DOE Bioenergy Technologies Office (BETO) 2021 Project Peer Review

Novel and Viable Technologies for Converting Wet Organic Waste Streams to Higher Value Products

March 9th, 2021
Technology Area Session

Dr. Yanna Liang
The Research Foundation of SUNY, University of Albany

College of Engineering and Applied Sciences
University at Albany
State University of New York

Project Overview

Context

Food waste: 1) Only 8.5% is used for beneficial purposes. Annually, 56 million wet tons are landfilled or combusted; 2) Several states in the northeast have now banned the disposal of food waste in landfills.

Sewage sludge: 1) The US generated 14.8 million dry tons of wastewater residuals in 2016 with half landfilled; 2) Landfilling sludge has been discouraged by some states.

Project history

BP1: 10/1/2019-05/31/2020

BP2: 06/01/2020-08/31/2021

BP3: 09/01/2021-02/28/2023

The overarching goal

This project seeks to evaluate the whole process from wet wastes to high value products using a systematic approach.

Project overview (con't)

Objectives

(1) Identification of the optimal pretreatment method for each target waste stream,

(2) Determination of the best process parameters for arrested methanogenesis (AM),

(3) Evaluation of product yield and titer of volatile fatty acids (VFAs) from the waste streams separately through Microbial Electrosynthesis (MES) with CO_2 capture and conversion,

(4) Developing an innovative membrane-based liquid-liquid extraction process for extracting VFAs out of the fermentation broth,

(5) Performing preliminary life-cycle analysis (LCA) and techno-economic analysis (TEA) for each process block,

(6) Operating the integrated process continuously at a 5-Liter scale for at least 3 months,

(7) Operating the integrated process continuously at a 50-Liter scale for at least 100 hours.

1 – Management

Team members:

University at Albany, SUNY: **Task 1.0:** Initial Verification

Task 2.0: Pretreatment of feedstocks individually or combined

Task 7.0: Continuous operation at 5 Liter scale by the whole team

Task 8.0: Continuous operation at 50 Liter scale by the whole team

Argonne National Laboratory: **Task 3.0**: Use of AM to produce VFAs from untreated/ treated feedstocks

Task 6.0: TEA and LCA

Princeton University: **Task 4.0**: Use of MES to produce VFAs from wastes and CO_2

University of Michigan: **Task 5.0**: Extracting VFAs from various fermentation broth

Communication:

Weekly lab meetings, monthly team meetings, other meetings scheduled as needed.

Stakeholder involvement:

Stakeholder inputs have been constantly sought.

A regional conference is scheduled in summer of 2021 and fall of 2022.

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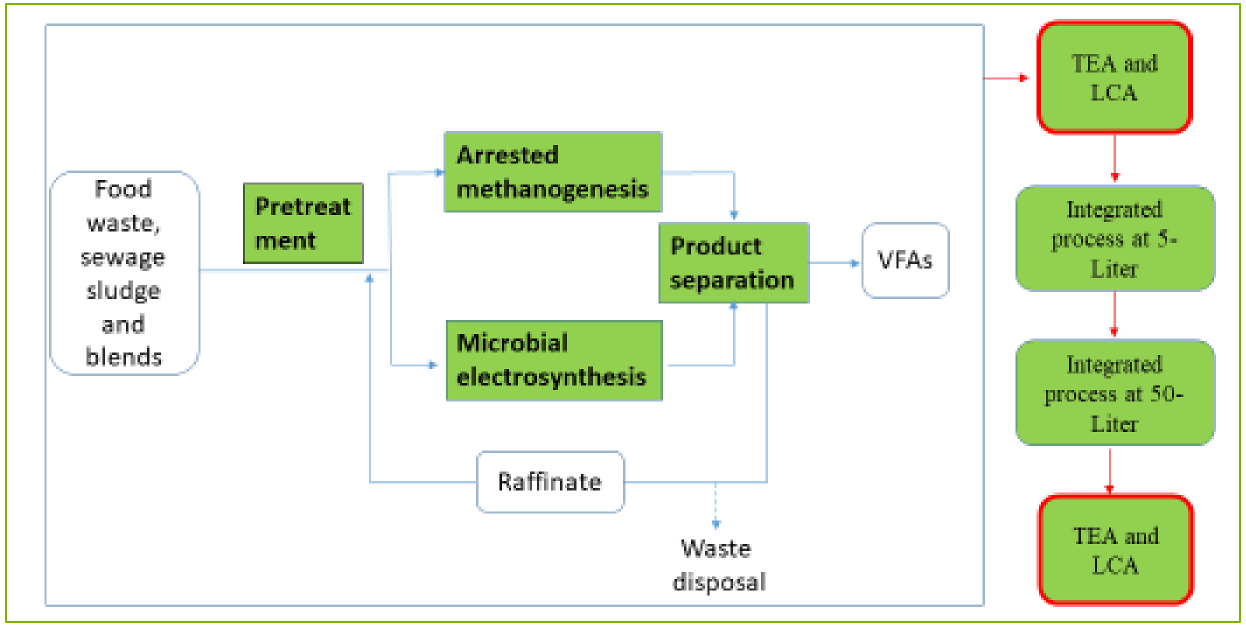
Challenges and the overall approach

- The big challenges:
- Efficiency for converting wet organic wastes to VFAs is low.
- Titer of VFAs is not high.
- Separating VFAs from fermentation broth has not been cost-effective.
- CO_2 emitted from digestion needs to be converted to achieve carbon negative.
- A continuous process targeting VFAs production from organic wastes does not exist.



