DOE Bioenergy Technologies Office (BETO) 2019 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)

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Waste-to-Energy Area Review

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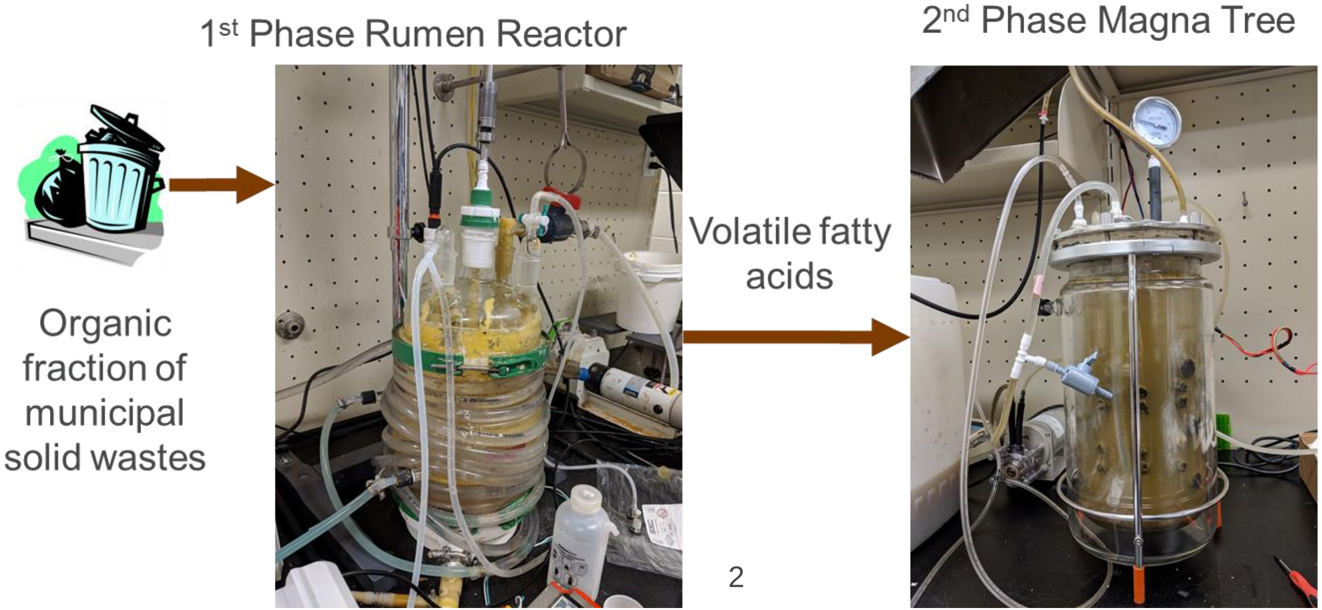
GOAL STATEMENT

Project goal: Improve the techno-economic viability of biopower production by developing a two-phase anaerobic membrane bioreactor (AnMBR) system that diverts the organic fraction of municipal solid waste (OFMSW) and food waste while generating methane and renewable bioproducts.



GOAL STATEMENT

Project outcome:

A scalable, high performance, low-cost, two-phase modular AnMBR technology at TRL 4, which has the potential to extend the economic viability of AD to smaller scales

Relevance to the bioenergy industry:

- Slow degradation kinetics of waste streams and large footprint of AD limit renewable methane production at small-scale digesters
- Modular high rate rumen inspired AD technology at TRL 4 (0.45 L/g VS @ 100 gallon scale reactor size)
- Small footprint AnMBR technology with low CAPEX and OPEX

QUAD CHART OVERVIEW

Timeline:
- Start: Aug 15, 2018
- End: Aug 14, 2021
- Percent complete: 15 %

	Total Costs Pre FY17**	FY 17 Costs	FY 18 Costs	Total Planned Funding (FY 19-Project End Date)
DOE Funded	N/A	N/A	237,518	1,500,000
Project Cost Share*	N/A	N/A	80,000	650,000

Partners:
- ANL: 48%
- LANL: 12%
- U of Michigan : 40%
- 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

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

End of Project Goal: 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

PROJECT OVERVIEW

- High volume of wet organic waste streams in the US (254 to 347 million tones/yr)
- Bio-power production for scales <1 ton/day is not economically feasible
- Slow degradation rate and incomplete degradation of feedstocks

