DOE Bioenergy Technologies Office (BETO) 2021 Project Peer Review

Electro-Enhanced Conversion of Wet Waste to Products Beyond Methane

March 9, 2021
Organic Wastes

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Colorado State University

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An engineering, science and technology university
NREL Transforming ENERGY
Colorado State University
UCI University of California, Irvine

Project Overview

- U.S. produces >77 MM dry tons of organic waste, including food waste and manure, every year
  - Most is landfilled or land applied, incurring disposal costs
  - Anaerobic digestion (AD) produces low-value methane and CO_2 ⇒ poor economics
  - Disposal costs are significant to dairies and other animal operations
- Organic waste has substantial energy content

Feedstocks	Annual Resource Generation Estimated Annual Resources	Inherent Energy Content (Trillion Btu)	Fuel Equivalent (MM GGE)[1]
Wet Feedstocks	77.17 MM Dry Tons	1,078.6	9,290.8
Wastewater Residuals	14.82	237.6	2,046.6
Animal Waste	41.00	547.1	4,713.0
Food Waste[2]	15.30	79.6	685.3
Fats, Oils, and Greases	6.05	214.3	1,845.9

Biofuels and Bioproducts from Wet and Gaseous Waste Streams: Challenges and Opportunities. 2017.

Project Overview

- The *technical* goal of this project is to valorize wet organic waste by using renewable electrons to drive targeted pathways in AD and subsequent bioconversions to higher-value products, including
  - Hexanoic acid: precursor to diesel-range blendstock and other products
  - Isobutanol: gasoline blendstock, upgradable to jet fuel
- Benefits:
  - Levelized cost of energy production will be improved by at least 25%
  - Net levelized cost of disposal will be improved by at least 25%
- The *educational* goals are to train students in biological waste conversion technology and to share innovative solutions with the public
- Benefits:
  - Train new STEM professionals to find new solutions to waste conversion

Project Overview

- Project award: October 2019
- Funding:
  - NREL: November 2019
  - Universities: December 2020
- Limitations owing to COVID-19 pandemic:
  - 3-month lab closure at NREL and universities
  - Capacity restrictions since re-opening

1 – Management

Volatile fatty acid = VFA

- Project structure
  - Task 1 (alter AD to enhance VFA production)
  - Task 2 (upgrade AD product streams)
  - Task 3 (process modeling and TEA)
  - Task 4 (integrate education with research)

Research is highly integrated, within and across tasks

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1 – Management

Volatile fatty acid = VFA

- Project structure
  - Task 1 (alter AD to enhance VFA production)
    - Arrested methanogenesis (NREL)
    - Electro-enhanced AD (CSU, SDSM&T)
    - In-situ VFA extraction (NREL, SDSM&T)
    - Microbial consortium development (CSU)
    - Scaleup of enhanced AD (SDSM&T)

Collaboration within task:

- Measurement methods
- Inoculum development and sharing
- Experimental design
- Shared sample analysis

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VFA = Volatile fatty acid
SC = short chain (C2-C4)
MC = medium chain (C5-C8)

1 – Management

- Project structure
  - Task 1 (alter AD to enhance VFA production)
  - Task 2 (upgrade AD product streams)
    - Develop VFA separation process (UCI, NREL)
    - Microbial electrosynthesis for conversion of CO_2 to VFAs (NREL, UCI)
    - Electro-elongation of VFAs to MC FAs (NREL)
    - Bioconversion of VFAs to MC alcohols (UCI, CSU)

Collaboration within task:

- Measurement methods
- Shared sample analysis
- Data interpretation

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1 – Management

- Project structure
  - Task 1 (alter AD to enhance VFA production)
  - Task 2 (upgrade AD product streams)
  - Task 3 (process modeling and TEA)
    - Engineering process modeling (CSU, SDSM&T)
    - TEA (CSU, SDSM&T)
    - Sensitivity analysis and optimization (CSU)

Collaboration <u>within</u> task:

- Process modeling tools

1 – Management

- Project structure
  - Task 1 (alter AD to enhance VFA production)
  - Task 2 (upgrade AD product streams)
  - Task 3 (process modeling and TEA)
  - Task 4 (integrate education with research)
    - Student and postdoc participation (all)
    - Cross-disciplinary training (all)
    - Vocational/JC connections (CSU)
    - Education/outreach at CSU Spur campus (all)

Collaboration within task:
- Shared training methods
- Joint effort to create outreach program

1 – Management

- Project structure
  - Task 1 (alter AD to enhance VFA production)
  - Task 2 (upgrade AD product streams)
  - Task 3 (process modeling and TEA)
  - Task 4 (integrate education with research)

Collaboration across tasks

- Electrobiochemical methods
- Data for all modeling
- Product → input stream composition and samples
- TEA guidance for experiments
- Research output to education and outreach

1 – Management

- Project structure
- Communication
  - Biweekly project team meetings
  - Exchange of materials and data
  - Collaboration on experiments and modeling
  - Exchange of students and postdocs

1 – Management

- Project structure
- Communication
- Decision-making
  - PI in consultation with task leads

1 – Management

- Project structure
- Communication
- Decision-making
- Project risks
  - Monitoring:
    - Project update meetings with follow-up
    - Review of quarterly progress reports
  - Mitigation:
    - Discussion and input
    - Process model highlights knowledge gaps
    - Evaluation of alternatives
    - Parallel efforts

1 – Management

- Project structure
- Communication
- Decision-making
- Project risks
  - o Monitoring:
    - Project update meetings with follow-up
    - Review of quarterly progress reports
  - o Mitigation:
    - Discussion and input
    - Process model highlights knowledge gaps
    - Evaluation of alternatives
    - Parallel efforts

Examples of risk mitigation:

- Development of high-value product: planned parallel efforts
- Approaches to enhanced VFA production: planned parallel efforts and down-selection

