DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

Develop an efficient and cost-effective novel anaerobic digestion system producing high purity of methane from diverse waste biomass

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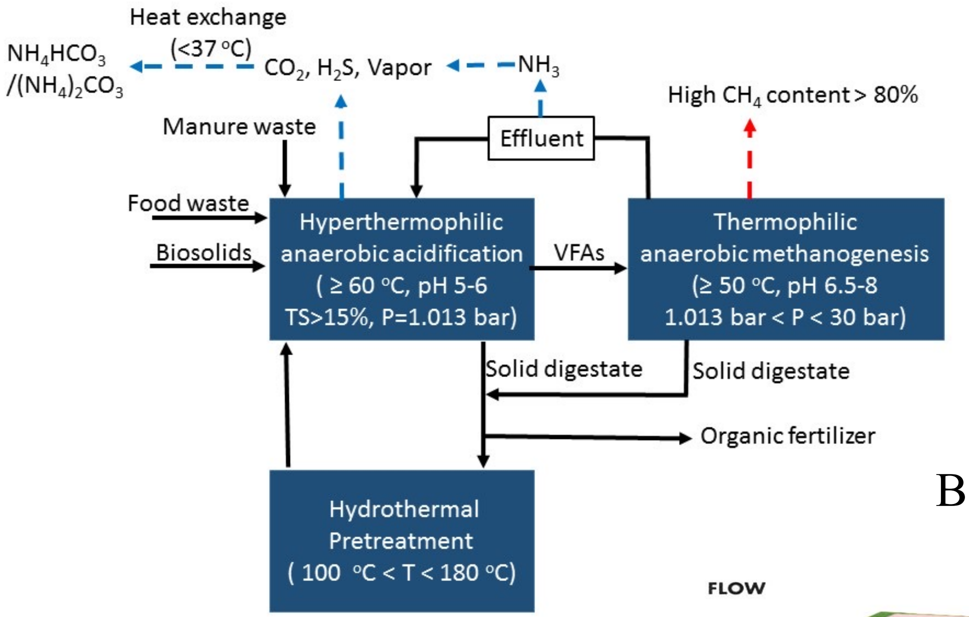
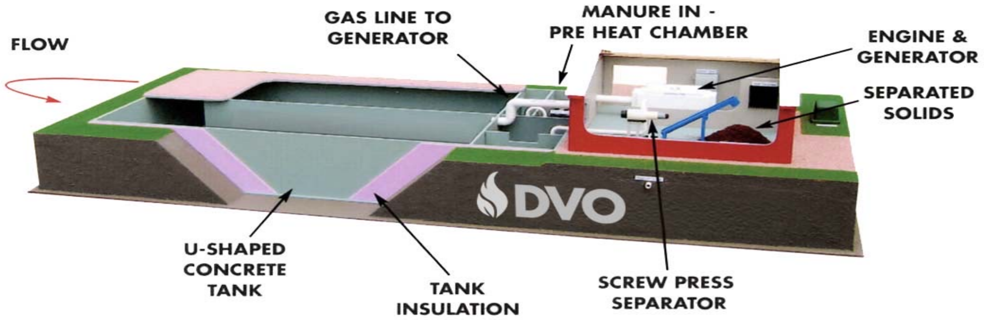
Project Overview

- **Founding program:** Fiscal Year 2019 Commercial Trucks and Off-Road Application FOA (DE-FOA-0002044): Two project periods: P1: 10/1/2020-9/30/2022; P2: 10/1/2022-9/30/2024.
- **Project goal:** To reduce the production cost of pure biomethane derived from waste through anaerobic digestion (AD) by pretreating recalcitrant feedstock and intensifying core processes.
- **Relevance to BETOs' goal**: advance the state-of-the-art technology to convert organic waste to renewable natural gas.
- **Technical barriers that dictate the high production cost of renewable natural gas**
  - Slow disintegration and hydrolysis of recalcitrant feedstocks in conventional AD leads to low productivity – high production cost.
  - Low methane content of biogas produced from AD requires downstream purification – additional production cost.
  - Waste rich in protein results in high ammonia concentration that inhibits the process – low productivity and high production cost.

Intensified Versatile Anaerobic Digestion (IVAD) System – Overall Process



Base Line Technology



Novel Approach for Overcoming Barriers

- Biomass heterogeneity and low methane yield: employing a hydrothermal Reactor unit to treat the recalcitrant solid digestate to improve digestibility.
- Hydrolysis as a limiting step and low reaction rate of anaerobic digestion process: Using hyperthermophilic anaerobic acidification reactor (AAR $\geq 60^{o}$C) for high-rate conversion of organic waste into volatile fatty acids (VFAs).
- Low productivity and low methane purity: using a pressurized thermophilic anaerobic methanogenesis reactor (AMR, $\geq 50^{o}$C) for accelerated transformation of the VFAs into high purity methane.
- Ammonia inhibition: Recovering ammonia nitrogen to reduce inhibition and producing fertilizer as a co-product.

