DOE Bioenergy Technologies Office (BETO): 2023 Project Peer Review

High Solids In Situ Product Recovery; The Next Generation of Arrested Anaerobic Digestion Technology (DE-EE0009765)

4/7/2023

Performance-Advantaged Bioproducts and Bioprocessing Separations

Xumeng Ge

Quasar Energy Group

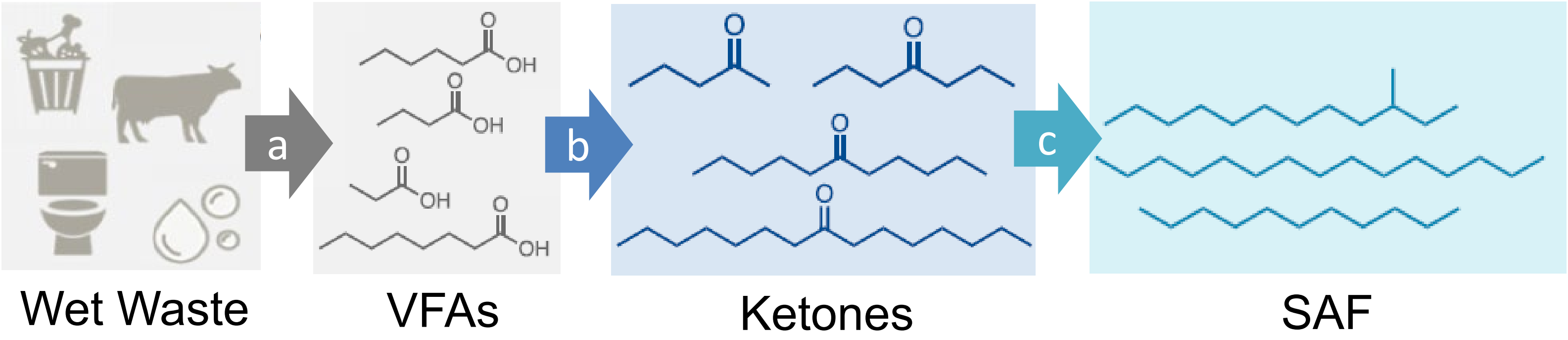
energy economy environment

Project Overview: Sustainable Aviation Fuel (SAF)

Background: Huge and increasing demand vs. Low production of SAF

- **>20,000 million gallons** of jet fuel are consumed and expected to double by 2050 [1,2].
- Airlines commit to **reduce their carbon footprint by 50%** before 2050 [1].
- **~ 2 million gallons** of renewable jet fuel are produced currently [2].

Opportunities: Organic waste to volatile fatty acid (VFA) to SAF via
a. Arrested Anaerobic Digestion (AAD), b. Ketonization and c. Hydrodeoxygenation



Challenges:

(1) The difficulty of solids handling has limited arrested anaerobic digestion (AAD) units to whey and thin stillage, which can only meet 5% of U.S. SAF demand.

(2) Current VFA separations trains consume more energy than the energy content of the VFA.

[1] PNAS 2021 Vol. 118 No. 13 e2023008118; [2] DOE/EE-2041. US Department of Energy Efficiency & Renewable Energy; 2020.

Project Overview: Project Objectives Aligned with BETO Goals

This project

Goal: a pilot-scale demonstration of the National Renewable Energy Laboratory's (NREL) **patented high solids separations technology** (US patent 63/020,598) to separate **VFAs** from **digester** and produce a Sustainable Aviation Fuel (SAF) product.

Specific objectives:

1. **Reduce separation cost by ~50%**
2. **Demonstrate at 80L scale for >100 h**
3. **Produce >1.5 kg of VFAs at > 95% purity**
4. **Demonstrate positive energy balance**
5. **Produce >1 kg of SAF from VFAs**

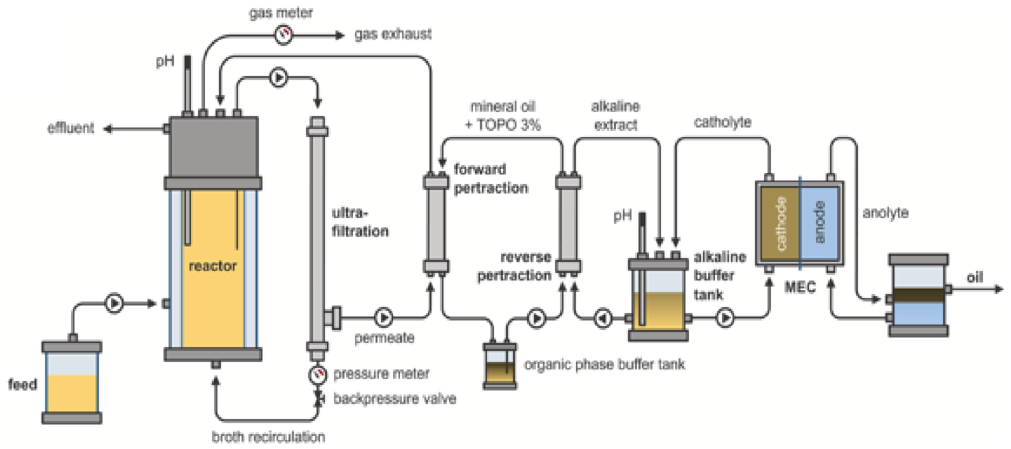
BETO (Topic Area 3a)

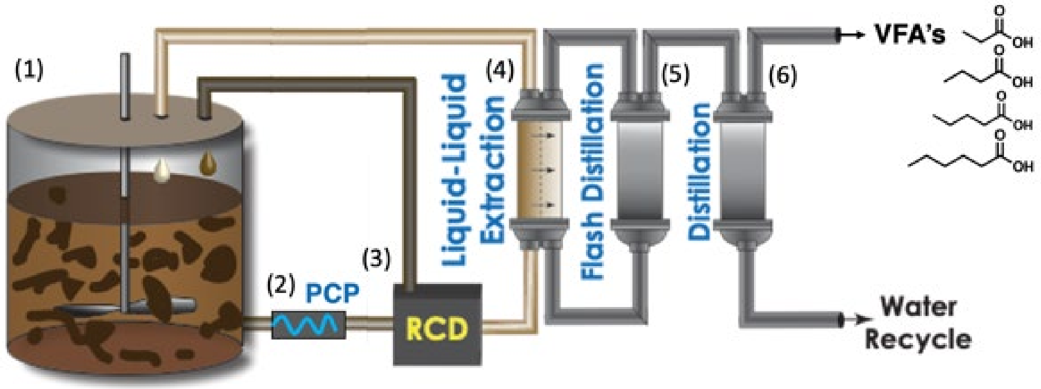
Goal: Develop **efficient and cost-effective separations approaches** to isolate and potentially upgrade **organic acids** and products of interest from **digesters**.