Challenges and Approach- Pretreatment

- ## Food waste
- Treatments by thermal hydrolysis and ultrasonication have led to increased VFAs' yield, but the optimal pretreatment conditions are unknown.
- ## Sludge
- Thermal and sonication treatment have been practiced at commercial and pilot scales to enhance biogas release. It is unclear, however, whether these treatments will result in high VFAs production.
- ## Approach
- Food waste: identify optimal condition for increasing concentration of soluble chemical oxygen demand (SCOD) using real food waste.
- Sludge: fine tune established pretreatment condition for enhancing VFAs yield.

Challenges and Approach- AM

Current State of the Art:

- Low titer, yield and productivity; product toxicity and separation; robustness and resiliency of microbial consortium

Approach:

- Produce short chain organic acids (lactic acid, VFAs) via arrested methanogenesis by regulating acidogenic metabolism
- Establishment of resilient, robust and productive microbial consortium
- High conversion and organic loading rates of organic waste streams compared to conventional AD operations
- Produce VFAs continuously in digesters with a titer of ≥20 g/L on a sustainable basis

Challenges and Approach - MES

Current State of the Art:

- Release of CO_2 from organic matter degradation in the anode chamber although the CO_2 is biogenic.
- Mixed products from CO_2 conversion complicates product separation.
- Efficiency of CO_2 bioconversion is low.

Approach:

- Establishing an enrichment culture that converts CO_2 to mainly acetic acid.
- Testing different cathode materials for improved cathodic electron transfer.
- Testing new reactor configurations with small internal resistance.

Challenges and Approach – VFAs separation

Current State of the Art:

- Expensive, low efficiency separation / purification of VFAs from the fermentation broth accounts for 30-50% of the total VFA production costs. High efficiency separation of bio-based VFAs is critical for ensuring their commercial viability.

Approach:

- Developed a novel liquid-liquid extraction technique, termed CLEANS (Continuous Liquid-Liquid Extraction and In-situ Membrane Separation).
- CLEANS utilizes emulsification between the feed and extractant to significantly increase mass transport.
- Novel surface responsive membranes continuously break emulsions and separate the retentate and permeate phases, allowing for continuous liquid-liquid extraction at high throughput.
- The CLEANS approach can significantly enhance extraction efficiency, reduce the number of extraction stages, and improve overall production economics.

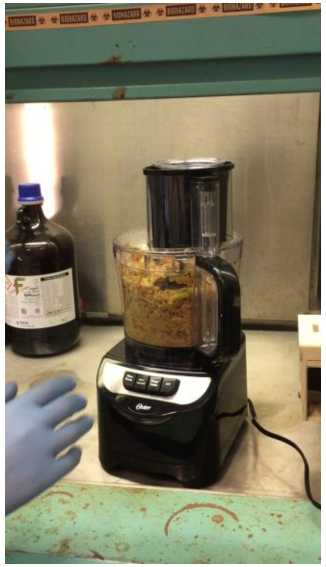
Challenges and Approach- TEA and LCA

- Challenges
  - The combination of food waste/sludge pre-treatment with controlled anaerobic digestion and separation for VFAs production is a novel system design; its cost, efficiency, energy balance and environmental impacts is not currently available. This information is needed to inform R&D for screening, benchmarking, and down selecting.
- TEA approach
  - Develop a TEA framework for conceptual understanding of every process block
  - Project cost potentials and research targets to produce economically viable products for market success
  - Provide guidance and decisions on research and development efforts
- LCA approach
  - Leverage ANL's extensive LCA research experience and waste to energy/product pathways by adding a new module to GREET model to represent waste to VFAs pathways. Data from TEA/experiments will be used for LCA modeling.

3 – Impact

- Success of this project will contribute significantly to DOE BETO's mission to develop and transform domestic renewable biomass resources into commercially viable, high-performance biofuels, bioproducts, and biopower.
- Utilization of organic wastes for VFAs production diverts these materials from being disposed at landfills.
- Integration of all process blocks successfully will lead to a carbon-negative process that can be operated continuously.
- A cost-effective modular system can be developed and deployed at where wastes are generated.
- Results from this project will be disseminated through peer-reviewed publications, conference presentations, seminars and conferences organized by the team to the scientific community and broad stakeholders.

4 – Progress and Outcomes - food waste thermal hydrolysis



Run #	Temp. (ºC)	Time (min)	TS (g/L)	SCOD fold increase
1	170	35	150	1.49907
2	60	35	50	1.0905
3	115	60	150	1.375
4	170	60	100	1.76904
5	115	60	50	1.28889
6	115	35	100	1.2
7	115	10	150	0.92637
8	115	35	100	1.24045
9	115	35	100	1.2764
10	60	35	150	0.992551
11	170	35	50	1.51131
12	115	35	100	1.31236
13	115	35	100	1.2427
14	170	10	100	1.15233
15	60	10	100	1.06388
16	115	10	50	1.08889
17	60	60	100	1.18919

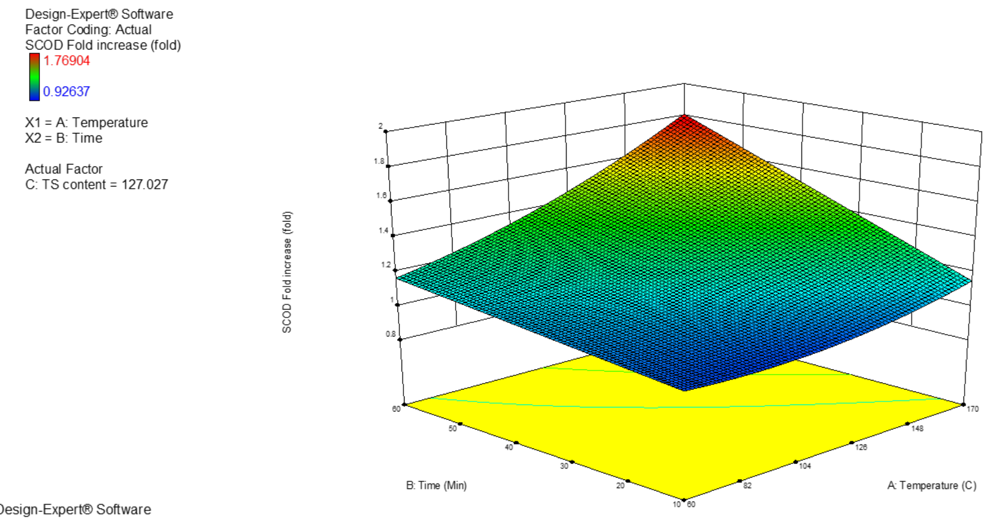
ANOVA for Response Surface Reduced Quadratic model