2 – Approach

	Y1				Y2				Y3				Y4				Y5			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task/Subtask								G/NG						G/NG						G/NG
Task 1: Enhancement of VFA Production in AD																				
Task 1.1: Arrested methanogenesis			M1.1.1			M1.1.2		G/NG 1	(depends on down-selection)											
Task 1.2: Electro-enhanced AD					M1.2.1			G/NG 1	(depends on down-selection)											
Task 1.3: In-situ VFA extraction		M1.3.1						G/NG 1	(depends on down-selection)											
Task 1.4 Microbial consortium development							M1.4.1	G/NG 1	(depends on down-selection)											
Task 1.5 Baseline AD performance and scaleup								G/NG 1												
Task 1.6 Enhanced AD – 2 to 20L scaleup													M1.6.1	G/NG 2						
Task 1.7 Enhanced AD – 20 to 2000L scaleup																				G/NG 3
Task 2: Capturing and upgrading AD product streams																				
Task 2.1: Development of electrodialysis for VFAs														M2.1.1						
Task 2.2: MES for conversion of CO2	M2.2.1															M2.2.2				G/NG 3
Task 2.3: Electro-elongation of VFAs to MCFAs																		M2.3.1		M2.3.2
Task 2.4: Bioconversion of VFAs to higher alcohols								G/NG 1	M2.4.1					G/NG 2	M2.4.2					G/NG 3
Task 3: System Evaluation and Optimization																				
Task 3.1: Engineering process modeling				M3.1.1																
Task 3.2: Techno-economic analysis								M3.2.1				M3.2.2					M3.3.2			G/NG 3
Task 3.3: Sensitivity, scenario, and optimization										M3.3.1										
Task 4: Integrate education with research																				
Task 4.1: Student and PD researcher participation								G/NG 1												
Task 4.2: Internship programs for undergraduates																			M4.2.1	
Task 4.3: Cross-disciplinary forums														G/NG 2						
Task 4.4: Outreach programs to partner universities											M4.4.1									
Task 4.5: Summer engagement programs														G/NG 2						
Task 4.6: Education at CSU Spur Campus											M4.6.1									

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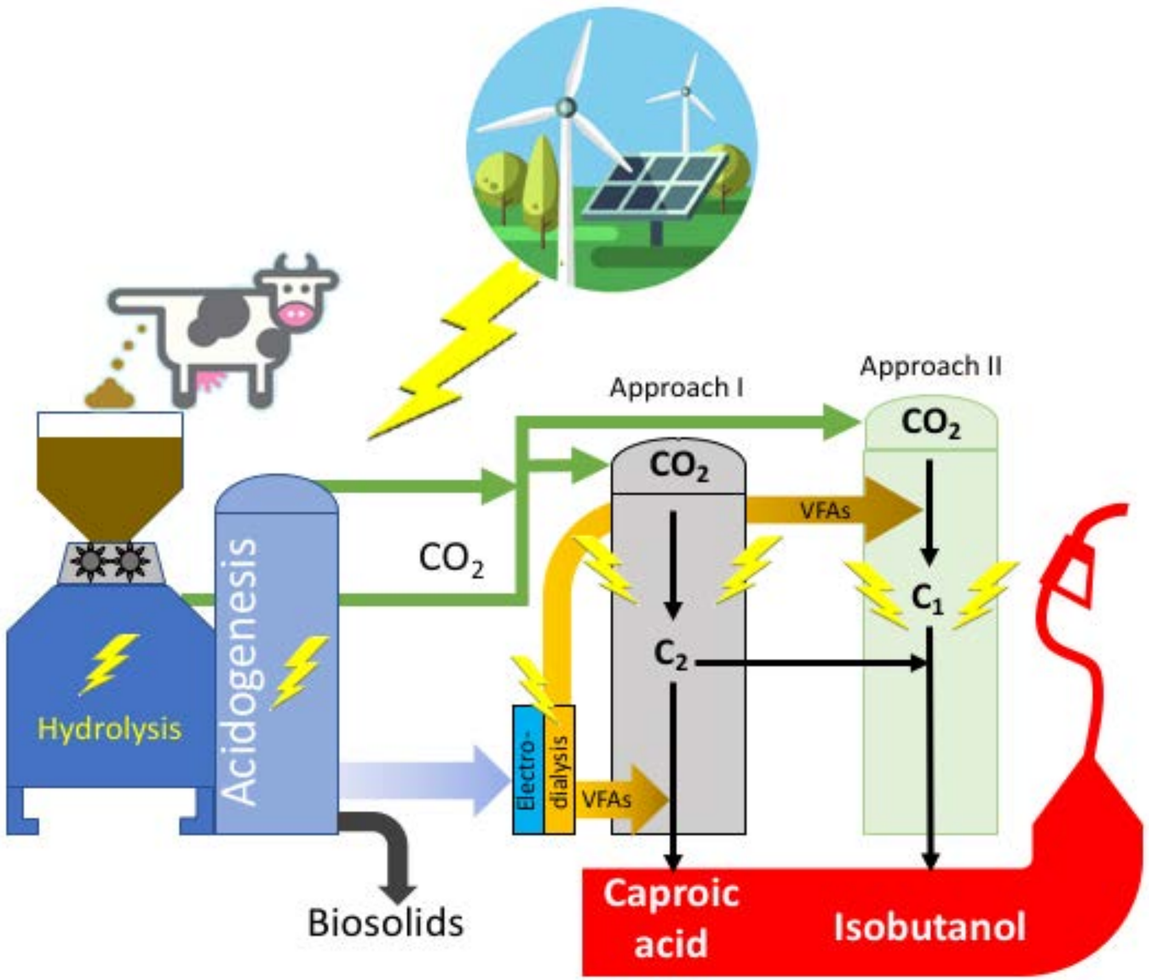
2 – Approach



Task 1: Alter AD to enhance VFA production

Task 2: Upgrade AD product streams

Task 3: Process modeling and TEA

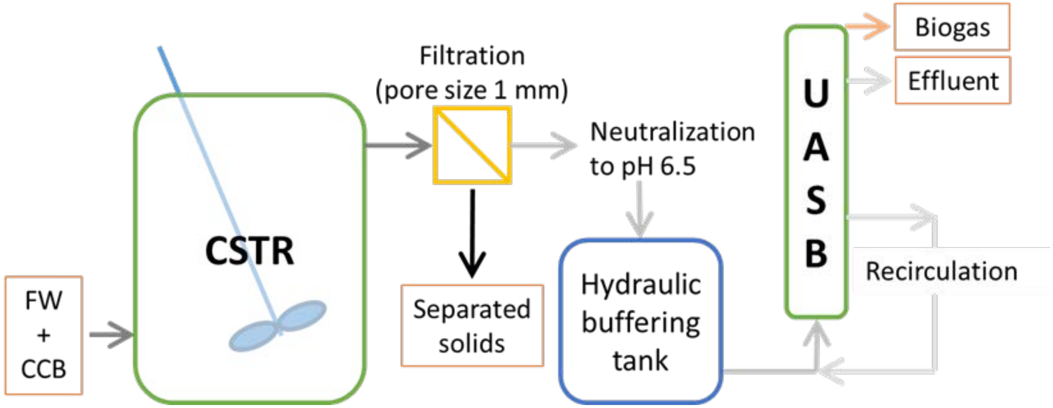
Task 4: Education and Outreach

2 – Approach

Task 1: Enhancement of Volatile Fatty Acids Production in AD

- Arrested methanogenesis
  - T, pH, microaeration
- Electro-enhanced AD
- In-situ VFA extraction
- Microbial consortium development
- Enhanced AD scaleup
  - 2 L to 2,000 L (GasCube)