Specific Requirements:

- Sufficient efficiency, purity and yield for downstream application
- Reduce separation energy by at least 50%
- Demonstrate >=100 continuous hours of stable operation
- Recover >=1 kg of product(s)
- Identify the value proposition and environmental impact

1 – Approach: Baseline and Proposed Technology

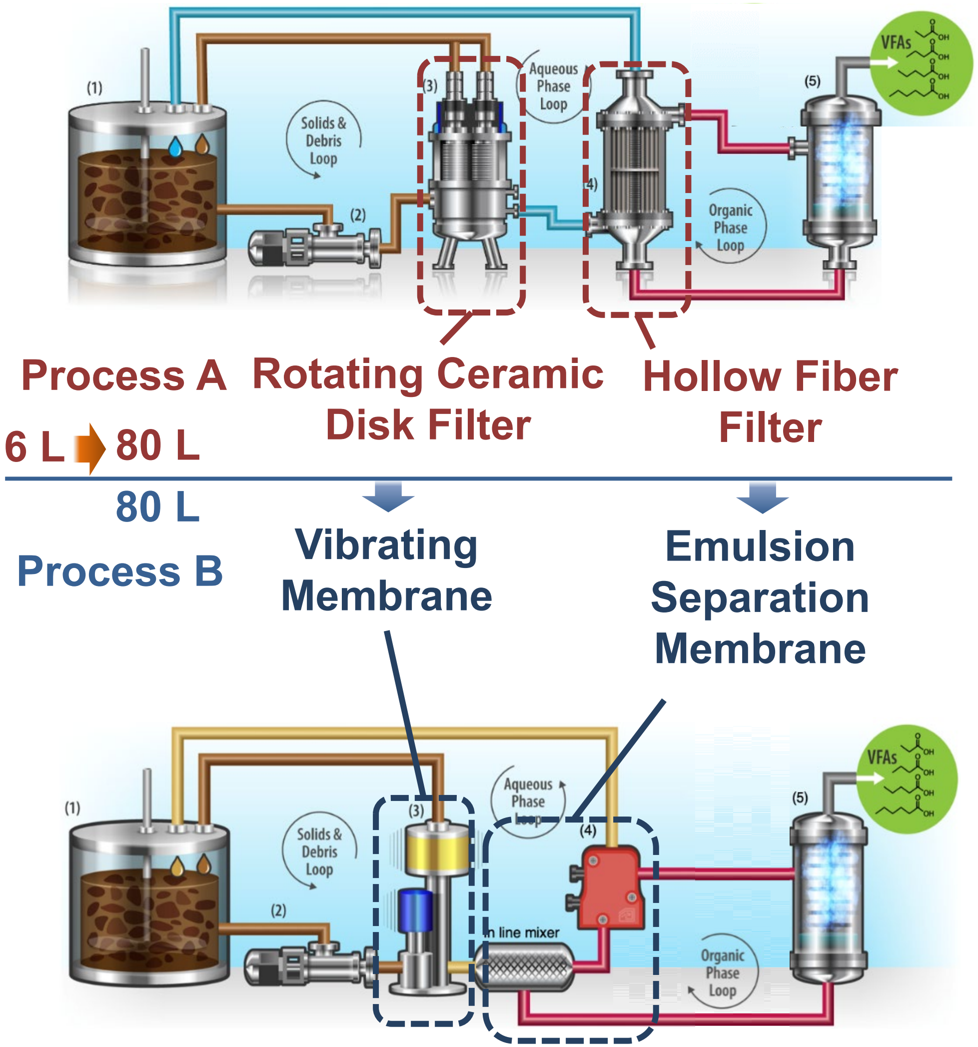




Items	Baseline[1]	Proposed
Feedstock	TS of 1-3%	TS of 10-18%
	Limited to Thin stillage	Food waste applicable
SAF potential	5% of demand	20% of demand
Energy Consumption	160 kWh/kg	0.72 kWh/kg
	222% higher heating value of VFA	18-22% higher heating value of VFA
GHG footprint	-54.7 g CO_2 eq/MJ	As low as -120 g CO_2 eq/MJ

[1] J. M. Carvajal-Arroyo, et. al., Chemical Engineering Journal 416 (2021) 127886

1 – Approach: Innovations



Technology	Advantages
Rotating Ceramic Disk (RCD)	•Sterile permeate •Low energy consumption •Permeate withdraw in high solids up to 20%
Hollow Fibers	•High mass transfer rate •Rapid VFAs extraction
Vibrating Membrane	•70% less capital expense than RCD •80% less maintenance cost than RCD
Emulsion Separation Membrane	•Direct scale up to 40L/min •10X lower capital expense than hollow fibers •High membrane flux and extraction rate

1 – Approach: Go/No-Go Decision Points

Go/no Go #1 (Quarter 1)

- Proof data and time on stream data for high solids ISPR system with solids content > 10 wt.%.
- Deliver equipment inventory and baseline key performance parameters of equipment.
- Present baseline data of titer > 5 g VFAs /L, productivity >0.5 g/L/day, separation efficiency >80%, energy efficiency < 50% of the higher heating value of the VFA product
- Present initial TEA / LCA using data from the 6L scale that demonstrates a pathway to SAF at < $5/gallon from solid food waste and compare this to the current arrested anaerobic digestion SAF price points which are generally > $7/gallon.

Go/no Go #2 (Quarter 6)

Using the commissioning data, TEA shows the ability of integrated system to achieve the Subtopic 3a specific metrics; specifically

- energy consumption of < 50% of the State-of-the-art AAD systems,
- continuous operation for more than 100 hours with throughput great enough
- to obtain at least 1 kg of purified VFA product, VFA recovery (>80%), and VFA purity (>95%) needed for catalytic upgrading.