Management: Project Execution, Risk Mitigation and Communication

- *Technical risks and mitigation strategies*
  -Synergizing biological and hydrothermal processes to reduce inputs
  -Taking a holistic approach to optimizing the overall system
  -Capitalizing on the experience of industrial partners to lower engineering risks

- Active participation of experienced industrial partners to provide reality check in technology research and development and scale-up

- Emphasize planning and communication
  -Written plans for managing project, intellectual property, and data
  -Regular weekly among the research team, and monthly and quarterly meetings involving industrial partners and DOE project manager
  --Using Basecamp as a project management platform to assure efficient execution

Target Performance Metrics

Parameters	Base-line Technology	Target improvement	Degree of improvement
LCOE (cent/kWh)	26.9	11.6	Improved > 25%
EROI	2.76	5.15	Improved > 25%
AD hydraulic retention time (days)	22	7	Reduced to third
Biogas Yield (m^3/ton VS) (Methane Yield 60%)	230 (138)	345 (207)	150%
*Baseline conditions: Current DVO mixed plug flow digester cost for 2000 cow dairy producing 21 dry ton manure waste per day.			

I. LCOE (levelized cost of Energy), EROI (Energy return on investment)

II. Theoretical methane yield of dairy manure (400– 450 m^3/ton VS)

Varol, A. and Ugurlu, A., 2017. Comparative evaluation of biogas production from dairy manure and co-digestion with maize silage by CSTR and new anaerobic hybrid reactor. *Engineering in Life Sciences*, *17*(4), pp.402-412.

Progress and Outcomes: Meeting Overall Project Goals and Timeline

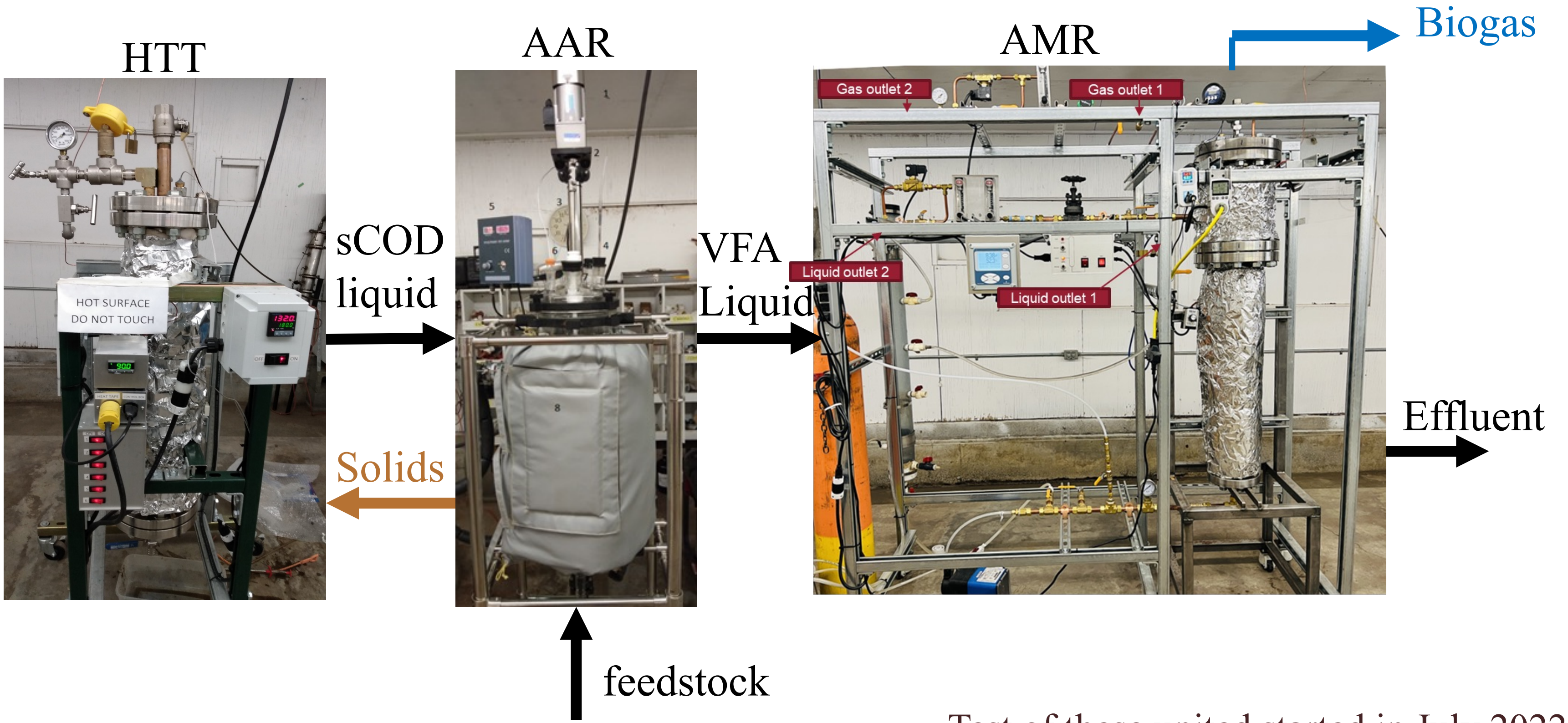
- Reached all six milestones scheduled for Budget Period 1. Three more milestones remain for Budget Period 2.
- Lab and bench scale performance of the unit operations supports the concept.
- Updated TEA provides positive predictions for the LCOE (levelized cost of Energy), EROI (Energy return on investment).
- Study on microbial communities and the associated enzyme system support the stability and superior performance of the hyperthermophilic acidification process.
- Bench scale system provides critical information for the design and operation of the pilot system.