GasCube at SDSM&T



2 – Approach

Task 1: Enhancement of Volatile Fatty Acids Production in AD

BP 1 Go/No-Go: Demonstration of one method, or methods in combination, that ***increase total VFA yield by at least 50%*** over baseline total VFA yields (g VFA/g TS) of 0.1 from manure and 0.3 from food waste; Demonstration of baseline GasCube performance of total VFA yields of 0.10 g/g TS for manure or 0.30 g/g TS for food waste.

BP 2 Go/No-Go: Selection of consortium, feedstock, and AD operational conditions for demonstration in pilot-scale GasCube digester from those demonstrated to achieve total VFA yields at the 20-L scale of 0.12 g/g manure or 0.36 g/g food waste.

BP 3 Go/No-Go: Demonstrate AD total VFA yields at the 2000-L scale of at least 0.096 g/g manure or 0.29 g/g food waste.

2 – Approach

Task 2: Capturing and upgrading AD product streams

- Development of VFA separation process
  - Chemical extraction or electro-dialysis
- Microbial electrosynthesis for conversion of waste CO_2 to VFAs
- Electro-elongation of MES products and VFAs to hexanoic acid and other medium-chain FAs
- Bioconversion of VFAs to isobutanol and other medium-chain alcohols
  - Metabolically engineered strain

MC FAs: higher value than VFAs; can be produced with higher yield than other products
MC alcohols: higher value than VFAs; fuel blendstocks

2 – Approach

Task 2: Capturing and upgrading AD product streams

BP 2 Go/No-Go: Demonstrate production of higher alcohols from engineered *E. coli* in electrodialysis-purified AD and MES effluent.

BP 3 Go/No-Go: Scale-up of the MES process to at least 1 L without significantly decreasing MES performance compared to pure CO_2 feed; Demonstrate total higher alcohol (1-propanol, 1-butanol, isobutanol) production with a final titer of 1.0 g/L at 20-L scale with continuous feeding of electrodialysis-purified AD and MES effluent.

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2 – Approach

Task 3: System Evaluation and Optimization to Assess Economic Viability

- Engineering process modeling
- Techno-economic analysis to quantify economic performance metrics
- Sensitivity, scenario, and optimization

2 – Approach

Task 3: System Evaluation and Optimization to Assess Economic Viability

BP 2 Go/No-Go: Demonstration via TEA of a pathway that meets a MFSP of less than $5/GGE.

BP 3 Go/No-Go: Demonstration of a pathway that meets the DOE target of $3/GGE and improvement of nLCOD to $60/ton (25% improvement) or less for at least one configuration of the developed process.

2 – Approach

Task 4: Integrate Education and Outreach with Research

- Graduate student and post-doctoral researcher participation, with leadership roles
- Undergraduate internship programs with industry
- Intensive summer engagement programs for undergraduates
- Outreach programs to partner community college
- Education/outreach program at the CSU Spur campus

- Multi-disciplinary research engagement
- Stimulating and training the next generation of STEM professionals to transform waste valorization

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2 – Approach

Task 4: Integrate Education and Outreach with Research

- Graduate student and post-doctoral researcher participation, with leadership roles
- Undergraduate internship programs with industry
- Intensive summer engagement programs for undergraduates
- Outreach programs to partner community college
    - Engage students in this topic for further education
- Education/outreach program at the CSU Spur campus
    - Thousands of visitors annually (anticipated)
    - K-12 education focus

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2 – Approach

Task 4: Integrate Education and Outreach with Research

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2 – Approach

Task 4: Integrate Education and Outreach with Research

BP 1 Go/No-Go: Involvement of 4 graduate students and 1 postdoctoral researcher directly in research.

BP 2 Go/No-Go: Completion of at least 4 forums for project participants to develop research skills and discuss challenges; Cumulative engagement of at least 12 undergraduate students, at least 6 from institutions other than CSU, UCI, and SDSM&T, in summer research on the project.