1 – Approach: Risk Mitigation Plan

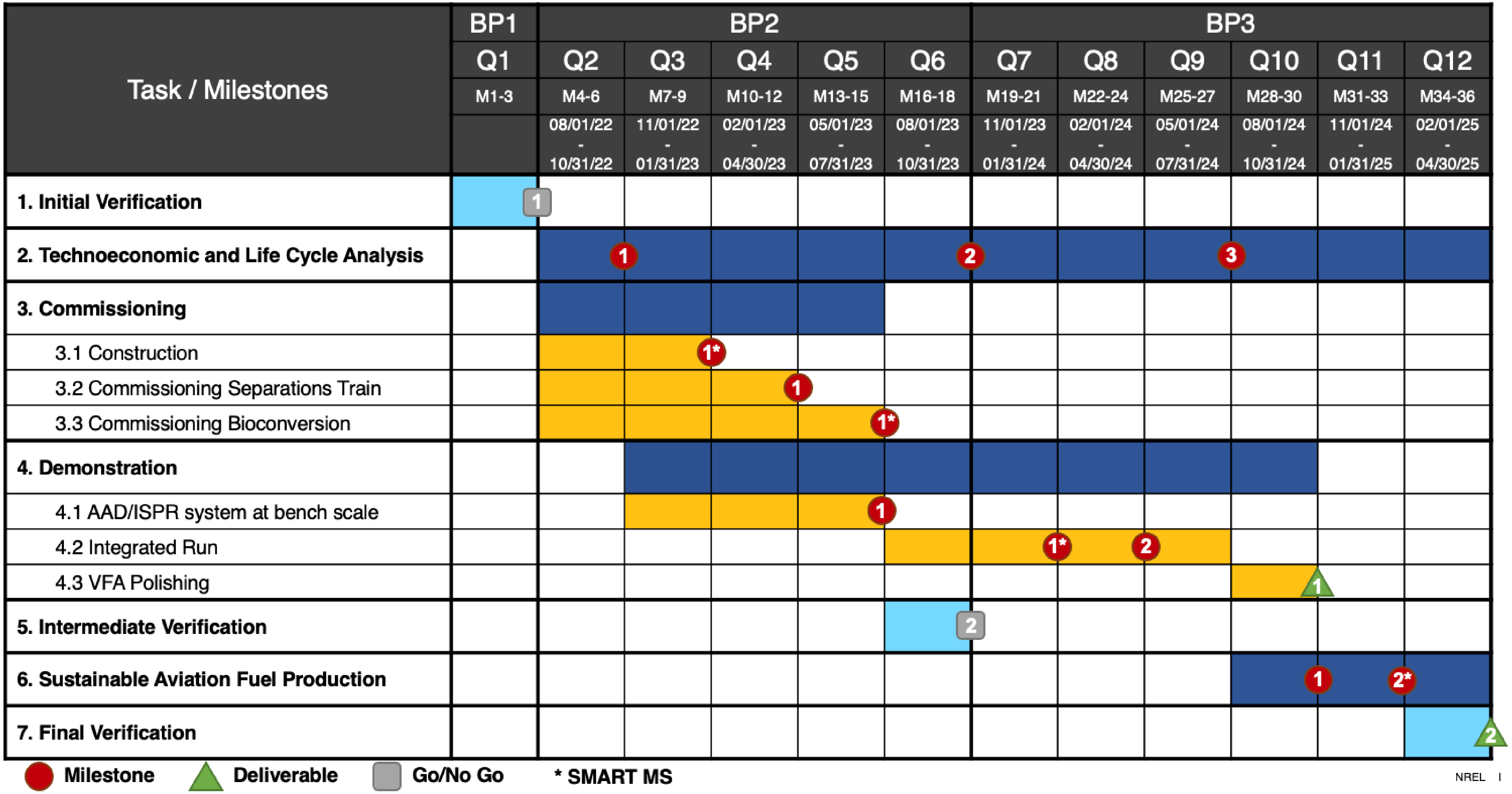
Risk	Mitigation	Severity
Vibrating membrane filter does not exhibit equivalent or greater flux per area than the Rotating Ceramic Disk Filter unit at > 13 wt.% solids loadings.	The team will revert to using the Rotating Ceramic Disk Filter unit as a high solids cell and debris retention device.	Minor
Emulsion separation membrane does not allow greater or equivalent throughput to the hollow fibers.	The team will have larger scale technologies available or revert to using the hollow fibers.	Minor
Chain elongation is not present in the bioreactor culture.	The team will institute a two-stage bioreactor design wherein the first reactor facilitates food waste hydrolysis and the second stage facilitates chain elongation. Literature demonstrates that consistent pH ~4.5 allows stability for this culture.	Moderate

Cell Reports Physical Science, 2021, 2 (10), 100587. DOI: 10.1016/j.xcrp.2021.100587
Green Chemistry. 2018, 20, 1791-1804, DOI: 10.1039/C7GC03747C

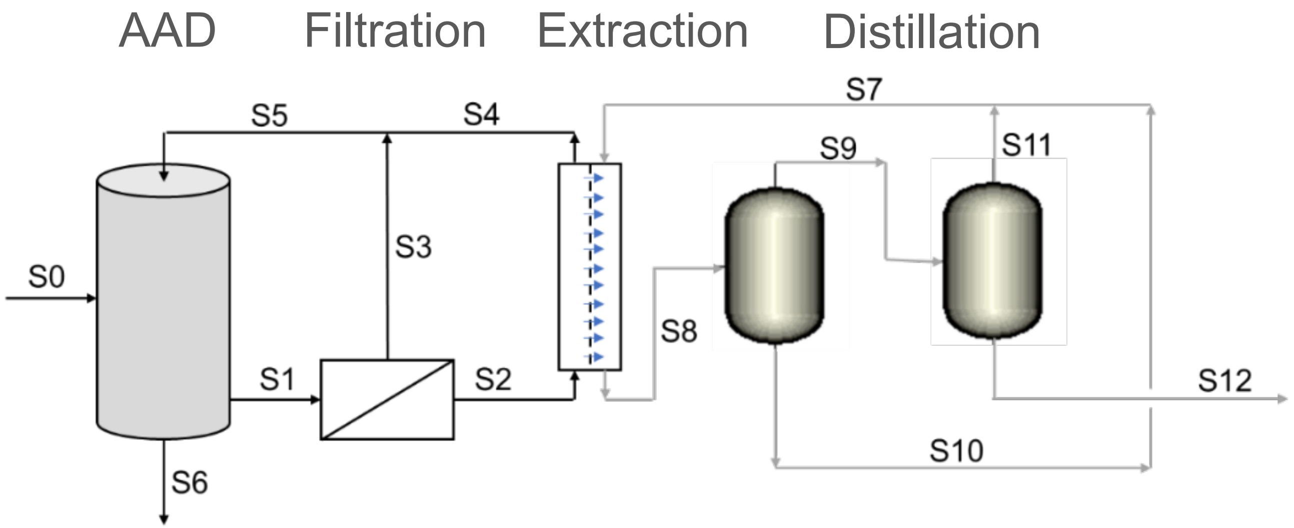
1 – Approach: Diversity, Equity, and Inclusion (DEI) Plan

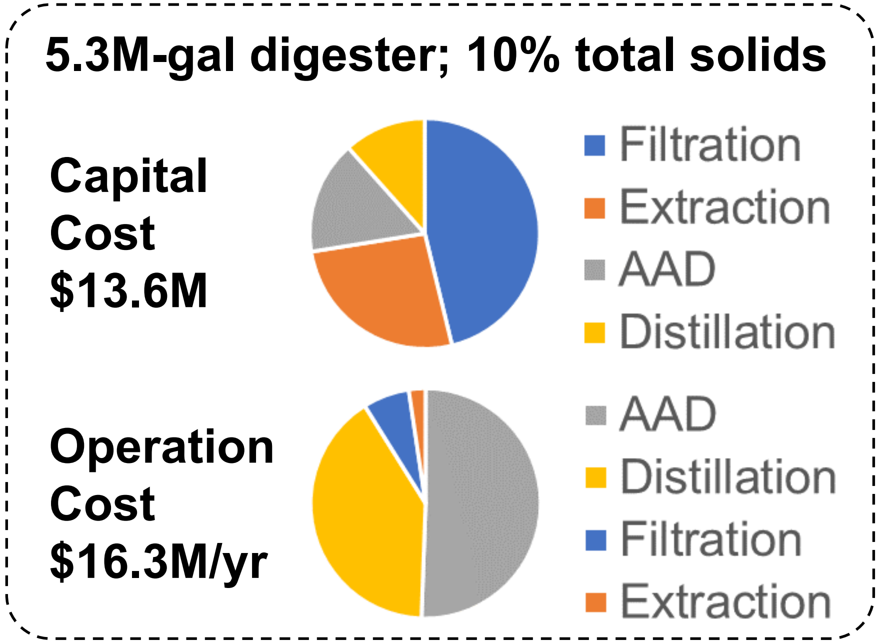
DEI Milestones	Milestone Description	Due Date	Completion	Accomplishments Achieved
1	Include >1 individual from underserved communities to the project as key personnel	07/31/2022	100%	• Three scientists who have Asian identity work on this project as Principal Investigator (PI)/key personnel.
2	Include >1 women staff and/or women-owned business to the project	10/31/2023	100%	• Three women scientists work on this project as Co-PI/key personnel. • One female co-founded company joined this project as a partner.
3	Include student(s) from underrepresented groups and/or underserved communities as intern.	04/30/2025	N/A (next budget period)	• N/A