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

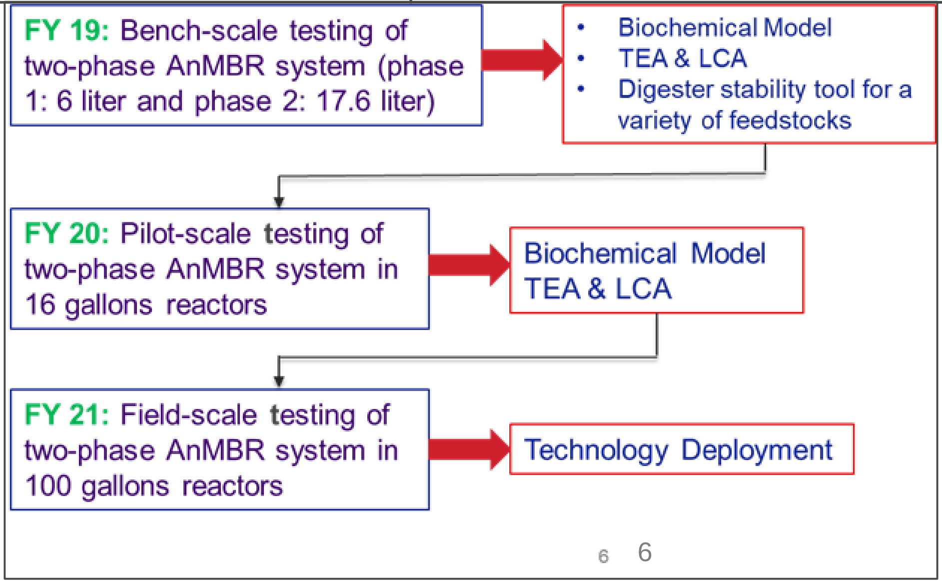
Specific Project Goals:

- Develop scalable, high performance, low-cost, two-phase modular AnMBR at TRL 4 (100 gal)
- Establish an industrially relevant rumen inspired microbial community
- Develop new process modelling tools for AD of OFMSW
- 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

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 (100 gal) on a sustainable basis at TRL 4

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, Gray Brothers and MWRD

(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

(3) Develop a second-phase biofilm AnMBR to enhance methanogenesis and optimize the conversion of VFAs to methane. U. Michigan and ANL.

(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

PROJECT MANAGEMENT

- *Project Team:* Diverse project team with different but complementary expertise
    - ANL: Meltem Urgun Demirtas and Cao Hai (Tasks 1, 2, 3, 4, and 5)
    - LANL: Kurt C. Solander, Elchin Jafarov, Brent Newman (Task 4)
    - U. Michigan: Prof Lutgarde Raskin and Prof Steven Skerlos (Tasks 1, 2, 3, 4, and 5)
    - Roeslein Alternative Energy (Tasks 4 and 5)
    - Metropolitan Water Reclamation Distric of Chicago (Tasks 1, 4, and 5)
    - Gray Brothers (Task 1, 2 and 3)
- *Team Interaction:* Site visits, monthly project meetings, weekly task meetings
- *Progress measurement:* Milestones, industry partners guidance, BETO TMs feedback and TEA/LCA (ANL and NREL)
- *Data Sharing and Storage:* BlueJeans meetings, Secured Box storage and Software sharing – gitlab private repository (https://gitlab.com/Elchin1/adm1_hydrolysis)

TECHNICAL APPROACH

- *Approach:* Integrate rumen inspired organic waste degradation and anaerobic membrane bioreactor engineering with modelling and TEA driven new biofuel technology development strategies
- *Major challenges: (i) limited hydrolysis/acidogenesis related studies available, (ii) robustness of ruminant microorganisms over time, (iii) clogging and fouling of membranes*
- *Critical success factors:*
  - Demonstrate rumen inspired AD operations for targeted VFA production and high methane yield (0.45 L_{CH4} g VS_{fed}^{-1})
  - Develop and demonstrate a viable pathway to commercialization of new AnMBR technology at TRL 4 (100 gallon)
  - Develop a new process modelling tool for AD industry
  - Reduce dissolved methane saturation to equilibrium in permeate
  - Maintain effective solids/liquid separation with lower energy demand and cost