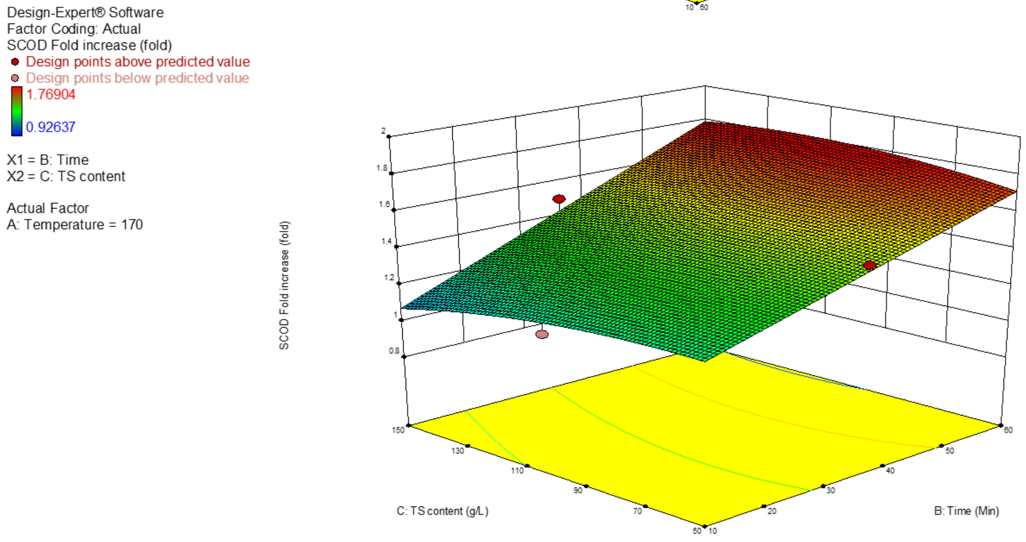
Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	0.67	7	0.096	37.62	< 0.0001	significant
A-Temperature	*0.32*	*1*	*0.32*	*124.82*	*< 0.0001*	
B-Time	*0.24*	*1*	*0.24*	*94.81*	*< 0.0001*	
C-TS content	*4.352E-003*	*1*	*4.352E-003*	*1.71*	*0.2238*	
AB	*0.060*	*1*	*0.060*	*23.68*	*0.0009*	
BC	*0.015*	*1*	*0.015*	*6.06*	*0.0360*	
A^2	*0.021*	*1*	*0.021*	*8.05*	*0.0195*	
C^2	*0.012*	*1*	*0.012*	*4.85*	*0.0551*	
Residual	0.023	9	2.550E-003			
Lack of Fit	*0.016*	*5*	*3.163E-003*	*1.77*	*0.2994*	not significant
Pure Error	*7.134E-003*	*4*	*1.784E-003*			
Cor Total	0.69	16				

Weilan Zhang, Huimin Cao, and Yanna Liang. 2020. Optimization of thermal pretreatment of food waste for maximal solubilization. Journal of Environmental Engineering. In press.

Results from food waste thermal hydrolysis

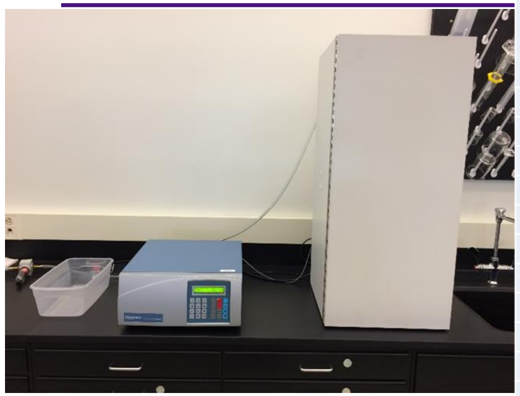


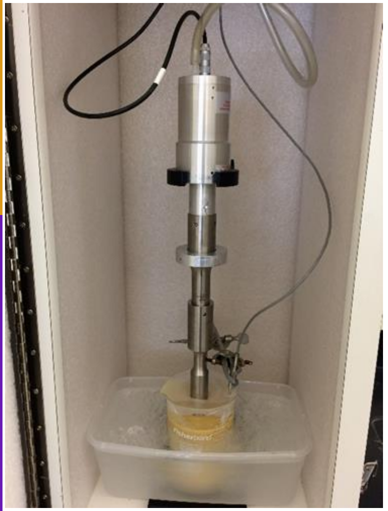


Final Equation in Terms of Actual Factors:

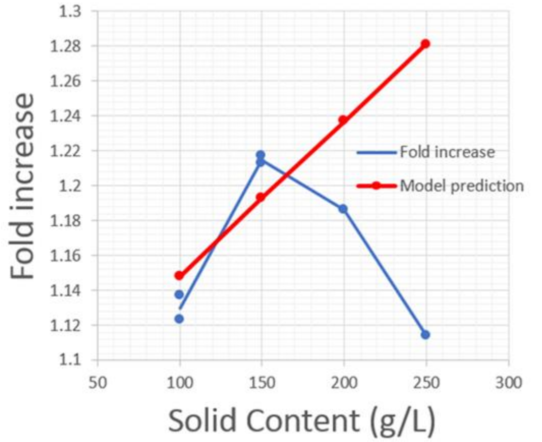
SCOD Fold increase	=
+1.24902	
-4.80068E-003	* Temperature
-8.29412E-003	* Time
+2.12252E-003	* TS content
+8.93456E-005	* Temperature * Time
+4.97260E-005	* Time * TS content
+2.30436E-005	* Temperature^2
-2.16471E-005	* TS content^2

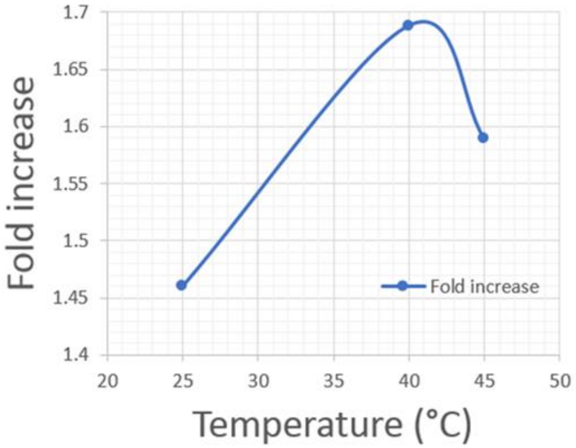
Food waste ultrasonication





Run	Solid Content (g/L)	Amplitude (%)	Sonication Time (min)	FW/Water (w/w)	Energy (J)	SCOD Fold Increase
1	60	60	11	0.2118	30232	1.060
2	20	60	20	0.0619	59270	1.060
3	60	20	20	0.2118	34075	1.079
4	60	20	2	0.2118	3409	1.037
5	20	20	11	0.0619	18983	1.047
6	60	60	11	0.2118	32037	1.069
7	20	60	2	0.0619	6072	1.011
8	20	100	11	0.0619	50681	1.073
9	100	100	11	0.411	50052	1.147
10	100	60	2	0.411	5947	1.052
11	100	20	11	0.411	17309	1.120
12	60	100	2	0.2118	9249	1.053
13	60	60	11	0.2118	32338	1.115
14	60	60	11	0.2118	33666	1.089
15	60	60	11	0.2118	33148	1.072
16	100	60	20	0.411	59007	1.155
17	60	100	20	0.2118	93364	1.107





ANOVA for Reduced Quadratic model

Response 1: SCOD fold increase

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.0204	4	0.0051	16.88	< 0.0001	significant
A-Solid content	0.0100	1	0.0100	33.18	< 0.0001	
B-Amplitude	0.0012	1	0.0012	3.90	0.0718	
C-Time	0.0077	1	0.0077	25.48	0.0003	
C^2	0.0015	1	0.0015	4.94	0.0463	
Residual	0.0036	12	0.0003			
Lack of Fit	0.0017	8	0.0002	0.4598	0.8376	not significant
Pure Error	0.0019	4	0.0005			
Cor Total	0.0240	16				

Final Equation in Terms of Ac

SCOD fold increase	=
+0.950852	
+0.000884	* Solid content
+0.000303	* Amplitude
+0.008537	* Time
-0.000231	* $Time^2$

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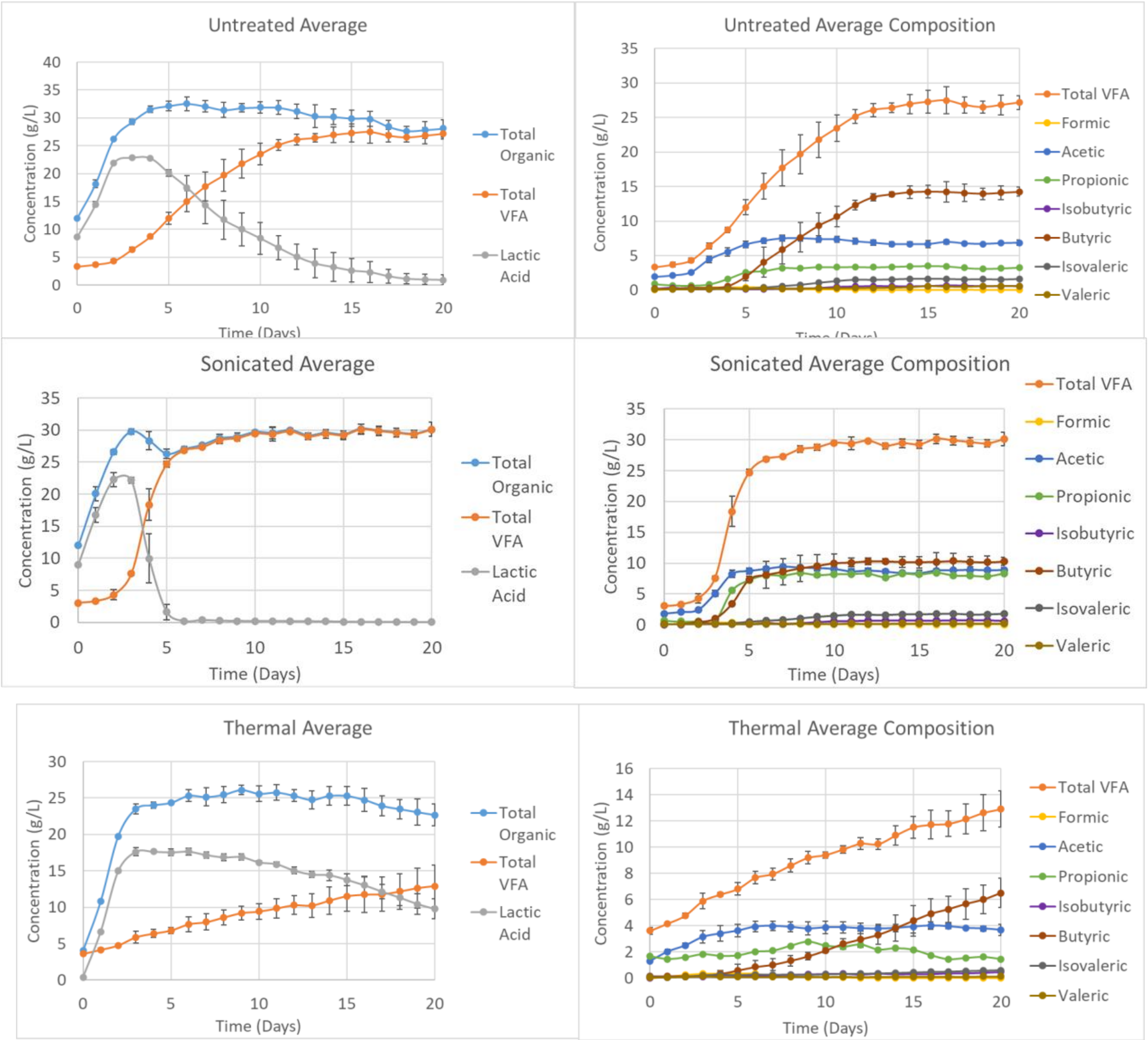
Progress and Outcomes - AM