Progress : Passed the Go/No-Go decision point

- ***Reaching the specified milestones***
  -Manure soluble COD reaches 80% ✓
  -Food waste soluble COD reaches 90% ✓
  -VFA productivity achieving 150% of baseline technology ✓
  -Total ammonia nitrogen maintained below 1,700 mg/l ✓
  -Biogas productivity achieving 150% of baseline technology ✓
  - Methane purity reaches 75% ✓

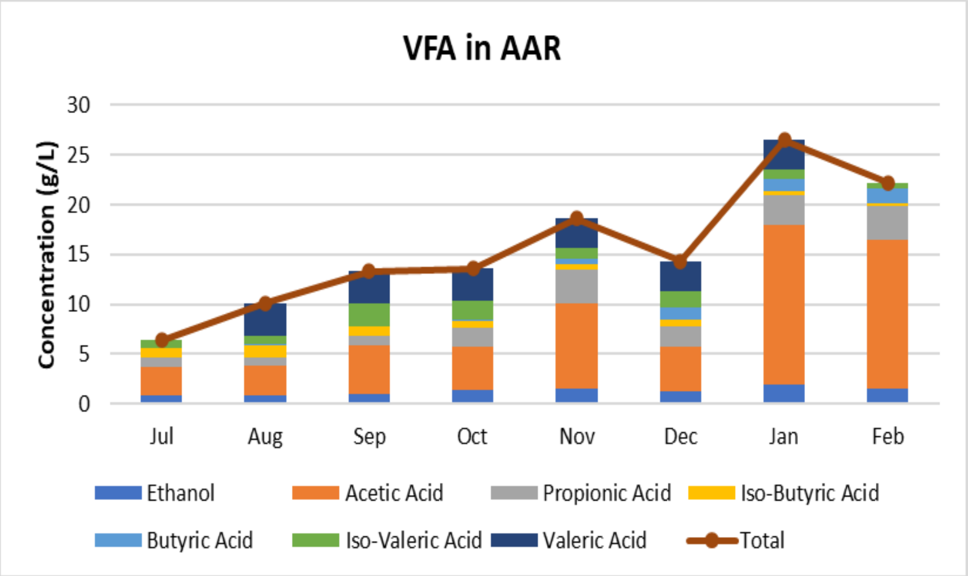
- ***Achieving reducing the levelized cost of energy (LCOE) and Energy Return on Investment (EROI) by 25% of the baseline technology, which is the mandated goal by the FOA***

Progress: integrated bench-scale system further prove the concept



Test of these united started in July 2022

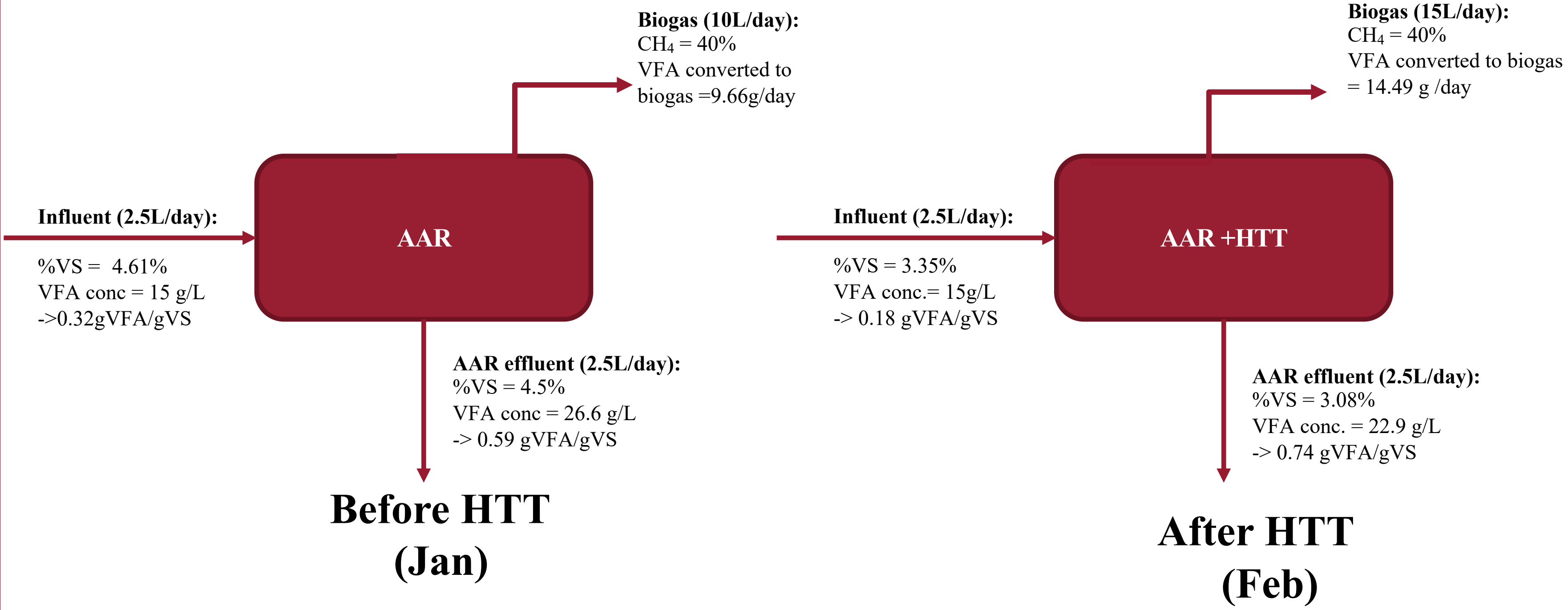
Performance of the bench-scale system: VFA productivity



