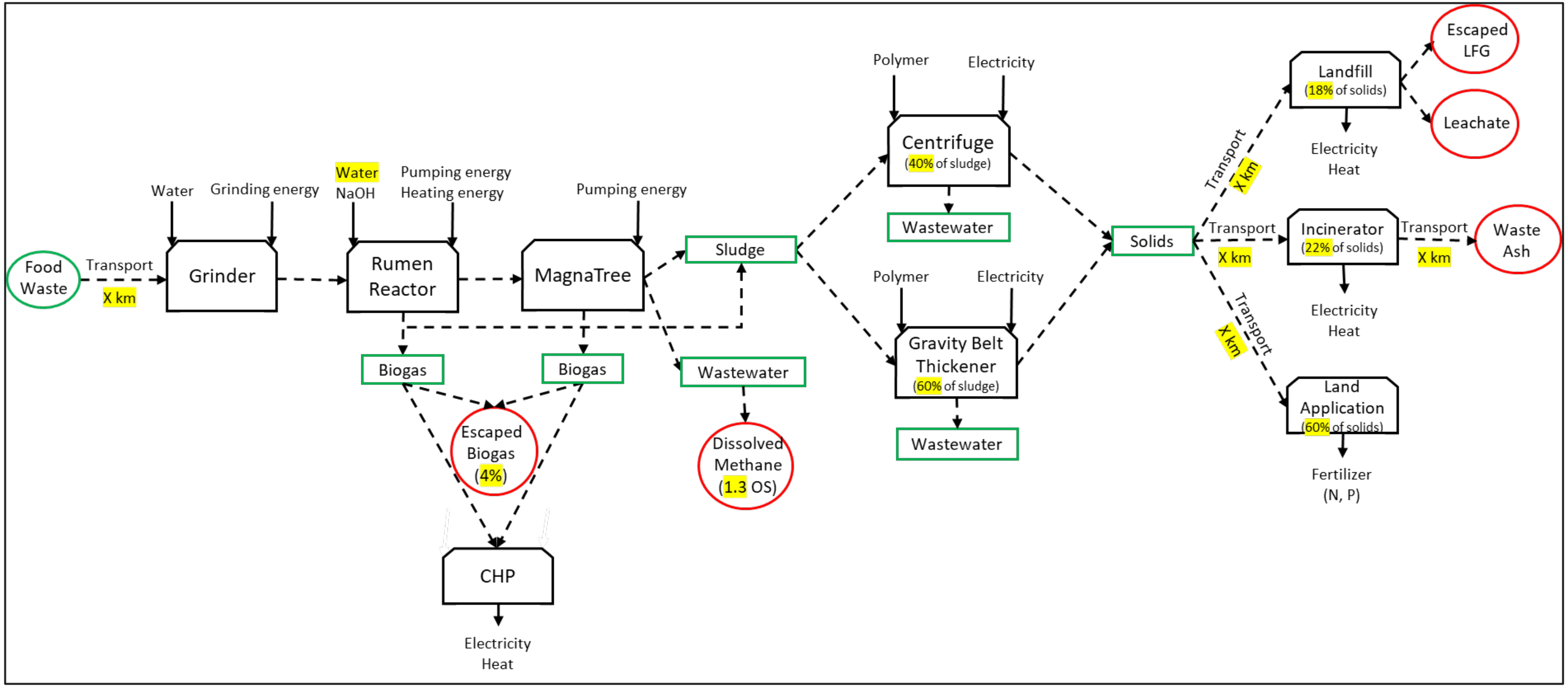
- The TEA results are based on bench-scale experimental data.
- Feedstock tipping fee was used as $20/ton, but this cost is subject to change depending on locations
- The organic loading rate to the second stage was low (0.5 g/l/day compared to conventional applications 2 g/l/day) due to the limitations in reactor configuration at bench-scale.
- In FY21, 2.5 g/l/day organic loading rate will be used in large fermenter. This will allow us to produce electricity with $0.11/kWh