Digester Experiments:

- 8% TS to simulate stand alone food digester operation in lab-scale digesters
- Operating Conditions
  - pH: 7.0
  - Temperature ~37 ^{o}C
  - Agitation: 150 RPM
  - Working Volume 400 mL
  - 80% FW substrate & 20% Stage 1 Sludge Inoculum
- Produce VFA titer > 20 g/L and average methane content in biogas <10%
- Met the milestone set for this task

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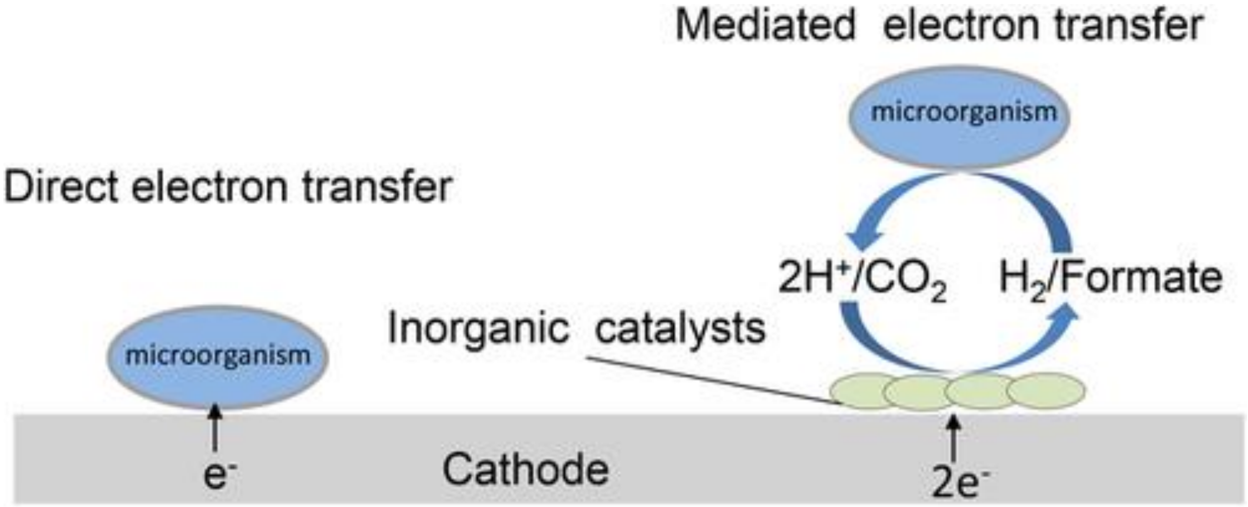
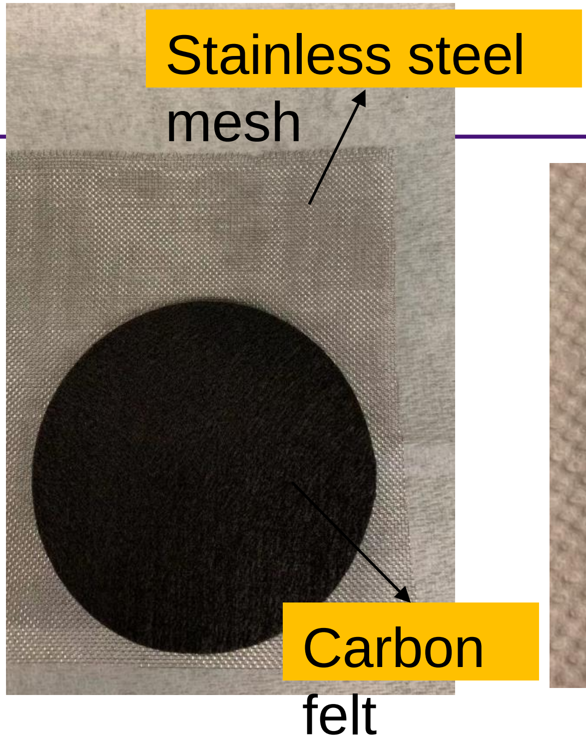
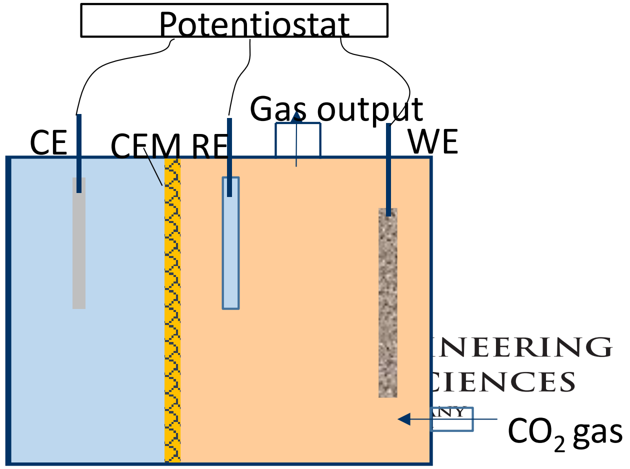
Progress and Outcomes - MES