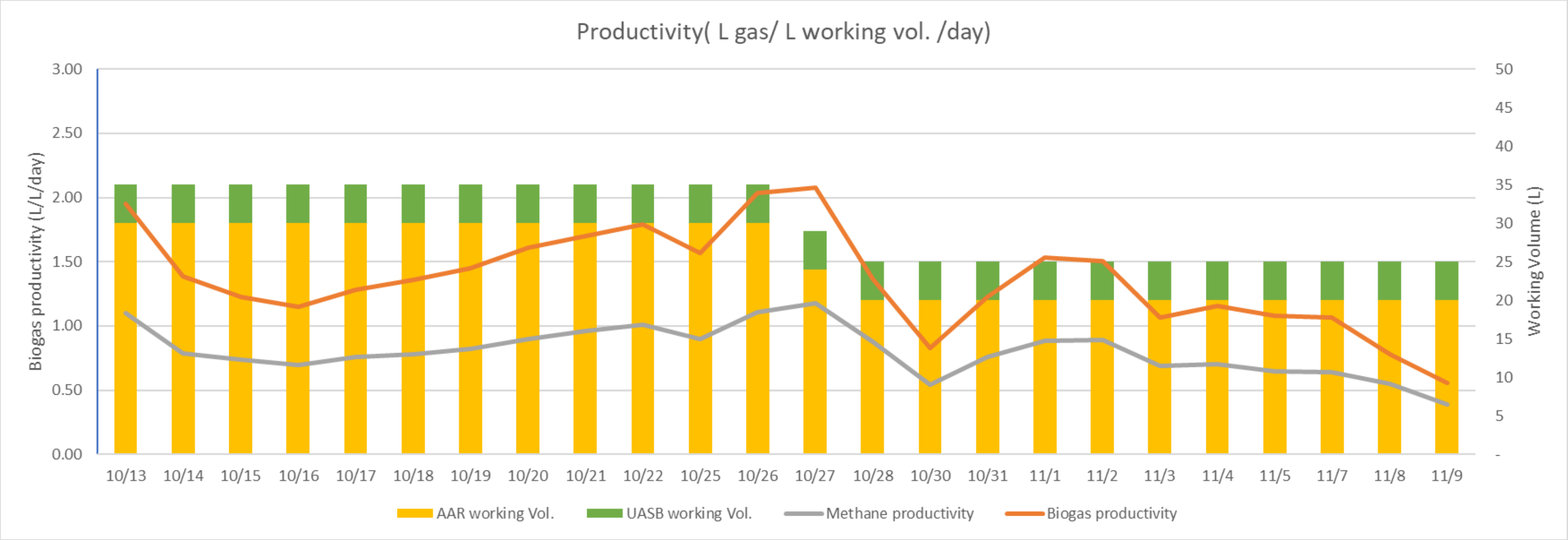
Month	VFA Conc (g/L)	gVFA/gVS	VFA productivity (g/L/d)	Working Vol (L)	HRT
Jul	6.1	0.30	1.10	40	8
Aug	9.5	0.47	0.82	40	8
Sep	12.75	0.40	1.25	30	6
Oct	14	0.34	1.74	30	6
Nov	16.2	0.44	1.83	25	5
Dec	14.02	0.34	0.56	25	5
Jan	26.1	0.59	1.70	25	5
Feb	22.2	0.74	2.55	25	5