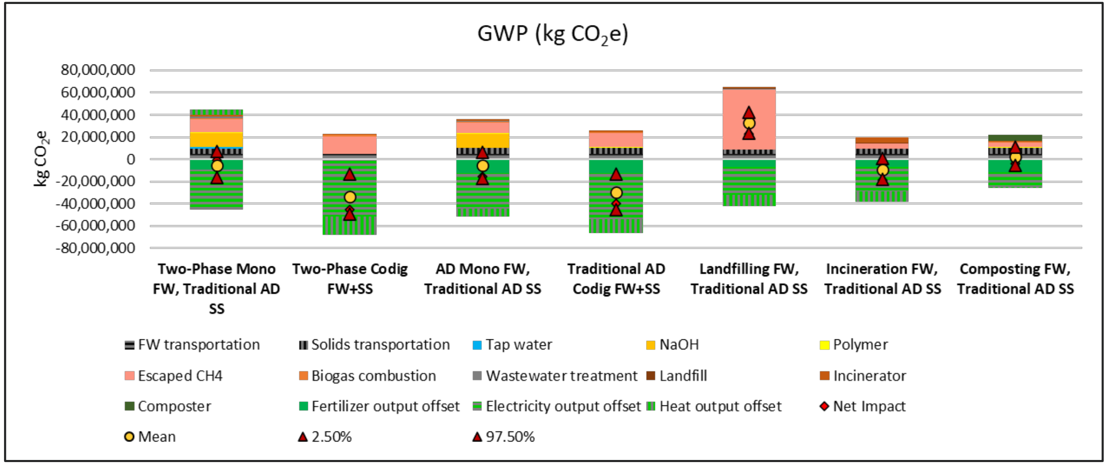
PRODUCTION COSTS	FY21 Operating Conditions
Net Operating Costs ($USD/yr)	$150,821
Total Annual Production Cost ($USD/yr)	$569,672
Annual Electricity Generation (kWh/yr)	5,622,533
Electricity Generation Cost ($USD/kWh)	$ 0.11

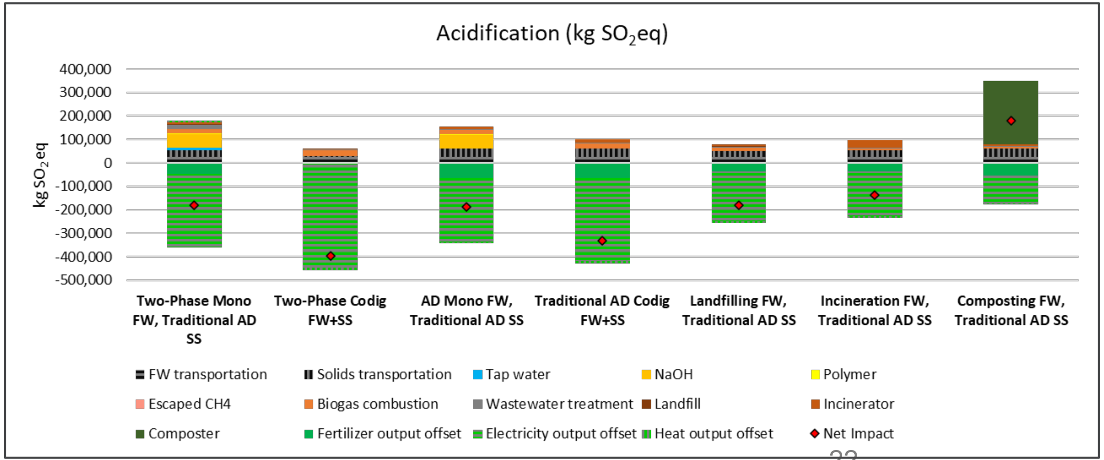
LCA of AnMBR



- Scenarios: 1. Conventional AD vs MagnaTree Operations 2) Conventional Biosolids Applications (Landfilling, Incineration, Composting) vs Power Generation from AD
- Detailed Life Cycle Greenhouse Gas, Water, and Air Emissions

LCA of AnMBR





Environmental Analysis included the following:

- Global Warming Potential
- Acidification
- Eutrophication
- Smog
- Respiratory

SUMMARY

- Rumen-inspired organic waste degradation and dynamic membrane AnMBR engineering with AD modelling and TEA driven new biofuel technology development strategies
- Develop scalable, high performance, low-cost, two-phase AnMBR technology at TRL 4 in FY21
  - Decrease digestion time from 10-20 days to 5-10 days
  - High organic loading rate >11 g VS L_R^{-1} day^{-1}
  - > 2-fold reduction in AD footprint, hence reduction in CAPEX
- Completed TEA and LCA models for two stage AnDMBR
- Developed a new modeling tool using ADM1 model and validated model performance with the MagnaTree reactor

QUAD CHART OVERVIEW

Timeline

- Project start date: 08-15-2018
- Project end date: 09-30-2021

	FY20	Active Project
DOE Funding	$500,000	$1.5 M for three years. Project started in FY18

Project Partners

- ANL,LANL, and U of Michigan
- Cost share partners: MWRD, Roeslein Alternative Energy, and Gray Brothers

Barriers addressed

- Ct-D. Advanced Scalable Bioprocess Development
  Scalable Modular AnMBR Technology
- CT-I: Development of Processes Capable of Processing High Moisture Feedstocks in addition to conventional AD
  Two phase novel biofilm AnMBR inspired by rumen operation

Project Goal: Improve the techno-economic viability of biopower production by developing a two-stage anaerobic membrane bioreactor (AnMBR).