- Cathode: carbon felt
- Microbes source: enriched community from serum bottle
- Cathode potential: -1.0 v vs Ag/AgCl (3M KCl)
- Carbon source: CO_2



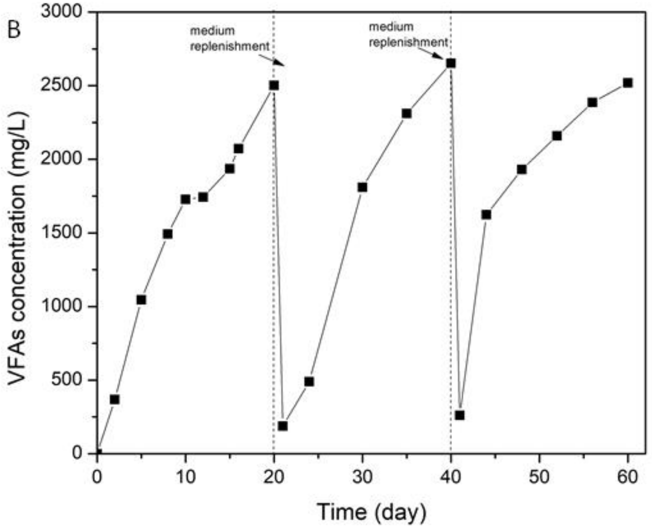


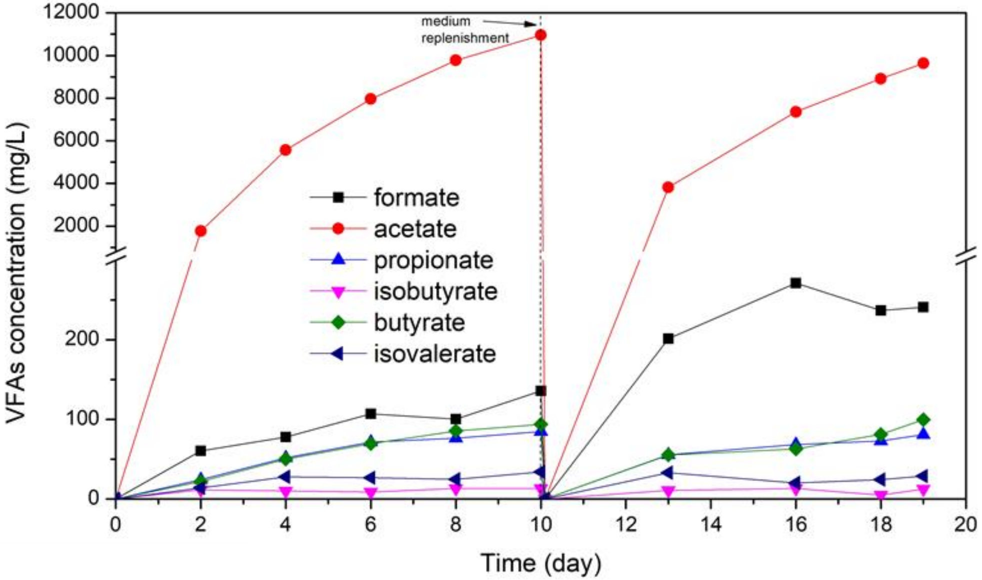


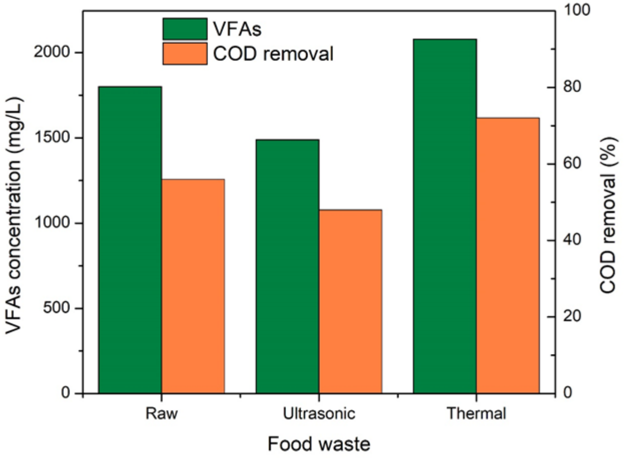
Progress and Outcomes - MES

A

B







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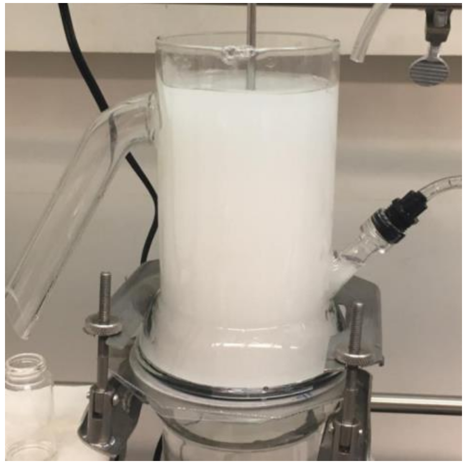
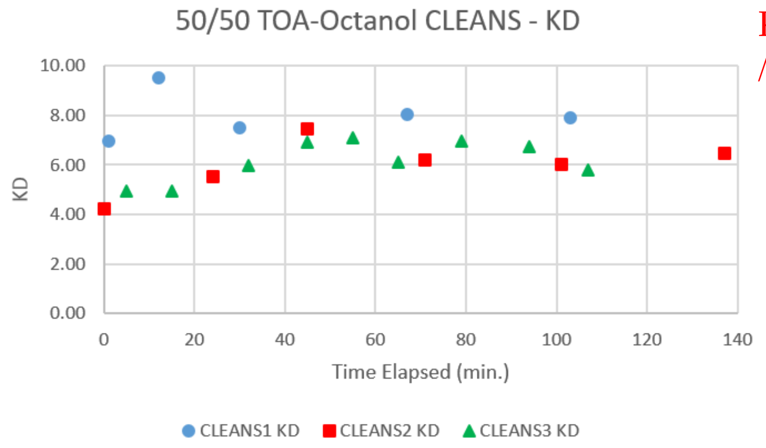
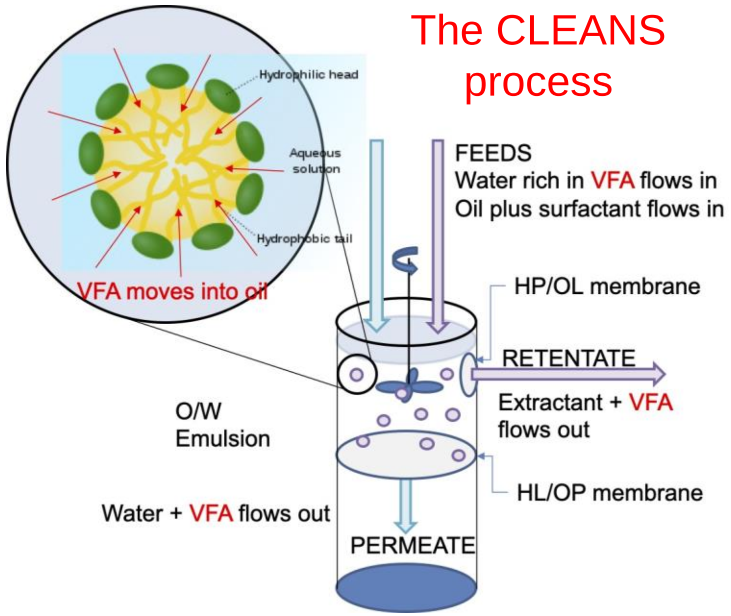
Progress and Outcomes – Product separation

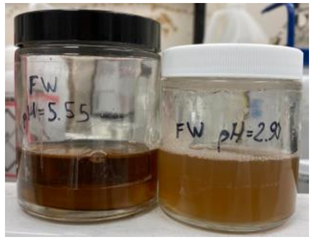




K_D = grams of VFA's in extractant /grams of VFA's in the raffinate



Demonstrated K_D values of ~ 8 with acetic acid in water during continuous operation. One of the highest ever reported separation efficiencies.