VFA produced in AAR every month

Implementing HTT Increased the VFA production in the Acidification Reactor

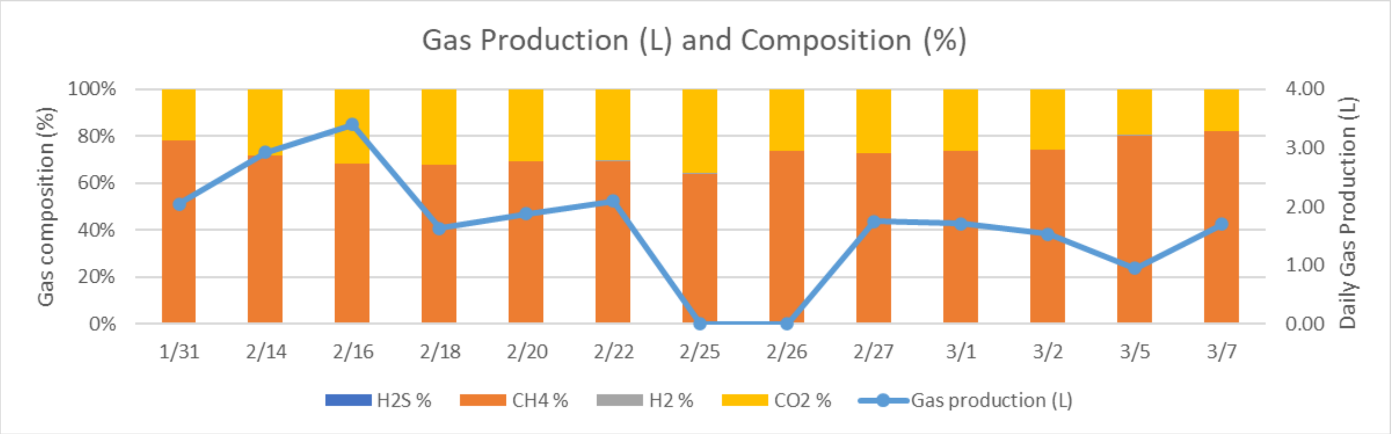


Progress: Performance of the Bench-scale System: Total Gas Productivity



- Total gas productivity calculation
  - Productivity (L/L/day)= Total daily gas production (L/day) / total reactor working volume (L)
  - The project milestone: 1.68 (m^3 biogas /m^3 vol. /d) or 0.96 (m^3 methane/m^3 vol. /d)
  - The peak were 2.07 (L/L/day) for biogas and 1.18 (L/L/day) for methane at 10/27
- Several peak days achieved milestones
  - 10/13, 10/21, 10/22, 10/26, and 10/27

AMR Performance - Gas Composition



- The gas composition was around 68.9 % before pressurized condition
  - The average of three sequential sampling day (2/18, 2/20, and 2/22)
- Under the pressurized condition (Setting pressure: 60 psi), the methane contents reached to 73.8% by increasing around 4.8% point
  - 73.6%, 72.6% and 73.8 % at 2/26, 2/27, and 3/1
- After slight pressure increase (65 psi from 3/2), the methane contents increased up to 82.8%
  - 74.1%, 80.3%, and 82.2% at 3/2, 3/5, and 3/7

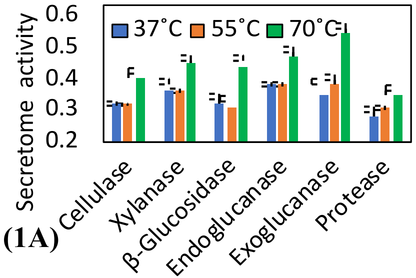
Highlights of the Updated TEA Results

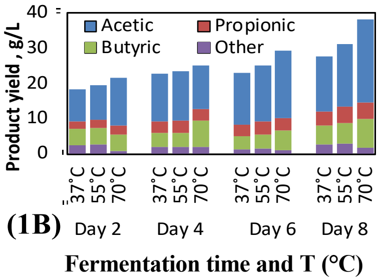
- Best case scenario: achieved biomethane productivity 184% of that of baseline technology
  - IVAD methane productivity: 1.18 m^3/m^3/day; baseline technology methane productivity : 0.64 m^3/m^3/day
- LCOE was reduced by 42% of the baseline technology > the Go/no-go decision point (25%).
  - IVAD LCOE: $10.40/MMTBTU; baseline technology LCOE: $18.05/MMTBTU
- EROI has increased by 87% of the baseline technology > the Go/no-go decision point (25%).
  - IVAD EROI: 3.19; baseline technology EROI: 1.71
- The calculation was based on performance data of the baseline technology provided by the industry partner, Aspen plus and a database, Excel spreadsheet for biorefinery economic analysis obtained from the National Renewable Energy Laboratory (NERL) website.