End of Project Milestone: A scalable, high performance, low-cost, two-phase modular AnMBR technology (0.45 L methane/g VS_{fed} at 100 gal) at TRL 4 which has the potential to extend the economic viability of AD to smaller scales

Go/No-Go Criteria (Met in September 2020): Produce methane in AnMBR system continuously on a sustainable basis at a yield of 0.4 liter /g Vs_{fed}

Funding Mechanism

Biopower Lab Call FY18

Q & A

Acknowledgments:

- BETO-DOE: Beau Hoffman and Mark Philbrick
- ANL: Haoran Wu, Rachel Dalke, Jesse Mai
- LANL: Elchin Jafarov, Kurt C. Solander
- U of Michigan: Lutgarde Raskin, Steven Skerlos, Kuang Zhu, Xavier Fonoll, Timothy Fairley, Sonja Gagen
- Wastewater Resource Recovery Plants and Roselein Alternative Energy

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ADDITIONAL SLIDES

NOMENCLATURE

AD: Anaerobic Digestion or Anaerobic Digester
AnMBR: Anaerobic Membrane Bioreactor
HRT: Hydraulic Retention Time
LCA: Lifecycle Analysis
OFMSW: Organic Fraction of Municipal Solid Waste
OLR: Organic Loading Rate
SRT: Sludge Retention Time
TRL: Technology Readiness Level
VFA: Volatile Fatty Acids

RESPONSES TO PREVIOUS REVIEWERS' COMMENTS

- Criticism #1: The project could improve by highlighting the importance of the progress of each of the two phases of the AnMBR process, how they are related and complementary, and how each enhances the outcome of increased biomethane production.
- Response #1: The first step reactor takes care of the transformation of food waste into soluble volatile fatty acids (Hydrolysis + acidogenesis). The second step bio-reactor transform the volatile fatty acids produced in the first step reactor into methane. The first step reactor has been designed to accelerate hydrolysis and acidogenesis. The second phase bio-reactor has been designed to accelerate methanogenesis without increasing capital and operational costs.
- Criticism #2: Weakness: Multi-feedstock goal seems unrealistic without more information from present work. The modeling effort should be done earlier to provide at least conceptual performance baselines.
- Response #2: Due to the novelty of the modeling work, relevant parameters for the model need to be measured experimentally using the inoculum from the first step bio-reactor. Therefore, the experimental and modeling work conducted in parallel. ADM1 model was revised to analyze the experimental data obtained in FY20.
- We met the Go/No-Go criterion in September 2020: Produce methane in AnMBR system continuously on a sustainable basis at a yield of 0.4 liter /g Vs_{fed}