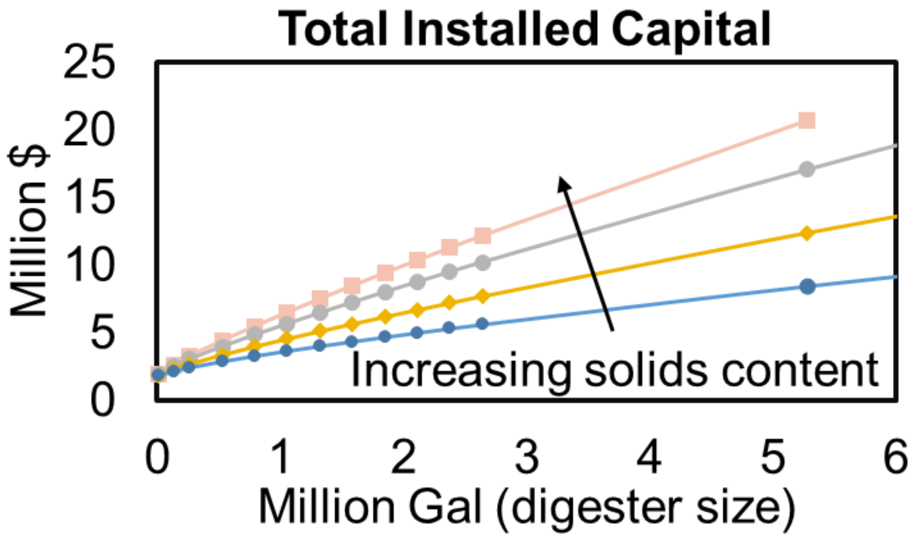
2 – Progress and Outcomes: Tasks and Milestones Overview

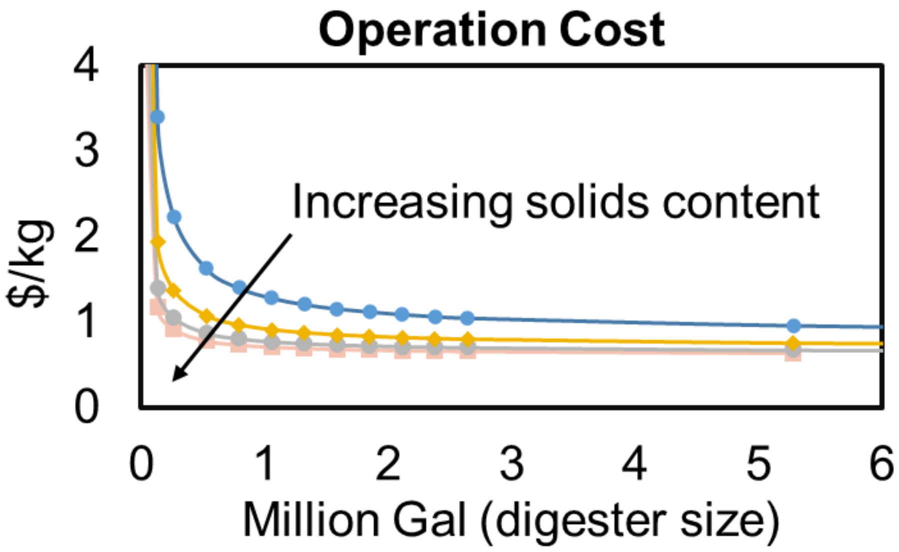


2 – Progress and Outcomes: Whole process TEA (nth plant) (Task 2)



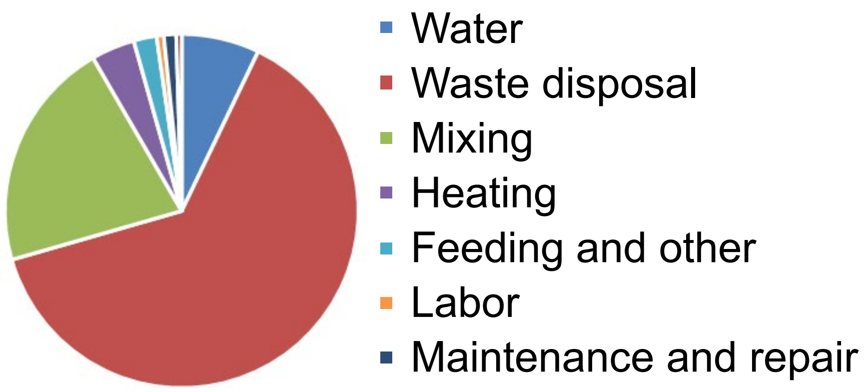




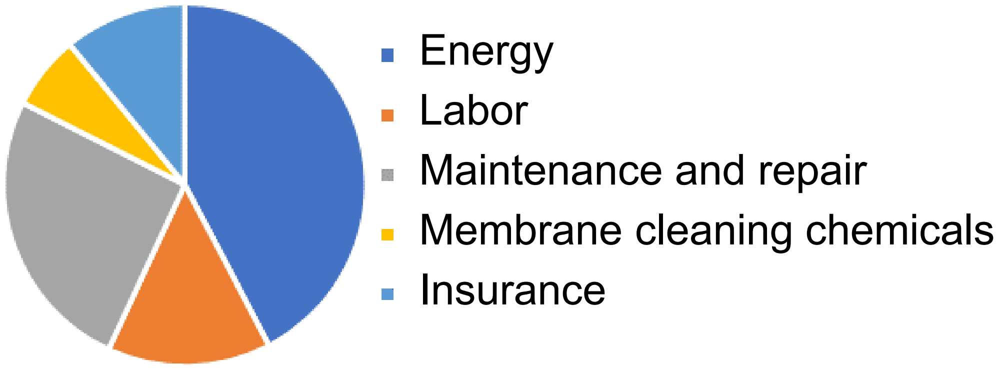


2 – Progress and Outcomes: Individual component TEA (Task 2)