Hyperthermophilic microbiomes are enriched in hydrolytic bacteria and hydrogenotrophic archae

Distinct features and improved performance of hyper-thermophilic microbiomes

bacterial population of microbiome





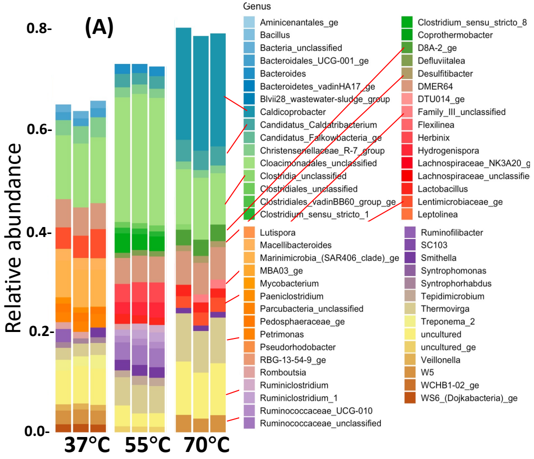
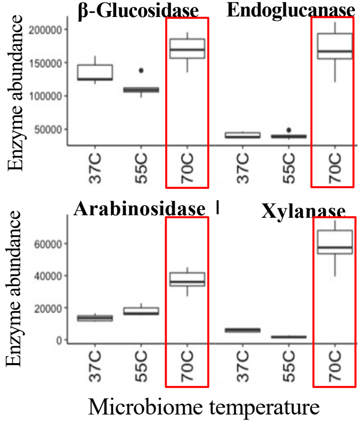


Fig 2. (A) Enrichment of hyper-thermophilic microbiome in hydrolytic bacteria



(B) Computationally predicted enzyme capacity of microbiomes

archaea population of microbiome

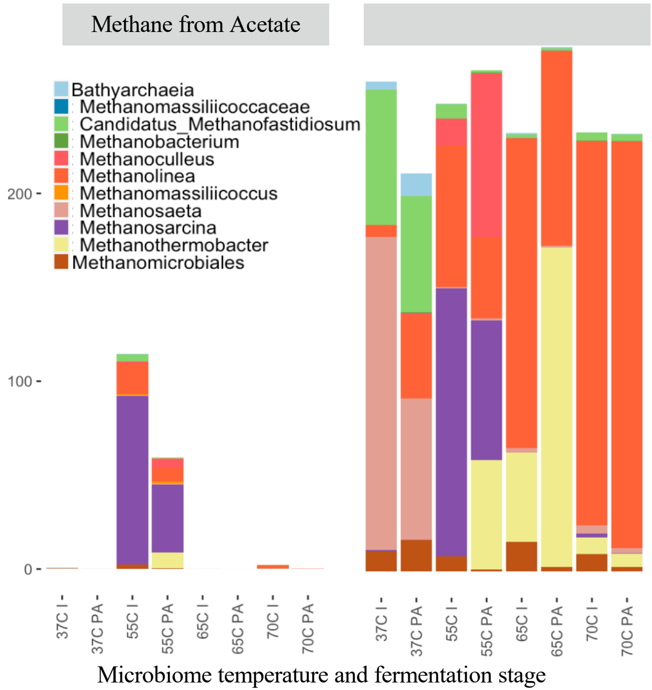
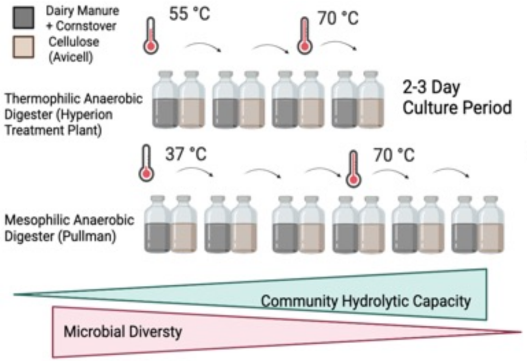


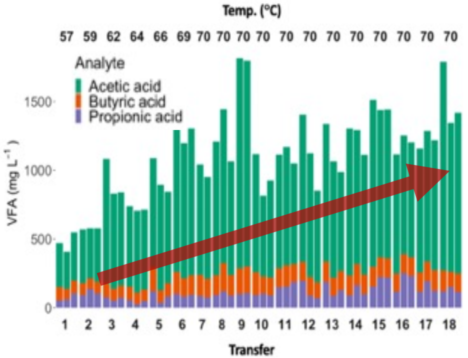
Fig. 3. Hyper-thermophilic methanogenic microbiome is dominated by hydrogenotrophic methanogens (methane from $CO_2 + H_2$)

Enriching Communities and Isolation of Single Species Based on Metabolic Function

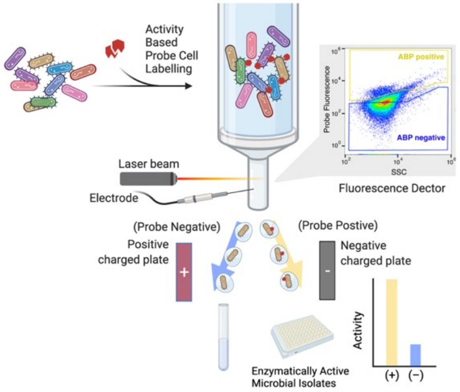
- DOE Office of Science EMSL Exploratory Grant awarded
- Develop and apply enzyme activity based enrichment/isolation tool
- Activity Based Probes (ABPs) label cells and proteins of specific function (*e.g.* hydrolytic enzymes)
- Fluorescence-Activated Flow Cytometry (FACS) allows sorting of lignocellulolytic target organisms
- Combine ABP-FACS with adaptation to hyperthermophilic T and lignocellulose utilization
- Proteomics applied to identify and characterize enzymes responsible for improved hydrolytic activity