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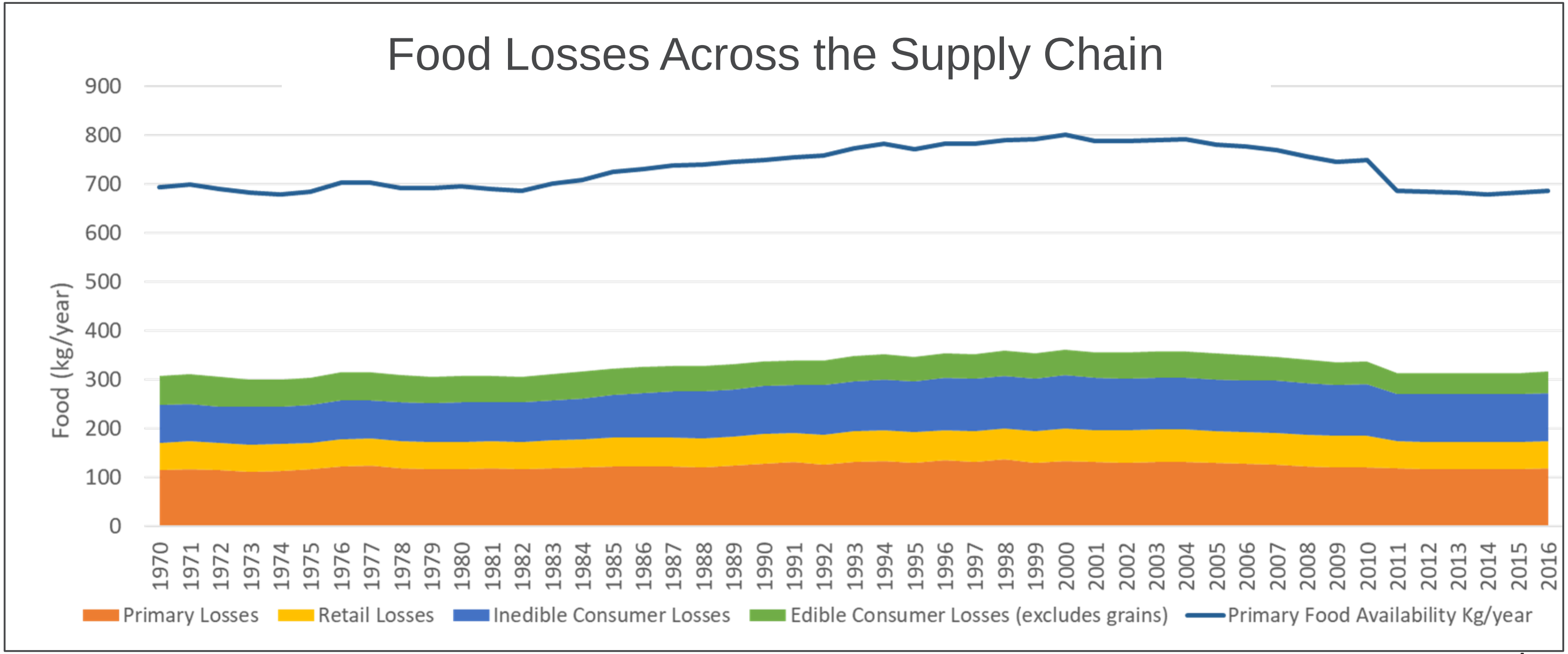
Develop flexible feedstock-blending plan

- Conducted extensive literature review
- Analyzed recent EPA and USDA reports
- Contacted about 30 utilities to determine the utilization of OFMSW and food waste
  - 4 utilities provided design and operating data

MWRD, IL; Downers Grove WRP, IL; Glenbard Wastewater Authority, IL; Essex Junction, VT



*Please note that food loss is given per capita

Develop flexible feedstock-blending plan

Sewage sludge

Food waste

Brewery waste

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

CrossMark

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PROJECT OVERVIEW- TASKS

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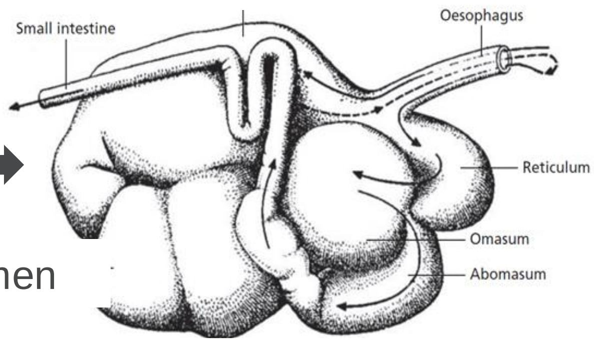
The rumen is a natural ecosystem with efficient lignocellulose hydrolysis → promote hydrolysis and acidegonesis

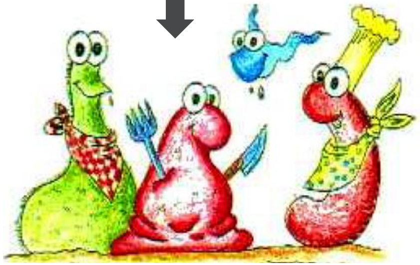
http://www.drgregsymko.com/eat-that-cow/