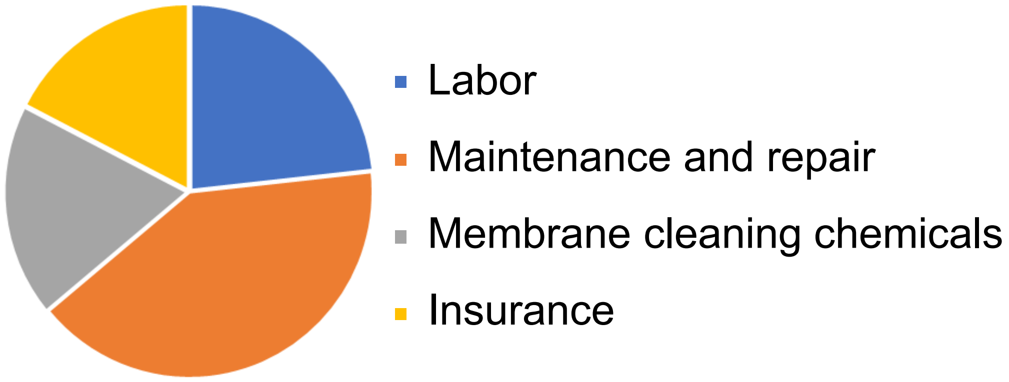
5.3 M gal, 10% total solids



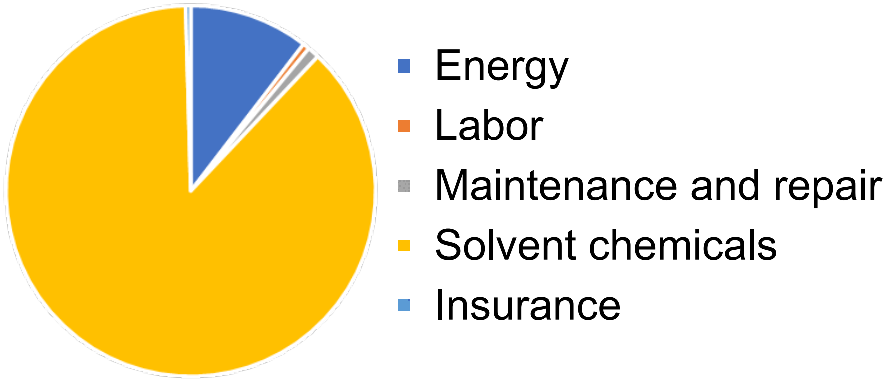
AAD $8.43 M/yr



Filtration $1.09 M/yr



Extraction $0.14 M/yr

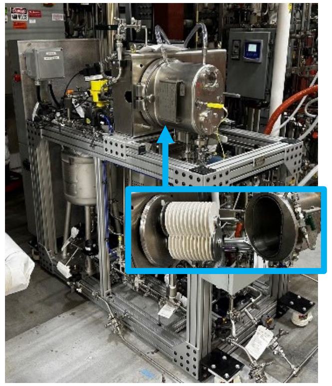


Distillation $6.76 M/yr

2 – Progress and Outcomes: Construction (Task 3)

- Process A Buildout: 98% accomplished


Anaerobic Digester ✓


Rotating Ceramic Disk ✓


Hollow Fiber ✓

Flash Distillation ✓

- Process B Buildout: 75% accomplished


Anaerobic Digester ✓


Vibrating membrane ✓

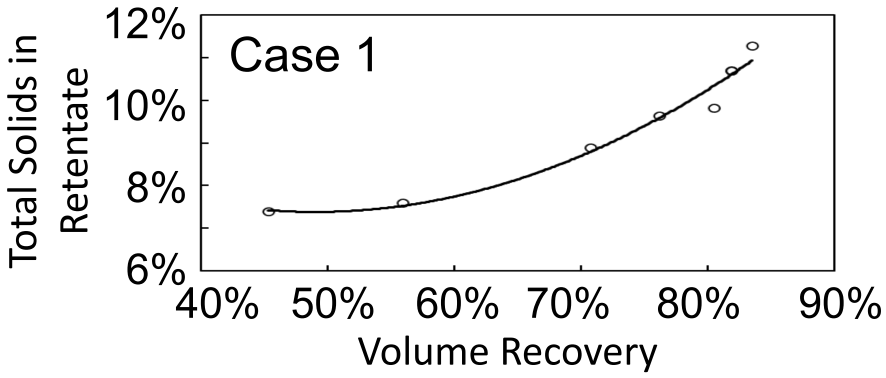
In fabrication


Emulsion Separation

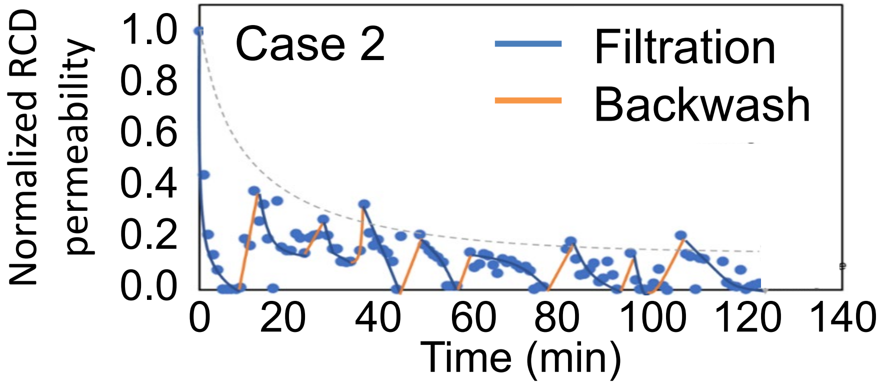
Flash Distillation ✓

2 – Progress and Outcomes: Rotating Ceramic Disk Commissioning (Task 3)

Feed solution	Case 1	Case 2
Feed solution	Enzymatic hydrolysate	Fermentation broth
Total Solids (TS) (%)	6.66	6.89
Insoluble solids (%)	1.77	0.45
Soluble solids (%)	4.89	6.44
Operating Conditions		
Disk rotating speed (rpm)	750 rpm	750 rpm
Water recovery (%)	45-83	45-83
Feed flow rate (L/min)	1.13-3.05	2.05
Retentate TS (%)	up to 11.3	~7.8
Performance		
Insoluble solid in permeate (%)	<0.01	<0.02
Insoluble solid rejection (%)	99.5-100	95.6
Total solid rejection (%)	9.3-12.8	9.3-12.8



EH: System plugged. **Not expecting same issues with broth.**



ABF: Severe membrane fouling observed. Fouling mitigation strategies will be applied, and **fouling should be less severe with "live" broth**.