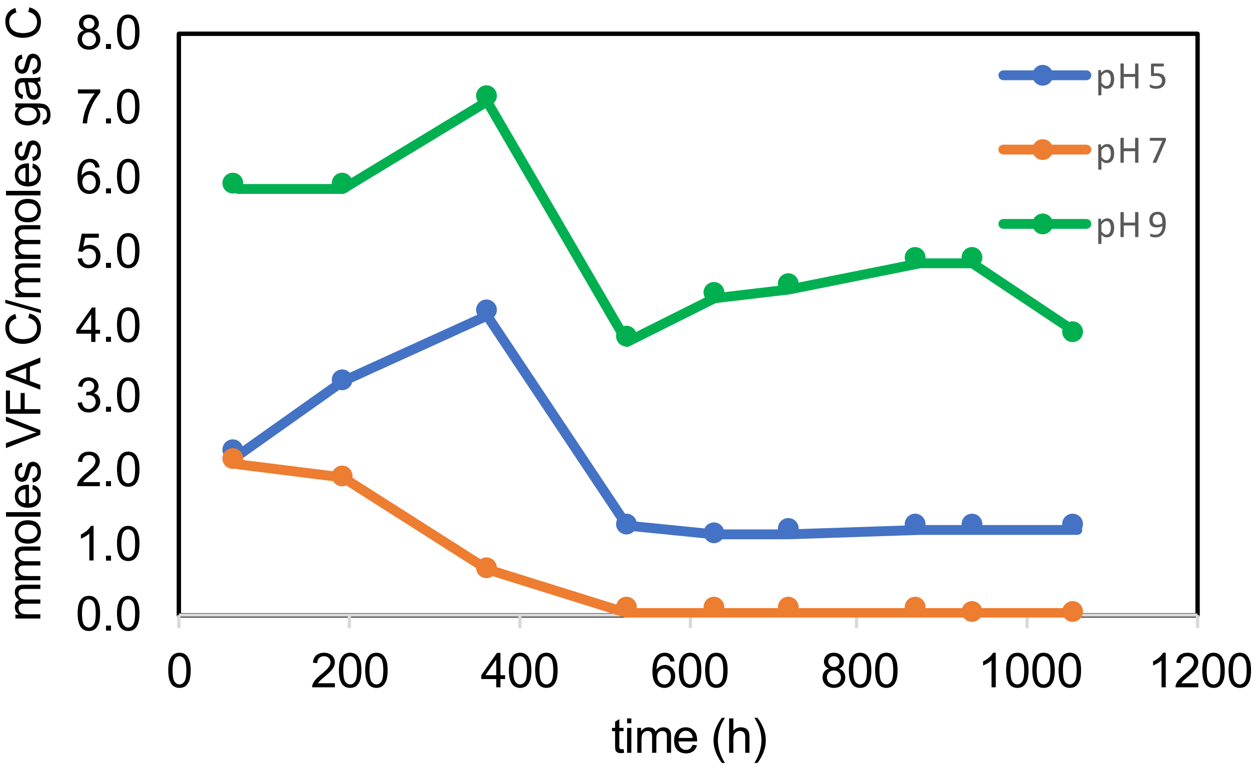
3 – Impact

- U.S. produces >77 MM dry tons of organic waste every year:
  - Valorizing biomass carbon (vs. GHGs) is high impact
  - Hexanoic acid is a precursor to fuels and other chemicals
  - Isobutanol is a gasoline blendstock and upgradable to jet fuel
- Contribute to development of renewable electrons as process input
- Technoeconomic impacts:
  - Levelized cost of energy production will be improved by at least 25%
  - Net levelized cost of disposal will be improved by at least 25%
- Valuable engagement with industry
  - Leprino Foods, others TBD
- Dissemination
  - Publications, patent applications planned
- Education and outreach to train a new generation in innovative waste conversion

4 – Progress and Outcomes

- Task 1: Enhancement of Volatile Fatty Acids Production in AD
  - Initial experiments on influence of organics loading, pH, inoculum

pH strongly affects distribution of feedstock carbon to VFAs vs. gas



Food waste

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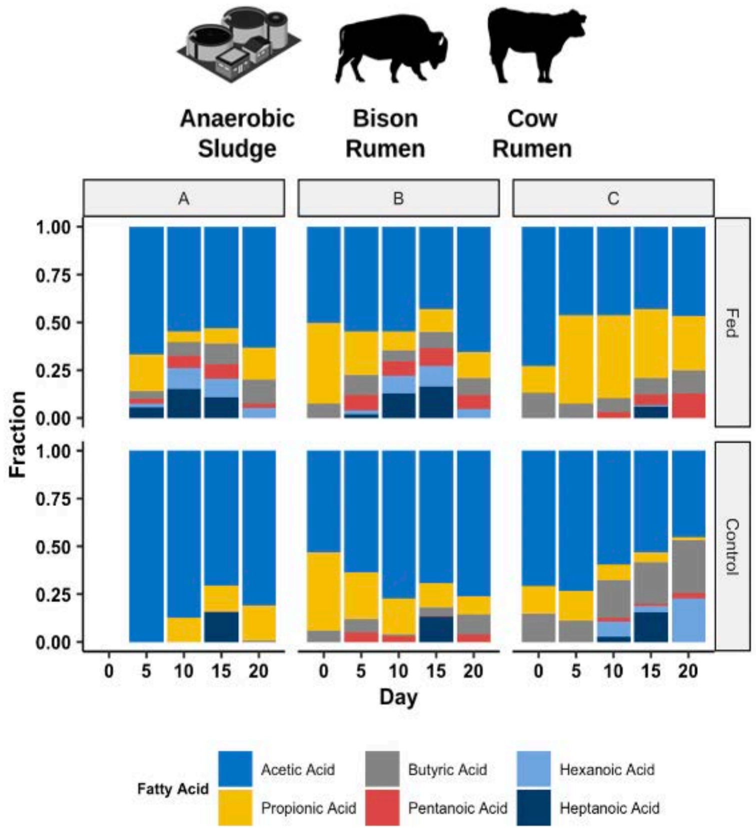
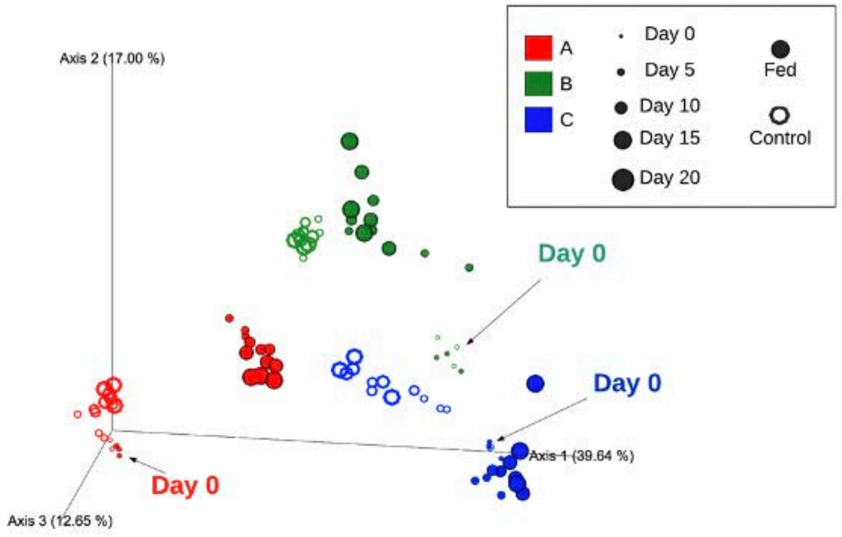
4 – Progress and Outcomes

- Task 1: Enhancement of Volatile Fatty Acids Production in AD
  - Initial experiments on influence of organics loading, pH, inoculum

inoculum strongly affects VFA distribution



Microbial Structure



Rico, J.L., K.F. Reardon, and S.K. De Long. *Bioresource Technology* 323 (2021): 124532.