	Alkaya	pH = 2.5		UMich	pH = 2.89	
Species	tVFA%	KD	%R	tVFA%	KD	%R
Acetic	55%	1.54	61%	19%	0.33	25%
Propionic	39%	2.56	72%	27%	1.97	66%
Isobutyric	-	-	-	2%	high	~100%
Butyric	4%	5.03	83%	42%	6.29	86%
Isovaleric	-	-	-	4%	high	~100%
Valeric	2%	40.79	98%	3%	high	~100%
Hexanoic	-	-	-	3%	high	~100%
Heptanoic	-	-	-	0%	high	~100%
tVFA	100%	2.07	66%	100%	**2.41**	71%

Demonstrated K_D values > 2 for all VFA's using actual samples from ANL under continuous operation (Flux > 100 L / m^2/ hr) at the 500 ml scale. Further process optimization is underway.

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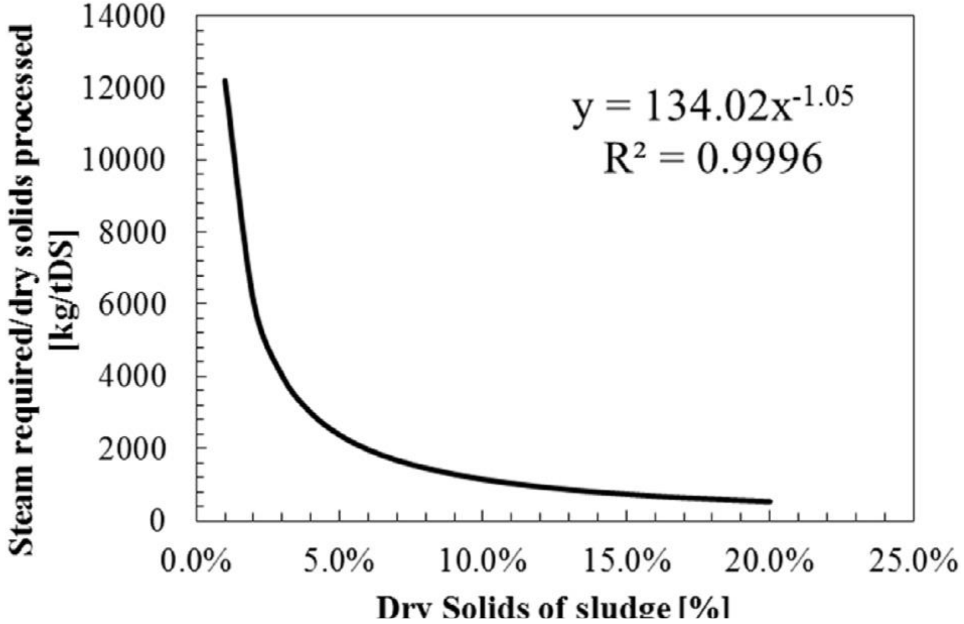
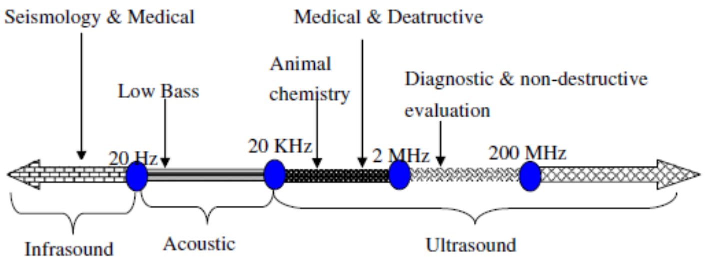
Progress and Outcomes - TEA and LCA