2 – Progress and Outcomes: Feedstock Characterization (Task 3)

Items	Result	Unit
Basic characteristics		
Density	1.3	kg/L
Total solids	**61.7**	%
Moisture	38.3	%
Volatile solids	**99.6**	%-dry
Ash	0.4	%-dry
Chemical oxygen demand	1,100,000	mg/kg-dry
Total carbon	437,601	mg/kg-dry
Sugar profile		
Total sugar	**777,706**	mg/kg-dry
Glucose	774,753	mg/kg-dry
Galactose	2,119	mg/kg-dry
Arabinose	835	mg/kg-dry
Xylose	-	mg/kg-dry
Fructose	-	mg/kg-dry

Items	Result	Unit
Macronutrients		
Nitrogen	**272**	mg/kg-dry
Phosphorus	109	mg/kg-dry
Potassium	334	mg/kg-dry
Sulfur	188	mg/kg-dry
Ammonia-N	103	mg/kg-dry
Sodium	1,740	mg/kg-dry
Calcium	41	mg/kg-dry
Magnesium	24	mg/kg-dry
Iron	5.8	mg/kg-dry
Aluminum	3.1	mg/kg-dry
Heavy Metals		
Zinc	0.41	mg/kg-dry
Other metals	<PQL	mg/kg-dry

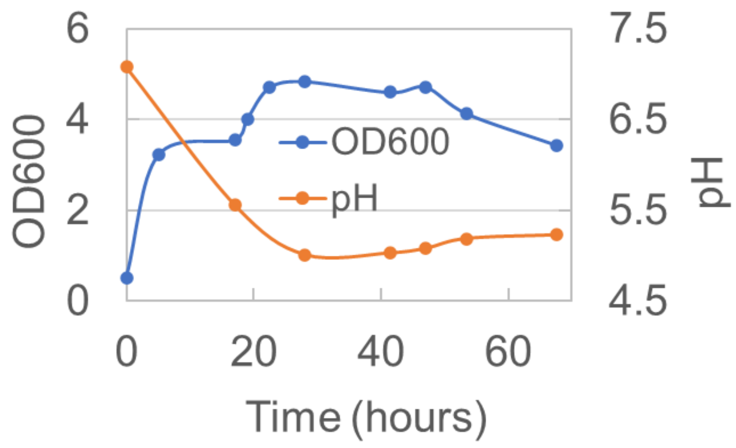
- High total solids and high volatile solids
- Mainly carbohydrates and moisture
- Glucan (either glucose or starch or both)
- Highly digestible carbon source

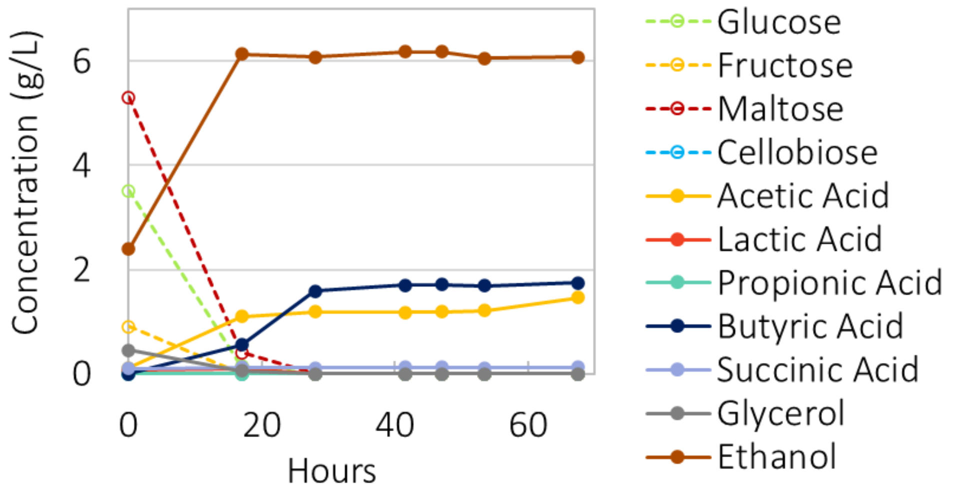
- Low levels of macro- and micro-nutrients
- Carbon to nitrogen ratio 1,500
- Zero cost nitrogen source has been identified for balancing the carbon to nitrogen ratio

2 – Progress and Outcomes:

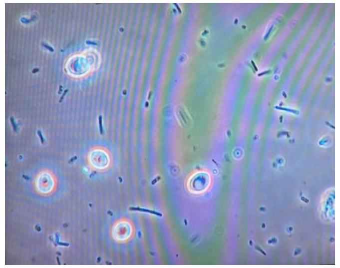
Utilization of food waste with chain elongation organisms (Task 3)