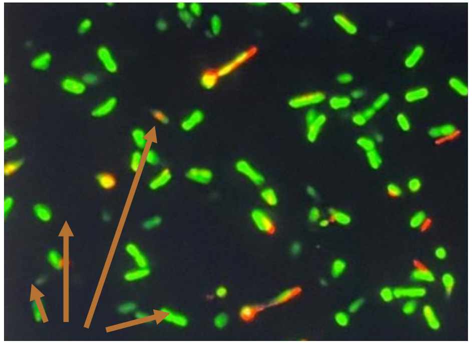
Preliminary adaptation of microbiome



Improved Hydrolytic capacity



ABP-FACS based isolation of microbes with specific function



Extracellular cellulolytic activity (red – extracellular enzymes)

Impact: Advancing AD Technology

- Advances AD technology to a new performance level by achieving the milestones and metrics demonstrated with the novel system
- Producing critical data for elevating the technology from TRL3 to TRL5, decreasing the risk of implementing
- Publishing the new knowledge discovered in journals and reporting project results in professional conferences contribute to the scientific and engineering communities
- Offering the novel AD system as a new platform for DOE's technology portfolio for the production of renewable natural gas from different types of municipal wastes
- Retrofitting the pretreating and acidification modules to the existing AD facilities improve the efficiency of these systems

Impact: Advancing AD Industry

- Success in this project will remove several key technical barriers that have constrained the potential of AD as an industry as a whole.
- Using the baseline data and engineering and scale-up assistance provided by our industry partners (DVO who has built most of the dairy anaerobic digesters in the US and Regenis as a major digester installer) makes the project highly relevant to the industry.
- DVO/Regenis are also providing very valuable feedback on the results and feasibility of the project.
- The keen interests and active participation of DVO and Regenis will accelerate the commercialization and adoption of the technology, enabling the utilization of a broader range of vast organic waste resources.

Quad Chart Overview

Timeline

- Project start date: October 1, 2020
- Project end date: September 30, 2024

	FY20 Costed	Total Award
DOE Funding	(10/01/2020 – 9/30/2022) *$894,963*	(negotiated total federal share) $2,234,051
Project Cost Share	$311,255	$558,842

Project Partners*

- Partner 1: PNNL, Richland Washington
- Partner 1: DVO Inc, Chilton, WI 53014
- Partner 2: Regenis, LLC, Ferndale, WA 98248

Project Goal

To reduce cost of pure biomethane derived from waste through anaerobic digestion (AD) through using diverse feedstock and process intensification

End of Project Milestone

Milestone 5.3.1: TEA and performance simulation (month 36)- Project will demonstrate conclusion on whether the project meet the performance targets: (1) the increase of digestion of mixed biowastes to 90%, (2) the increase of methane purity to 75%, and (3) improvements of levelized cost of energy (LCOE) and EROI over the baseline, by at least 25%.

Funding Mechanism

Application FOA (DE-FOA-0002044).

Fiscal Year 2019 Commercial Trucks and Off-Road Application

Next Steps

- Continue the evaluation and optimization of the bench-scale system to generate more data for the design of the pilot system
- Design, fabrication, installation, and evaluation of the pilot system to generate data for the design of the demonstration system
- Update TEA based on the performance data of the pilot system
- File IP protection of the technology
- Publish the results and disseminate the new knowledge
- Develop a plan and expand the partnership for technology transfer and commercialization

Summary

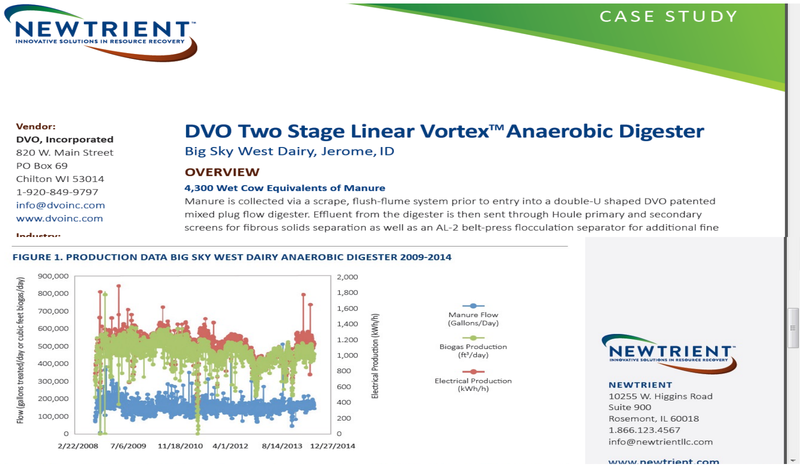
- This project aims at developing an AD system that integrates hydrotreating and in-situ methane purification so that diverse waste feedstocks can be accepted and needs for downstream processing can be reduced.
- The project has made good progress during Budget Period 1 and passed the Go/No-Go evaluation.
- The results to date have validated the concept of the technology. The technology in its entirety can expand DOE's technology portfolio. Its key component can be used to retrofit the existing AD facilities.
- With strong and active industry participation and using actual existing technology as baseline, this project is highly relevant to the industry, and the technology will be readily transferred if successful. It has the potential to produce significant broad impacts in advancing the industry.