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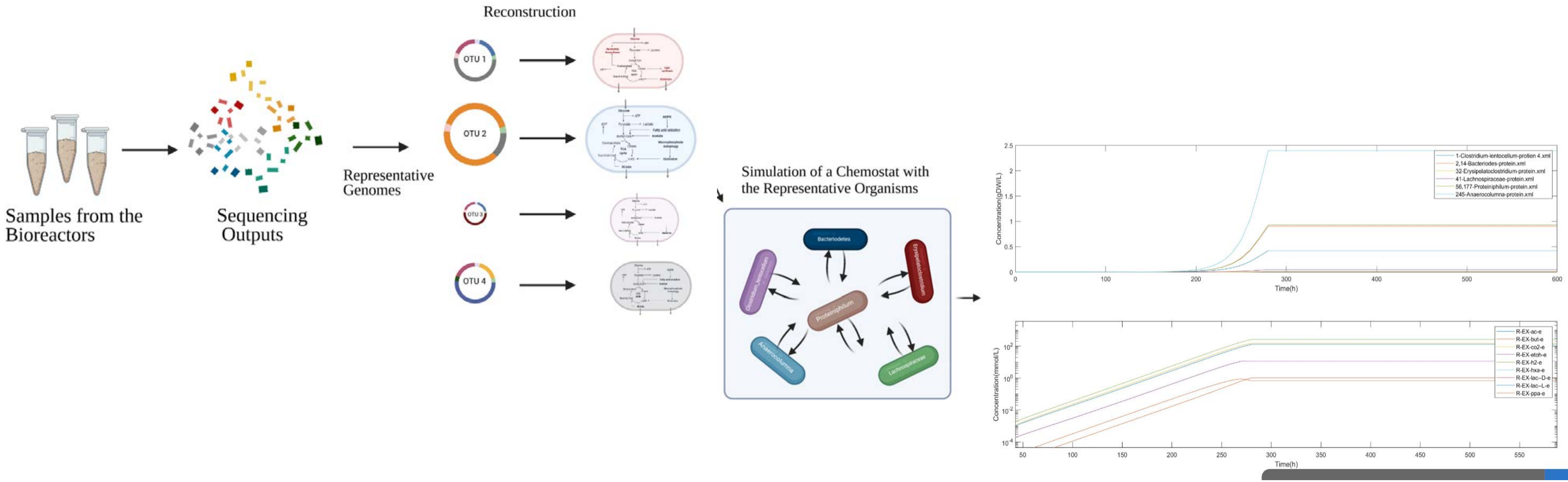
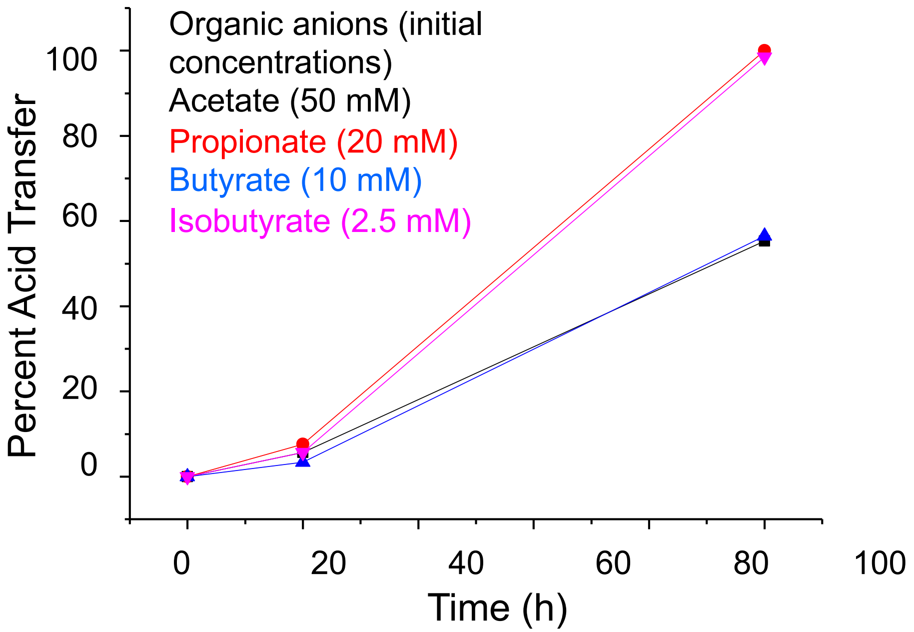
4 – Progress and Outcomes

- Task 1: Enhancement of Volatile Fatty Acids Production in AD
    - Initial development of metagenomic model of AD consortium



4 – Progress and Outcomes

- Task 2: Capturing and upgrading AD product streams
  - Electrodialysis process development



Cathode: stainless steel foil (10 cm^2)
Anode: Ir mixed metal oxide/Ti (4 cm^2)
Anion exchange membrane (4 cm^2)

Results to date:
~1%/h acid transfer at 100 mA, -1.4 V

Milestone 2.1.1:
70% acid transfer

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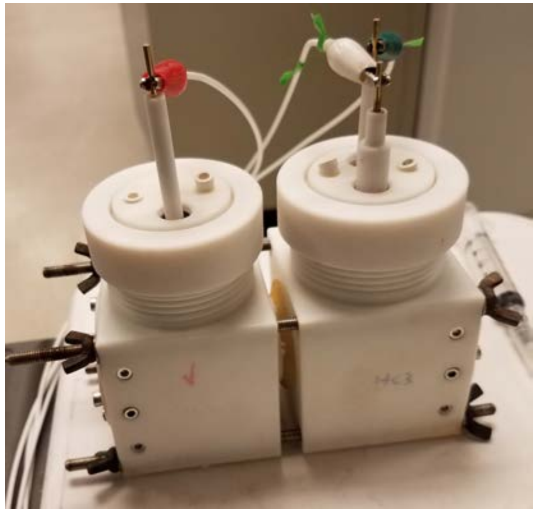
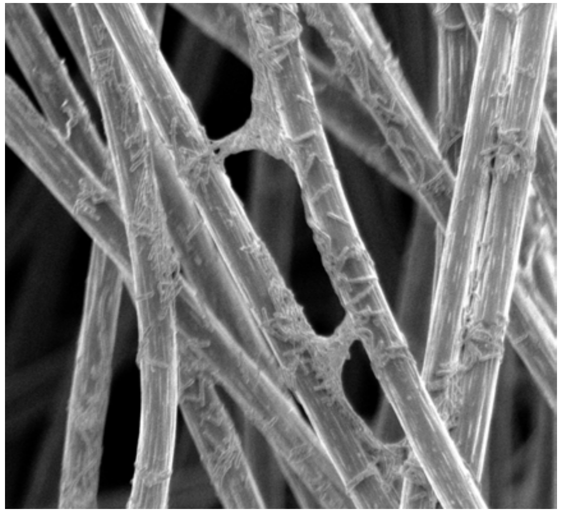
4 – Progress and Outcomes