Rumen



Rumen

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:

- Total volume = 10 L   Working volume = 6.2 L
- SRT = 128 ± 37 h   HRT= 12 h
- pH = 6.3   Temperature = 39^{o}C
- OLR= 18 ± 3 g VS L_R^{-1} day^{-1}
- Inoculum: Rumen content
- Cafeteria food waste:
    - 75 g VS kg^{-1}
    - 16.7% of VS are lignocellulosic

1st Phase Rumen Reactor

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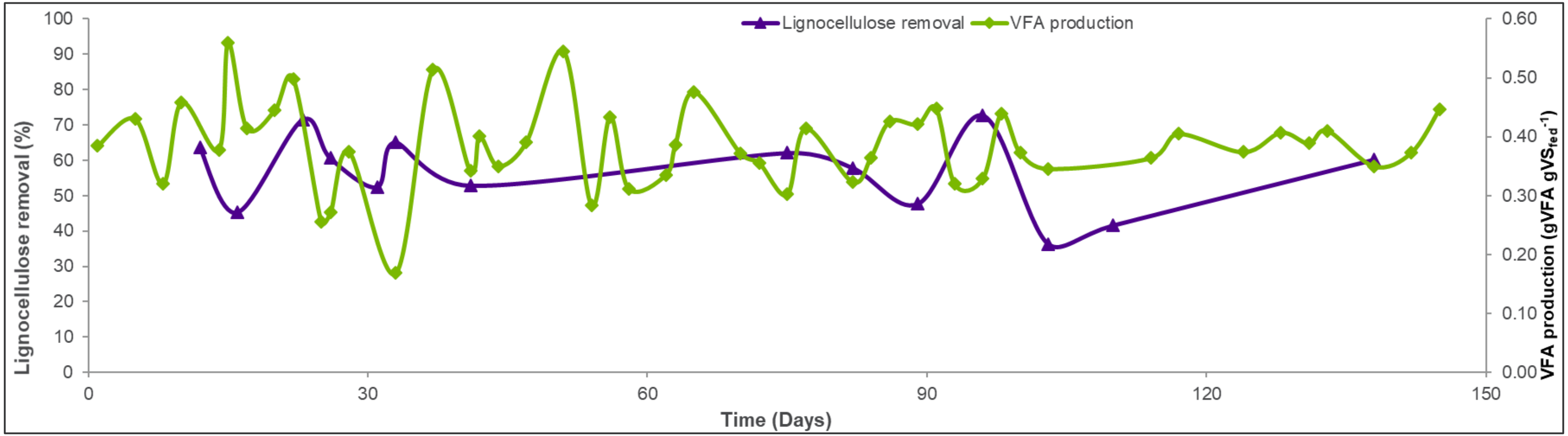
The rumen reactor hydrolyzes a high fraction of lignocellulose in a short time



Food waste acidogenesis

Conventional

HRT = 5-10 days

OLR <11 g VS L_R^{-1} day^{-1}

VFA= 0.3 – 0.4 g VFA g VS_{in}^{-1}

Rumen Inspired Novel AnMBR

HRT= 12 h

OLR = 18 ± 3 g VS L_R^{-1} day^{-1}

VFA = 0.38 g VFA g VS_{in}^{-1}

PROJECT OVERVIEW- TASKS

(1) Develop a flexible feedstock-blending plan for the urban organic waste streams produced by a typical U.S. city that meets treatment requirements and maximizes energy recovery while considering seasonal waste fluctuations ─ ANL and U of Michigan, Gray Brothers and MWRD

(2) Develop a first-phase AnMBR inspired by the stomach physiology of ruminants that enhances hydrolysis and acidogenesis to maximize volatile fatty acid (VFA) production. U of Michigan and ANL

(3) **Develop a second-phase AnMBR that exploits biofilm growth to enhance methanogenesis and optimize the conversion of VFAs to methane U of Michigan and ANL.**

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

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

4 – RELEVANCE

- This project addresses the DOE goals of developing economical and sustainable bioenergy systems by advancing efficient strategies for biofuels 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