Your questions and comments are appreciated

Additional Slides

Key Assumptions for TEA of IVAD System

- 4300-cow farm as baseline case
  - Fresh dairy manure (flow rate = 511 tonne/day or 35 dry tonne/day, TS=6.9%, Temperature=9.2 ^{o}C)
  - AAR (Temperature=70 ^{o}C, TS=15%, HRT=6 days)
    - VS destruction=46%
  - HTR (Temperature=180 ^{o}C, TS=10%, HRT=6 days)
  - TAMR (Temperature=55 ^{o}C, HRT=1 days)
  - MAMR (Temperature=37 ^{o}C, HRT=1 days)
  - Biomethane productivity is 184% of that of the baseline technology



Hydrothermal Treatment reactor (HTR) , Anaerobic Acidification Reactor (AAR), Thermophilic Anaerobic Methanogenic Reactor (TAMR), Mesophilic Anaerobic Methanogenic Reactor (MAMR), Hydraulic Retention Time (HRT), Total Solid (TS)

Responses to Previous Reviewers' Comments

- *Comment 1:* Concern that the incorporation of energy-intensive unit operations will result in prohibitive economics for commercial application.
  Response: The energy-intensive unit operation is relatively small because
  (1) it is used to treat only the solid digestate, a small portion of the flow; (2) the heat is reused in the downstream process with enhanced efficiency; (3) results showed the net energy and return are positive
- *Comment 2*: The lack of ability to retrofit existing AD plants may slow implementation
  Response: Two of the key unit operations, the pretreatment unit and the acidification unit can be retrofitted into the existing systems
- *Comment 3*: Would like to see a process flow chart and mass balance
  Response: A flow chart was included in the presentation. Mass balances were embedded in the results but too much to be included in this presentation

Publications, Patents, Presentations, Awards, and Commercialization

- Publications
  - **L. Yu,** D. Kim, P. Ai, H. Yuan, J. Ma, Q. Zhao, S. Chen. 2023. 'Effects of metal and metal ion on biomethane productivity during anaerobic digestion of dairy manure'. *Fermentation.*
  - **Kalidas,** Partial Wet Oxidation of Dairy Manure to Produce Acetic acid As a Source Growth of Methanogens. *In press. Waste Management*
  - **Kalidas,** A Review on the Use of Hydrothermal Treatment on Anaerobic Digestion of Dairy Manure: Process, Perspectives, and Challenges, *under revision.*
  - Dissertation: **Yaojing**, systematic laboratory evaluations of hyperthermophilic anaerobic digestion of dairy manure and corn stover with the emphases on hydrolysis and acidification
  - **Yaojing**, Hyperthermophilic anaerobic digestion: A comprehensive review on theories, applications, challenges, and strategies, *under revision*
  - **Yaojing,** Improved biodegradation and acidification of dairy manure and restructured microbial community with hyperthermophilic anaerobic digestion, *under revision*
  - **Yaojing,** Establishment of Biogas production and performance related to microbial community properties by digesting lignocellulosic biomass at different temperatures, *under revision*
  - **D. Kim,** S. Witherrite, L. Yu, Q. Zhao, S. Chen. 'Evaluation of Novel Ammonia Recovery from Anaerobic Effluent by Integrating Biogas Stripping and Gypsum Absorption'. Under Review, Submit to Bioresource Technology Report, 2022
  - **Liang**, Optimization of diary manure pretreatment process, *under preparation*
  - **Meghana and Liang**: Energy feasibility of retrofitting HTL process to enhance biogas production of mesophilic digestion, *under preparation*
- Patents
  - An invention disclosure entitled "A high rate two-phase pressurized anaerobic digestion system producing high purity of methane from diverse waste biomass" was filed on January 14, 2020. The research team is gathering the needed data for the patent application.
- Awards
  - DOE Office of Science EMSL Exploratory Grant awarded
- Presentations
  - L. Yu, D. Kim, S. Chen. 'Effects of metal and metal ion on biomethane productivity during anaerobic digestion of dairy manure'. ASABE 2022, Annual International Meeting, July 17– 21, 2022, Houston, TX, USA.
  - D. Kim, L. Yu, S. Chen. 'Ammonia Recovery from the Anaerobic Effluent by Integrating Biogas Stripping and Gypsum Absorption'. ASABE 2022, Annual International Meeting, July 17– 21, 2022, Houston, TX, USA.
- The status of any technology transfer or commercialization efforts
  - Bench-scale data provide a base for the design and evaluation of the pilot system, a critical step in technology transfer and commercialization