- Task 2: Capturing and upgrading AD product streams
  - Microbial electrosynthesis process development

Biocathode: $CO_2 \rightarrow$ acetate, ethanol; **Anode**: $H_2O \rightarrow O_2$



Bioelectrochemical cell (150 ml)



Clostridium ljungdahlii biofilms on carbon felt support

<u>Carbon felt support (2x2 cm^2)</u>

Yield (acetate) = 540 gm^{-2}day^{-1}; 0.2 g·L^{-1}·day^{-1}

Faradic efficiencies 90% @ -1.0 vs Ag/AgCl

Results:

~600 g·m^{-2}·day^{-1}

0.25 g·L^{-1}·day^{-1}; FE 50-90%

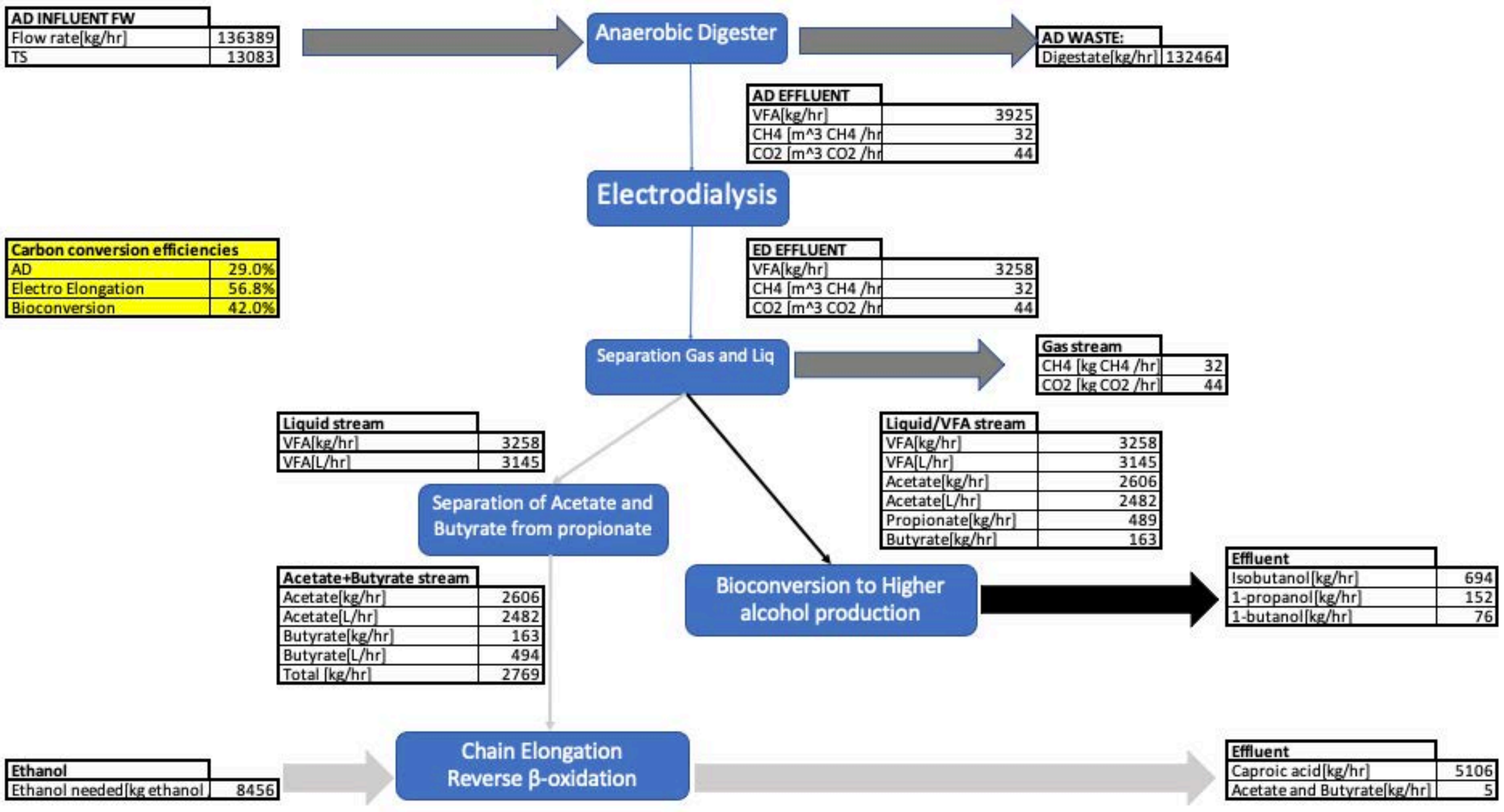
Milestone 2.2.1:

18 g·m^{-2}·day^{-1} ✓ achieved

FE 80%

4 – Progress and Outcomes

- Task 3: System Evaluation and Optimization to Assess Economic Viability
  - Completed initial process models completed
  - Completed initial TEA for MC FA and MC alcohol pathways