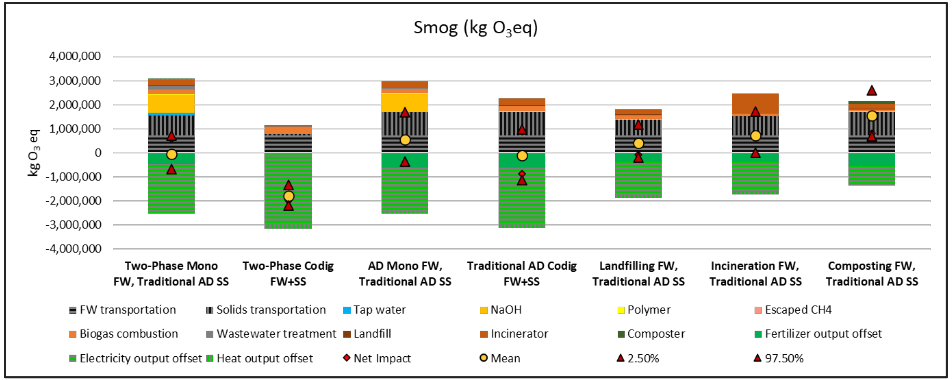
PUBLICATIONS, PATENTS, PRESENTATIONS, AWARDS, AND COMMERCIALIZATION

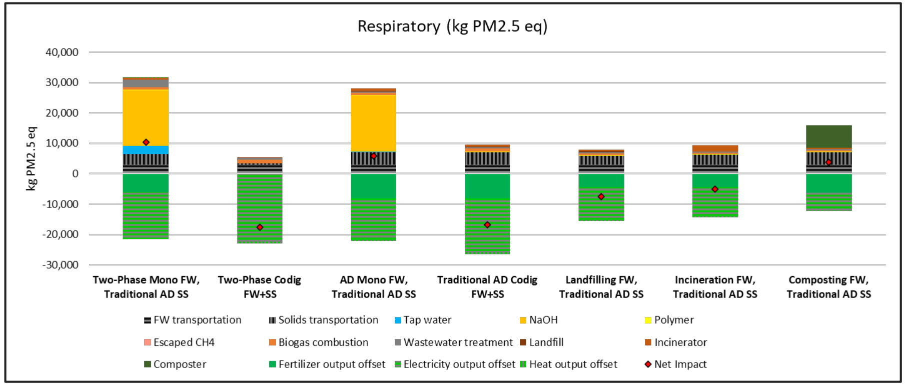
- R. Dalke, D. Demro, Y. Khalid, H. Wu, M. Urgun-Demirtas (2020) A review of anaerobic co-digestion of food loss and waste in the United States. Renewable & Sustainable Energy Reviews (under review)
- X. Fonoll, S. Shrestha, S. Khanal, J. Dosta, J. Mata-Alvarez, L. Raskin (2020). Understanding the anaerobic digestibility of lignocellulosic substrates using rumen content as a co-substrate and an inoculum. ES&T Engineering (*under review*)
- Zhang, W., Jafarov, E., Zhu, K., Snyder, E. E., Karra, S., and Solander, K. C.: Modeling Anaerobic Digestion with ADM1 (11 pp.), 2020 NSF MSGI, 2020-08-27 (Virtual, New Mexico, United States)
- X. Fonoll, S. Shrestha, L. Raskin. A novel anaerobic bioprocess to transform urban organic waste streams into sustainable resources. WEFTEC 2019. Chicago, USA, September 2019. Oral presentation
- T Fairley, X. Fonoll, C. Van Steendam, L. Raskin, S. Skerlos, N. Jalgaonkar. Maximizing Energy Recovery in Anaerobic Membrane Bioreactors (AnMBRs) by Minimizing Permeate Dissolved Methane and Eliminating Biogas Sparging. WEFTEC 2019. Chicago, USA, September 2019. Oral presentation

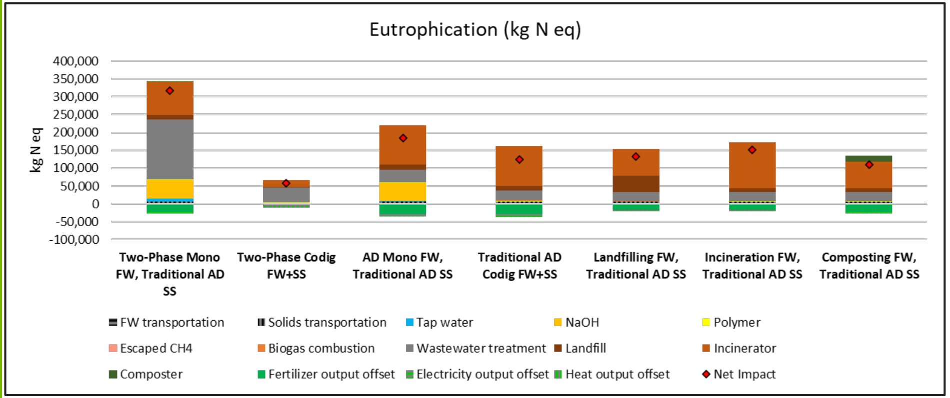
PUBLICATIONS, PATENTS, PRESENTATIONS, AWARDS, AND COMMERCIALIZATION (*continued*)

- X. Fonoll, T. Meuwissen, L. Aley, S. Shrestha, L. Raskin. Development of dynamic membrane bioreactor based on rumen physiology for efficient hydrolysis of lignocellulosic biomass. 16th IWA World Conference on Anaerobic Digestion (AD-16). Delft, Netherlands, June 2019. Oral presentation
- Urgun-Demirtas, M., Haoran W. Developing novel anaerobic bioprocesses to recover high-value resources from urban organic waste streams (Invited Talk), Symposium on Biotechnology for Fuels and Chemicals (SBFC) organized by Society for Industrial Microbiology and Biotechnology, Seattle, WA, April 28-May 1, 2019
- L. Raskin, X. Fonoll, S. Shrestha. Developing novel anaerobic bioprocesses to recover high-value resources from urban organic waste streams. 41st Symposium on Biomaterials, Fuels & Chemicals. Seattle, USA, April 2019. Oral presentation
- Invited speaker to the 12th Research debates for Energy and Natural Resources. Presentation title: Chemical Production from Organic Wastes Using Bioprocesses Based in Nature. Andorra La Vella, Andorra, June 2018. Oral presentation

LCA RESULTS







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