Caproiciproducens sp. 7D4C2

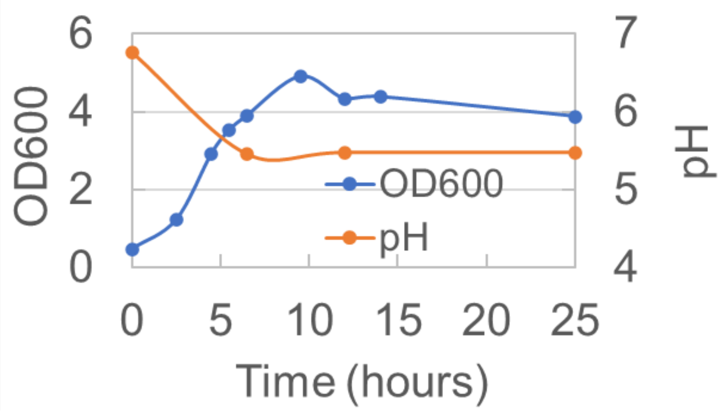


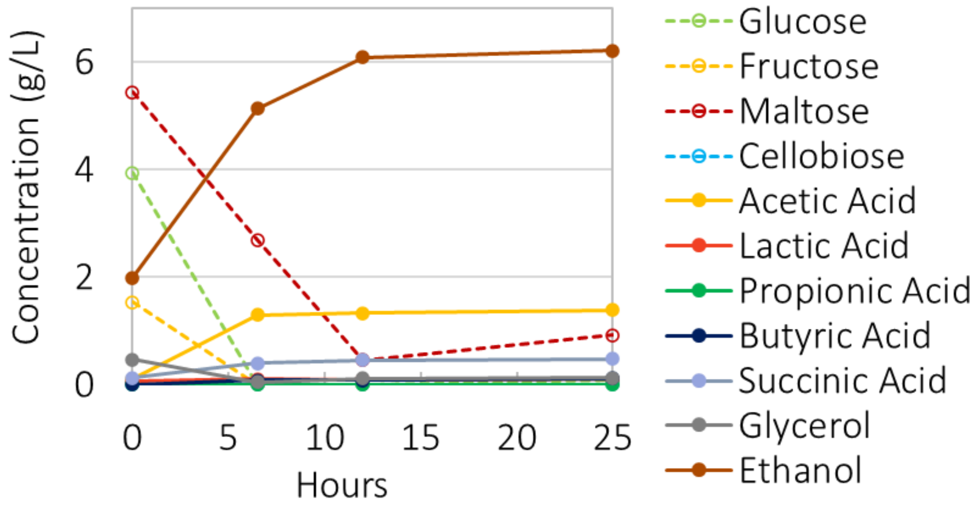


Hour 19

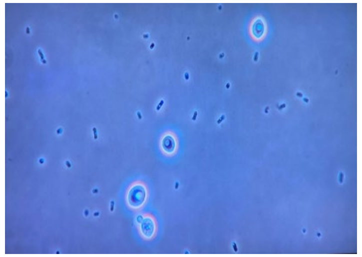


Actinobacillus succinogenes





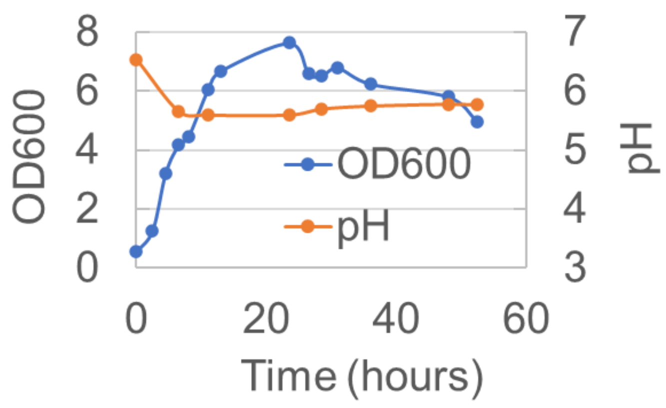
Hour 25

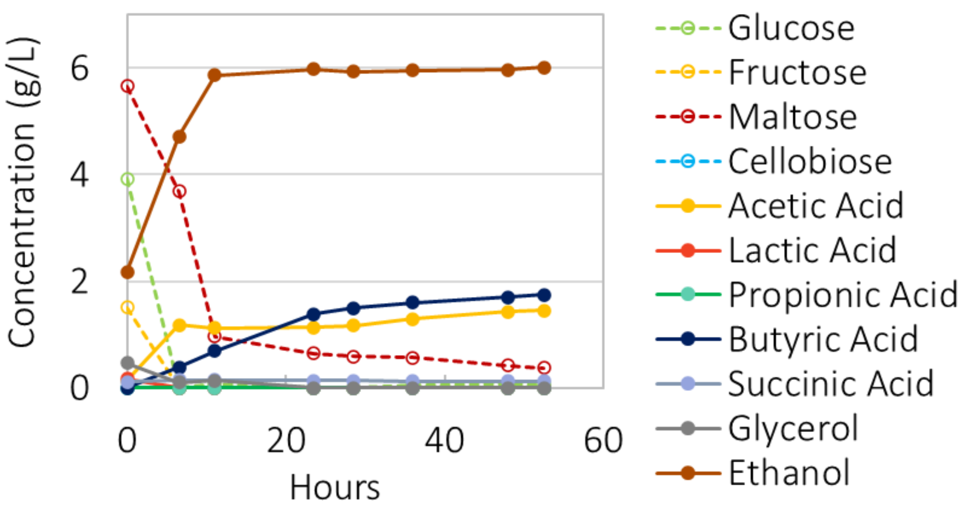


2 – Progress and Outcomes:

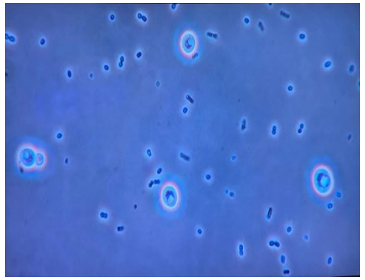
Utilization of food waste with chain elongation organisms (Task 3)

Megasphaera elsdenii

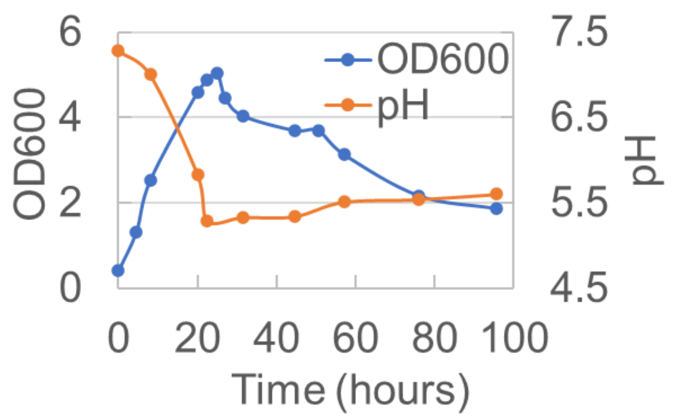


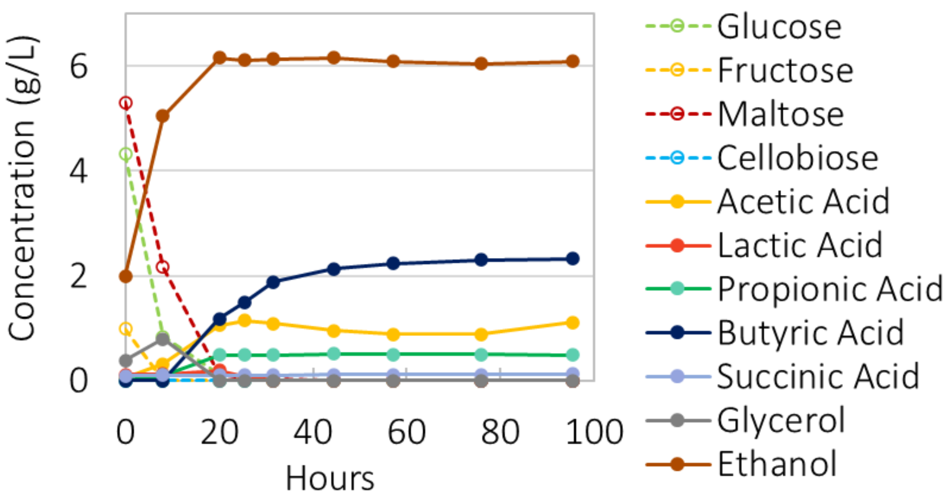


Hour 23

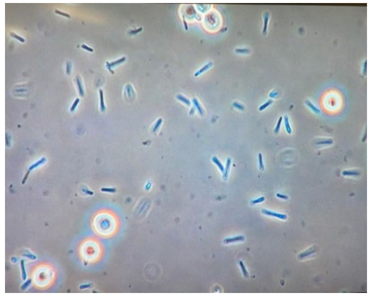


Caproicibacter fermentans





Hour 25



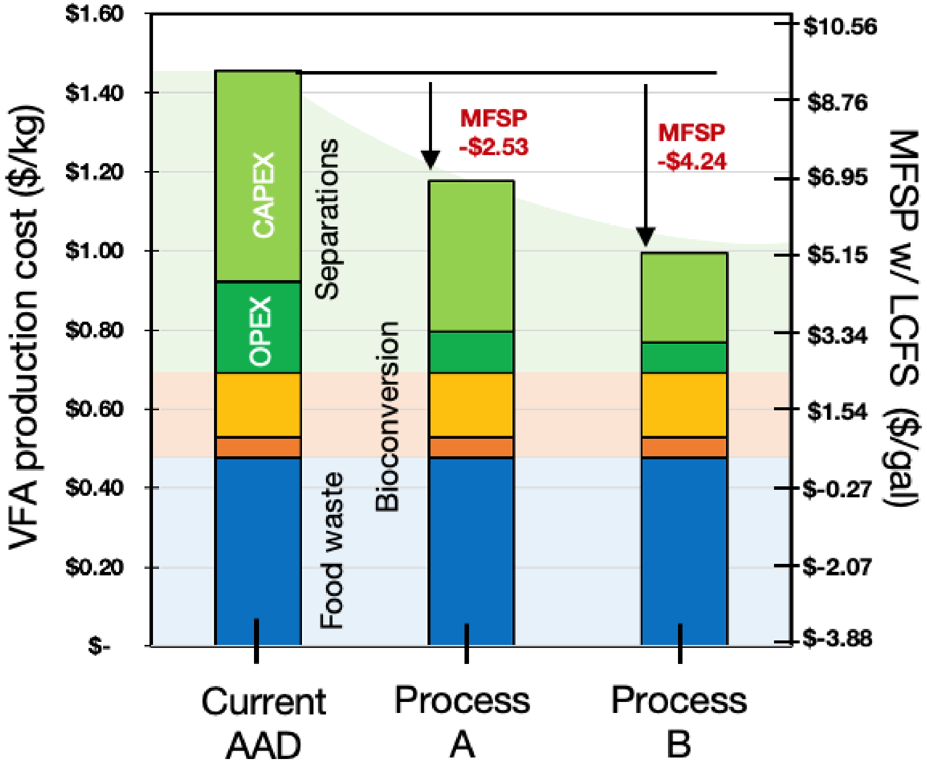
2 – Progress and Outcomes: Status of milestones in current budget period (BP2)