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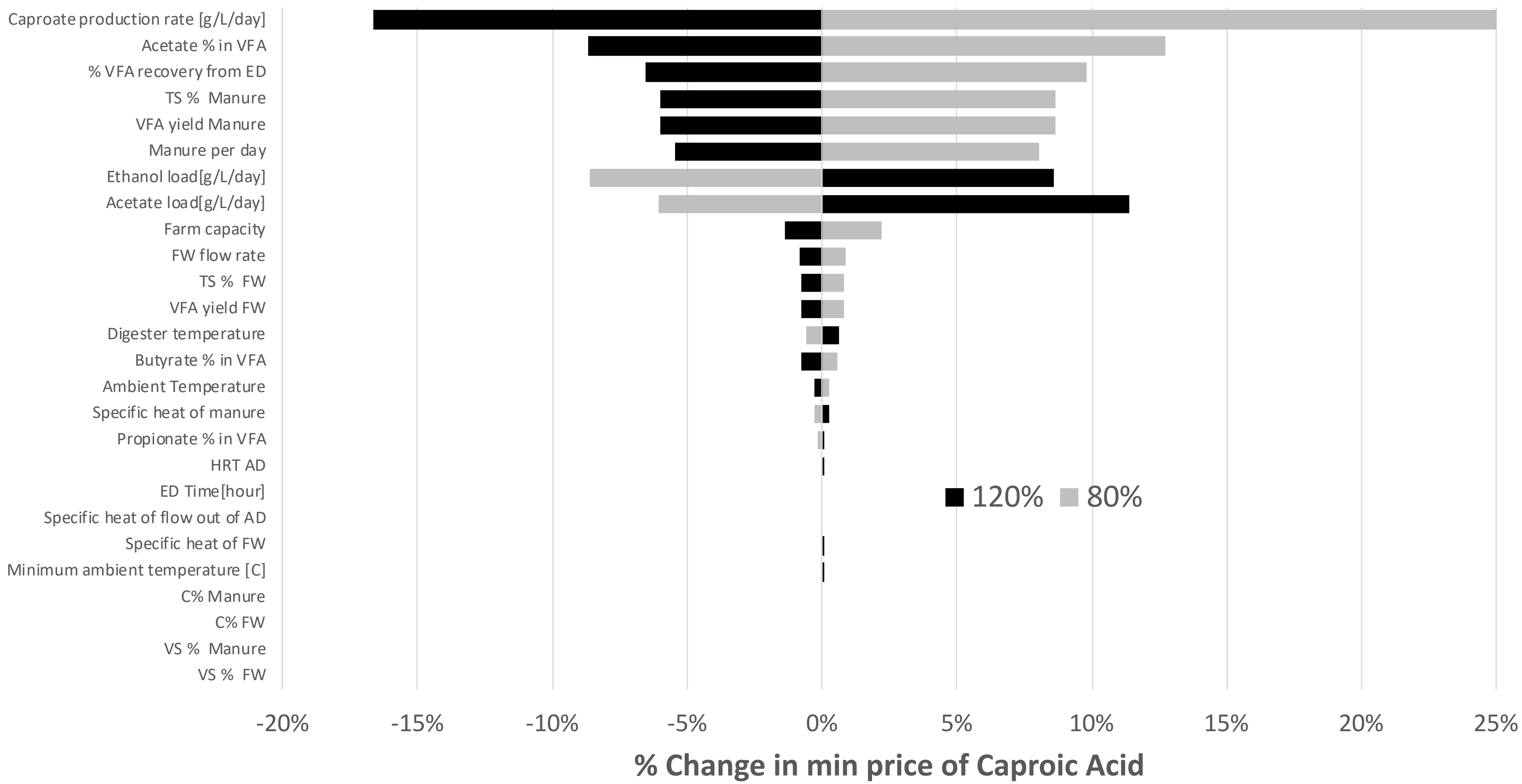
4 – Progress and Outcomes

- Task 3: System Evaluation and Optimization to Assess Economic Viability
  - Initial sensitivity analysis

Effects on hexanoic acid selling price



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4 – Progress and Outcomes

- Task 4: Integrate Education with Research
  - NREL hosted graduate student
  - Planning for summer undergraduate researchers

Summary

- Project team has met biweekly since January 2020
- Technical work initiated
  - Process modeling
  - Initial AD optimization experiments
  - Electrodialysis conditions
- Schedule delays owing to COVID-19 shutdowns/restrictions and funding delay

Project Team

Colorado State University
Danielle Bartholet, Joshua Chan, Susan De Long, Parsa Ghadermazi, Jocelyn Hittle, Jason Quinn, Ken Reardon, Jorge Rico, Abdo Soliman, Kathryn Venzor

National Renewable Energy Laboratory
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University of California, Irvine
Plamen Atanassov, Han Li

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Quad Chart Overview

Timeline
- 10/01/2019
- 11/30/2025

	FY20 Costed	Total Award
DOE Funding	(10/01/2019 – 9/30/2020) *$129,500*	(negotiated total federal share) *$5,067,538*
Project Cost Share	$0	$1,267,907

Project Partners
- NREL
- UC-Irvine
- South Dakota School of Mines & Technology
- Leprino Foods

Project Goal
The goal of this project is to re-engineer anaerobic digestion into an electrochemically enhanced conversion of wet waste to divert carbon from low-value methane into chemical products beyond methane, fix waste CO_2 into C2 compounds, upgrade these precursors to displace petroleum-based products, and leverage these improvements to enhance overall waste conversion efficiencies.

End of Project Milestone
Demonstration of a pathway that meets the DOE target of $3/GGE and improvement of nLCOD to $60/ton or less for at least one configuration of the developed process; Scale-up of the MES process to at least 1 L without significantly decreasing MES performance compared to pure CO_2 feed; Demonstrate total higher alcohol production with a final titer of 1.0 g/L at 20-L scale with continuous feeding of electrodialysis-purified AD and MES effluent; Demonstrate AD total VFA yields at the 2000-L scale of at least 0.096 g/g manure or 0.29 g/g food waste.