- Conducted literature search and review on each process



$$S = \frac{10.85\,\Delta T}{911\eta}\left[134 \times DS^{-1.05}\right]$$

Water Research 104 (2016) 53–71



No.	Parameter	Expression	Unit	Reference
1	Specific energy input	$E_s = \frac{P*t}{V*T*S}$	kJ/kg TS or kW s/kg TS	[46]
2	Ultrasound dose	$UD_o = \frac{P*t}{V}$	J/L	[33]
3	Ultrasound density	$UD = \frac{P}{V}$	W/L	[33]
4	Ultrasound intensity	$UI = \frac{P}{A}$	W/cm^2	[48]

E_s: specific energy in kW s/kg TS (kJ/kg TS); P: power input (kW); T: sonication time (s); V: volume of sludge (L); TS: total solids concentration (kg/L); A: surface area of the probe in cm^2.

Sonication time: 1.5 – 150 min
Sonication frequency: 10-31 kHz
Sonication density: W/volume (0.011-4.0)
Power input: kW
Specific energy: kJ/kg VS

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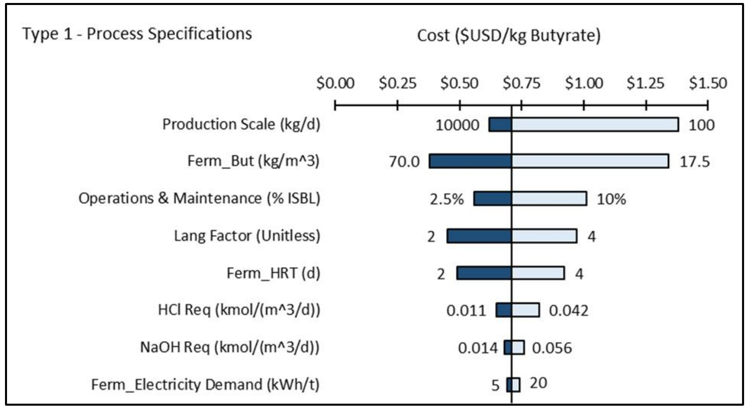
Progress and Outcomes - TEA and LCA

- TEA progress
  - Completed the initial TEA framework for AM process



Crude VFA Production Cost (Default Parameter Set)
0.71 $USD/kg Butyrate

- LCA progress
  - Identified the system boundary and key variables in each process through close communication with team members
  - Built a draft module in GREET to represent key processes (pre-treatment, CAD, and separation) and supply chain
  - *Pre-liminary LCA results for AM (CAD) process*

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Summary

- *Optimal conditions for pretreating food waste through thermal hydrolysis and ultrasonication have been identified and verified.*
- *Through AM, we observed > 20 g/L of VFAs in fermentation broth. Compared to untreated food waste, pretreatment of sonicated food waste led to increased titers of VFAs in shorter time.*
- *Demonstrated K_D values > 2 for all VFAs using actual fermentation broth under continuous operation (Flux > 100 L / m^2/ hr) at the 500 mL scale.*
- *Regarding MES, an enriched culture in the cathode produced > 11.3 g/L of VFAs from CO_2.*
- *Milestones set for each task were met successfully.*

Quad Chart Overview (Competitive Project)

Timeline
- Project start date: 10/01/2019
- Project end date: 02/28/2023

	FY20 Costed	Total Award
DOE Funding	*$109,851.42*	$2,698,541.00
Project Cost Share	$41,615.00	$709,550.00

Project Partners*
- Partner 1: Argonne National Laboratory
- Partner 2: Princeton University
- Partner 3: University of Michigan

*Only fill out if applicable.

Project Goal
The overarching goal of this project is to develop an integrated and efficient process for converting wet organic wastes to volatile fatty acids (VFAs).

End of Project Milestone
The conversion efficiency of carbon in food waste and sewage sludge is enhanced by at least 50% and/or the disposal costs of these two wet waste streams are decreased by at least 25%.

Funding Mechanism
FOA: DE-FOA-0002029

Topic area: AOI 9: Rethinking Anaerobic Digestion
Year: 2019

Additional Slides

Publications, Patents, Presentations, Awards, and Commercialization

- 1. Weilan Zhang, Huimin Cao, and Yanna Liang. 2020. Optimization of thermal pretreatment of food waste for maximal solubilization. Journal of Environmental Engineering. In press.
- 2. Yanna Liang, 2020. A Critical Review of Challenges Faced by Food Wastes Valorization. Waste and Biomass Valorization. In review.