No.	Milestone Description	Planned End Date	Completion
2.1	Process model of pilot scaled AAD/ISPR system (at 80-L and Nth plant) with mass balances, energy balance, feed rates, and quantify costs differences between the proposed system and the risk mitigation strategies.	10/31/22	100%
2.2	Report TEA, energy analysis, and LCA of the integrated process using the mock solution data from M3.3.1.	10/31/23	50%
3.1.1	Complete buildout of integrated AAD/ISPR system at QEG's facility. Demonstrate the system's ability to operate at > 10wt.% solids and process the entire 80 L digester working volume through the separations system every 30 h.	01/31/23	80%
3.2.1	Complete buildout of integrated separations train. Demonstrate the separations system's ability to recover > 95% pure VFAs from mock solutions from continuous operation in an 8hour working day.	04/30/23	60%
3.3.1	Demonstrate the full functionality of the entire integrated process at the 80-L scale at QEG's facility using food waste at > 10wt.% solids loading for an entire 8 hour working day at > 80% recovery. Report the performance of both the Disk and Vibratory membrane system and select the most appropriate device in terms of achieved permeance and cost.	07/31/23	0%

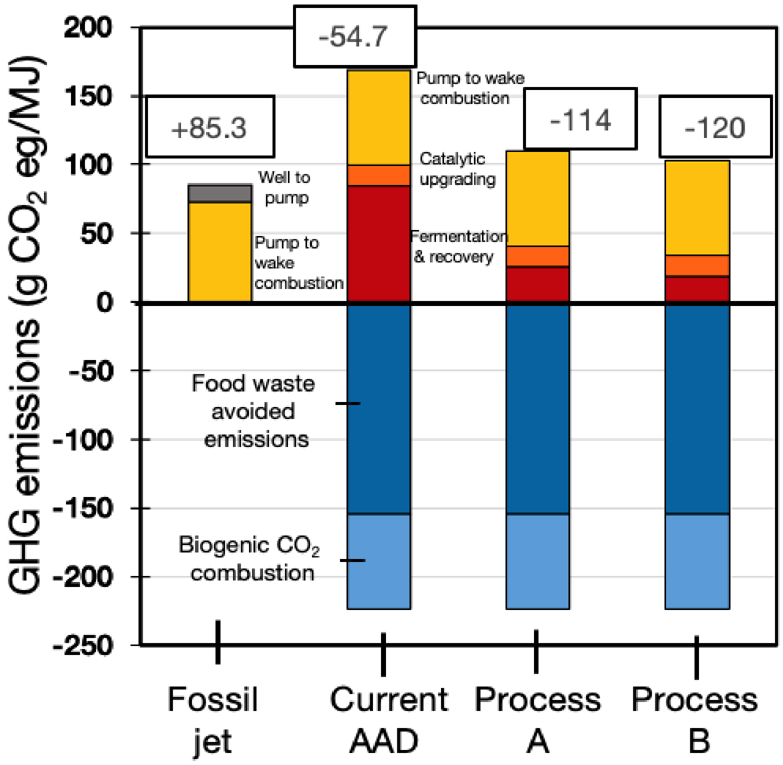
3 – Impact: Value proposition for the proposed work

❖ Advance separations trains to make cost-effective & carbon-negative SAF from food wastes

VFA production cost and resulting SAF MFSP



Resulting GHG emissions from SAF



- Reduce separation system costs by ~52%
- VFA price points < 1$/kg
- SAF Minimum Fuel Selling Prices (MFSP) of ~$5.00/gal

- Process A GHG footprint: -114 g CO_2 eq/ MJ
- Process B GHG footprint: -120 g CO_2 eq/ MJ

3 – Impact: Data Dissemination

- The team will disseminate research outcomes to the public *via* workshops, websites, and publications.
- Before data dissemination, the plan or publication will be reviewed and agreed by the intellectual property owner(s).
- All parties have executed a Non-Disclosure Agreement (NDA) for collaboration.
- New intellectual property potential and several scientific publications are anticipated to be generated during the execution of this project.
- All project members are required to maintain up-to-date records of their data, publications, and presentations to ensure those documents are accessible to all members at all time.

Summary

- **Background**
  - Waste to volatile fatty acid (via arrested anaerobic digestion) to sustainable aviation fuel
  - Difficulty in solids handling and high cost in separation process
- **Approach**
  - National Renewable Energy Laboratory's patented high solids separations technology
  - Integration of unique strengths of partners (digestion, filtration, extraction, fuel production…)
- **Innovation**
  - Process A: Rotating disk + Hollow fiber
  - Process B: Vibrating membrane + Emulsion Separation
- **Progress**
  - Process model developed with risk mitigation strategies
  - 50% completion in system construction and 30% completion in commissioning
  - Feedstock initial characterization completed with preliminary evaluation of biological conversion
- **Impact**
  - Reduce separation cost by >50%
  - Reduce GHG footprint to -120 g CO_2 eq/ MJ

Quad Chart Overview

Timeline
- *Project start date: 10/1/2021*
- *Project end date: 4/30/2025*

	FY22 Costed	Total Award
DOE Funding	*(10/01/2021 – 9/30/2022)* *$114,032*	*(negotiated total federal share)* *$3,500,000*
Project Cost Share	$44,375	$880,000

TRL at Project Start: 3
TRL at Project End: 5

Project Goal
A pilot-scale demonstration of the NREL patented high solids separations technology (US patent 63/020,598) to separate VFAs from digester and produce a Sustainable Aviation Fuel (SAF) product.

End of Project Milestone
Deliver techno-economic analysis report on the entire system economics for producing VFAs from the integrated system and their subsequent SAF product. Identify key cost drivers of the process and an MFSP estimate at the pilot scale and Nth plant.

Funding Mechanism
DE-FOA-0002396 Subtopic Area 3a Separations to Improve Arrested Anaerobic Digestion Process Development

Project Partners
- National Renewable Energy Laboratory
- New Logic Research
- Zaiput
- Alder Fuels