Funding Mechanism

DE-FOA-0002029, FY19 Bioenergy Technologies Office Multi-Topic

Topic Area 6 – Renewable Energy from Urban and Suburban Wastes

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Additional Slides

Responses to Previous Reviewers' Comments

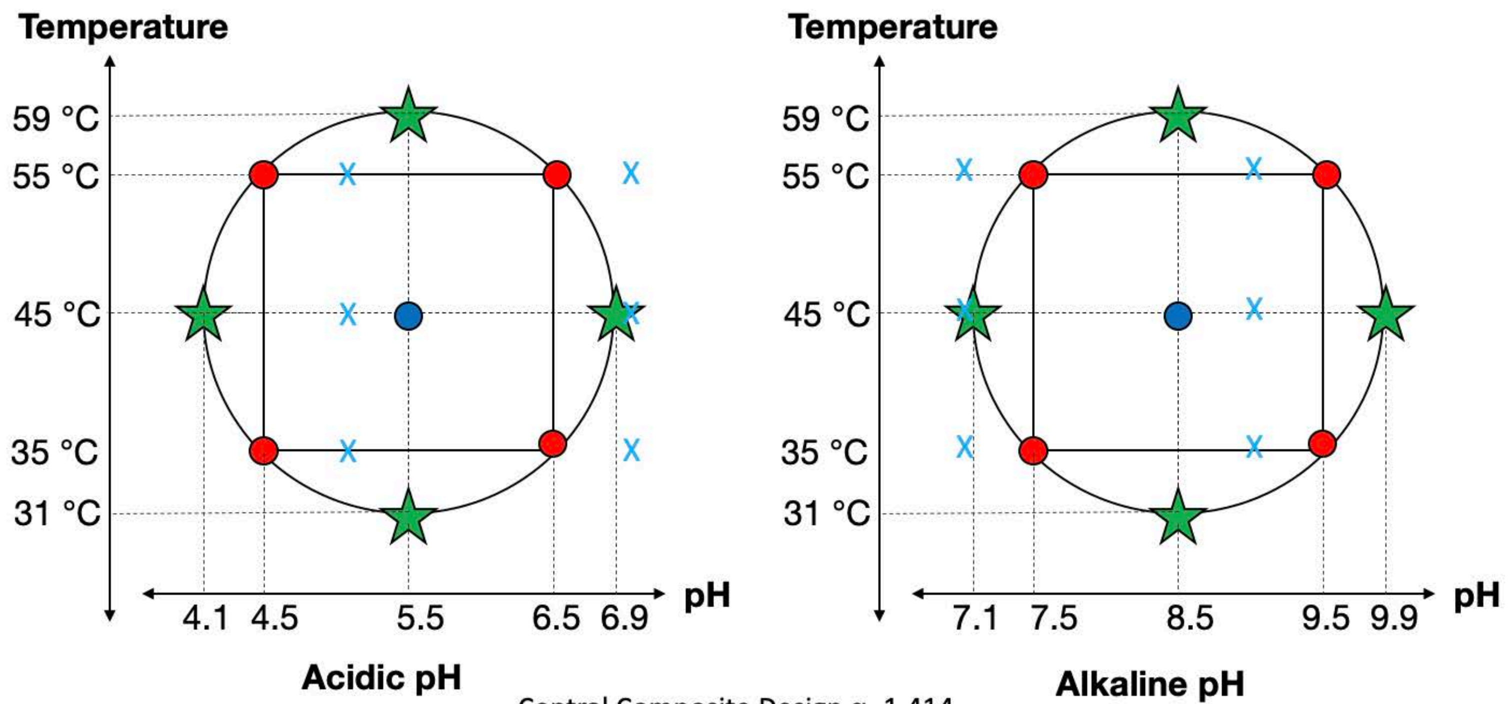
- NA

Publications, Patents, Presentations, Awards, and Commercialization

- Li et al. Extracellular electron transfer across bio-nano interfaces for CO_2 electroreduction. Nanoscale, 2021,13, 1093-1102. https://doi.org/10.1039/D0NR07611B
- In preparation: Review of effects of operating conditions on VFA production.

4 – Progress and Outcomes

- Task 1: Enhancement of Volatile Fatty Acids Production in AD
  - Determined design of experiments for T, pH, inoculum tests



Red circles represent axial points; Blue point represent center point; Green Stars represent "star points". Light Blue "X" represent acclimation conditions.

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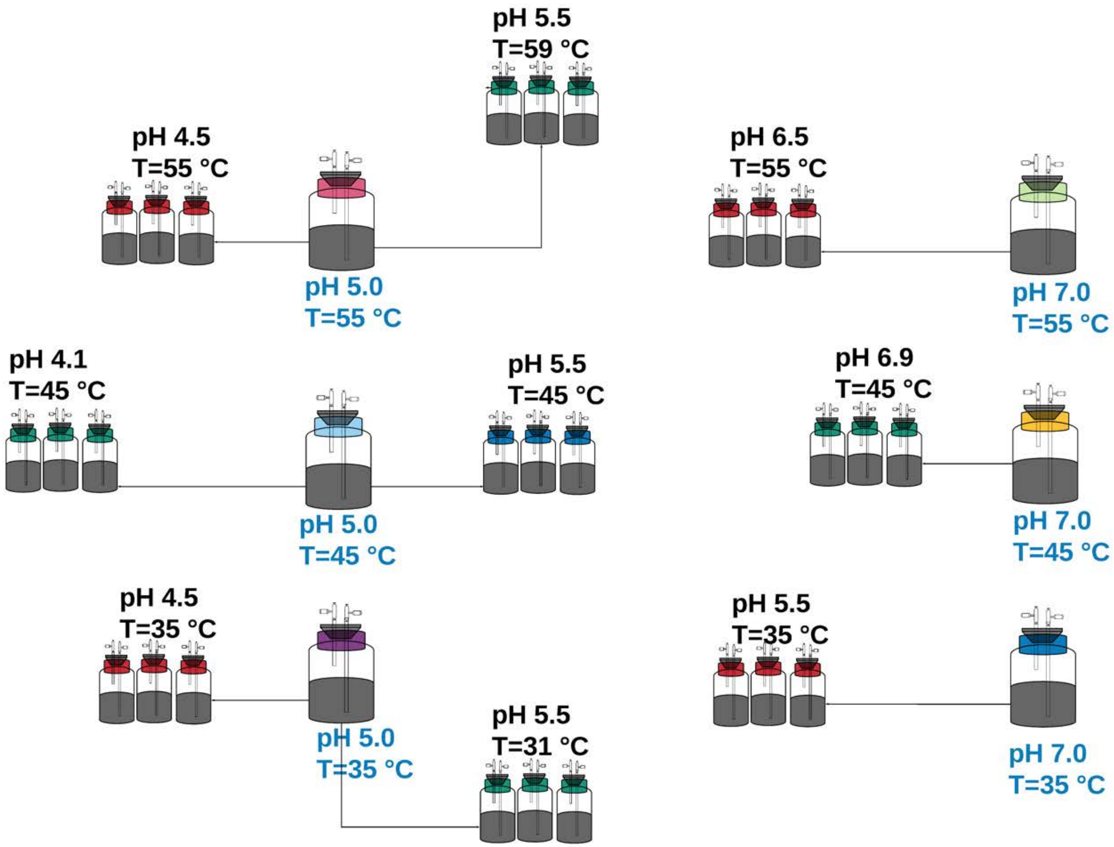
4 – Progress and Outcomes

- Task 1: Enhancement of Volatile Fatty Acids Production in AD
  - Determined design of experiments for T, pH, inoculum tests

Acidic pH experiment example



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