5 – FUTURE WORK

- *FY19 Target:* Develop a two-phase AnMBR system handling a flexible feedstock blend at a methane yield of 0.4 liter /g VS_{fed}
  - Complete high-throughput screening experiments for development of rumen inspired microbial consortium
  - Determine community structure and dynamics in AnMBRs based on 16S rRNA analysis methods (qPCR and metagenomic)
  - Produce VFAs at a yield of 0.35 g/VS_{fed} in phase1 AnMBR (6 liter)
  - Produce methane at a yield of 0.4 liter /g VS_{fed} in two-phase AnMBR system (phase 1: 6 liter and phase 2: 17.6 liter)
- *FY20 Target:* Produce VFAs at a yield of 0.35 g/VS_{fed} in first phase AnMBR (16 gal) on a sustainable basis
  - Develop a quantitative digester stability definition and assessment tool for a diverse blend of organic wet waste streams generated in a typical US city
  - Develop a model for two phase AnMBR process based on experimental data to drive the ADM1 and PFLOTRAN
  - Complete development of preliminary TEA model based on specified parameters

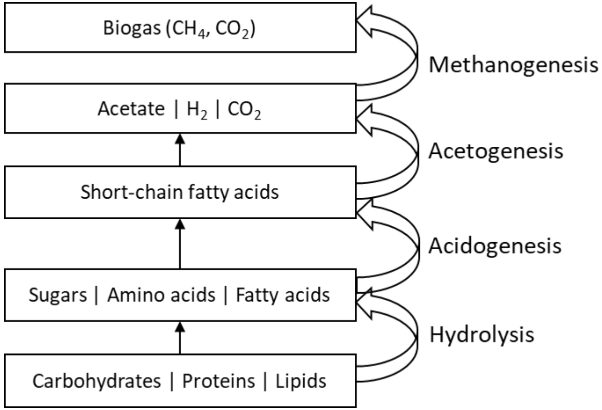
5 – FUTURE WORK

- *Go/No-Go Points (9-30-2020):* Produce methane in AnMBR system (phase 1: 6 liter and phase 2: 17.6 liter) continuously on a sustainable basis at a yield of 0.4 liter /g Vs_{fed}

- *FY21 Target:* A scalable, high performance, low-cost, two-phase modular AnMBR technology (100 gal) at TRL 4
  - Produce VFA in the first phase AnMBR (100 gal) on a sustainable basis at a yield of 0.4 g /VS_{fed}
  - Complete development of TEA and LCA model
  - Determine proper cleaning protocols for AnMBR systems to prevent membrane fouling
  - Scale up the AnMBR process from 16 gal to 100 gal

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 and sewage sludge	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

Modelling AnMBR performance

Sensitivity Analyses

→Linking existing sensitivity analysis software to ADM1

1. **M**odel **A**nalysis **T**ool**K**it (MATK)
   - Developed at LANL for Python computing environment
   - Enables quick analysis of model sensitivity, parameter estimation and uncertainty quantification
   - Parallel computing environment to compute sensitivity for multiple parameters at once
   - Open source: https://matk.lanl.gov
2. Model-Independent **P**arameter **EST**imation & Uncertainty Analysis (PEST)
   - Enables parameter estimation, sensitivity, regularization, and uncertainty quantification
   - No upper limit to parameter estimation number
   - Allows for parameter scaling & offsetting
   - Open-source (https://www.pesthomepage.org)

SUMMARY

- Conventional AD operations: slow degradation rate and incomplete biodegradation → large footprints and high cost of biogas production
  - Bio-power production for scales <1 ton/day is not economically feasible

- Develop scalable, high performance, low-cost, two-phase AnMBR technology at TRL 4
  - Decrease digestion time from 5-10 days to 12-48 h
  - High organic loading rate >11 g VS L_R^{-1} day^{-1}
  - CAPEX >1 fold less than conventional MF/UF membranes
  - > 2 fold reduction in AD footprint

- Future work: rumen-inspired organic waste degradation and dynamic AnMBR engineering with modelling and TEA driven new biofuel technology development strategies

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Q & A

Acknowledgments:

- BETO TMs: Beau Hoffman, David Babson
- BETO Waste-to-Energy Coordinator: Mark Philbrick
- ANL: Haoran Wu, Delaney Demro, Yusra Khalid
- LANL: Kurt C. Solander, Elchin Jafarov, Brent Newman
- U of Michigan: Lutgarde Raskin, Steven Skerlos, Xavier Fonoll, Timothy Fairley, Sonja Gagen, Sherri Cook (U of Colorado)
- Wastewater Resource Recovery Plants and Roselein Alternative Energy

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

This project was not subjected to prior review

PUBLICATIONS, PATENTS, PRESENTATIONS, AWARDS, AND COMMERCIALIZATION

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