DOE Bioenergy Technologies Office
(BETO) 2019 Project Peer Review

ARRESTED METHANOGENESIS FOR VOLATILE FATTY ACID PRODUCTION (WBS 2.2.4.100)

March 5, 2019
Waste-to-Energy Area Review

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GOAL STATEMENT

Project goals: Rewire dark fermentation process to produce VFAs and alcohols via arrested methanogenesis sustainably by regulating acidogenic metabolism towards enhanced VFA production

Project outcome: A scalable, low cost new arrested AD technologies at TRL 4 (200 gal reactors) to produce short chain organic acids (12.5 g/l) from organic waste streams

Relevance to the bioenergy industry:

- Tailored, robust microorganisms structure to produce desired chemicals
- Modular high rate arrested AD technology for chemicals production
- Less CAPEX and OPEX due to increased titer, yield and productivity, and product separation
  - Low costs of chemicals produced from waste streams

QUAD CHART OVERVIEW

Timeline

- Project start date: Oct 1, 2017
- Project end date: Sep 30, 2020
- Percent complete: 50%

	Total Costs Pre FY17**	**FY 17 Costs**	**FY 18 Costs**	**Total Planned Funding (FY 20-Project End Date)**
DOE Funded	N/A	N/A	$527,000	1,500,000
Project Cost Share*	N/A	N/A	N/A	N/A

- **Partners:**
  - **NREL**
  - **Roeslein Alternative Energy**

Barriers addressed

- Ct-D. Advanced Scalable Bioprocess Development

Scalable modular AnMBR technology for organic acids production

- CT-I: Development of Processes Capable of Processing High Moisture Feedstocks in addition to conventional AD

In situ organic acid production and separation technology

- Objectives: Rewire dark fermentation process to transform low value or negative value high-strength organic waste streams into high value short chain carboxylic acids (C2-C6) via arrested methanogenesis

- *End of Project Goal:* New cost effective arrested AD technologies from proof of concept, TRL 2 to TRL 4 (200 gal) to produce short chain VFAs (12.5 g/l) from organic waste streams.

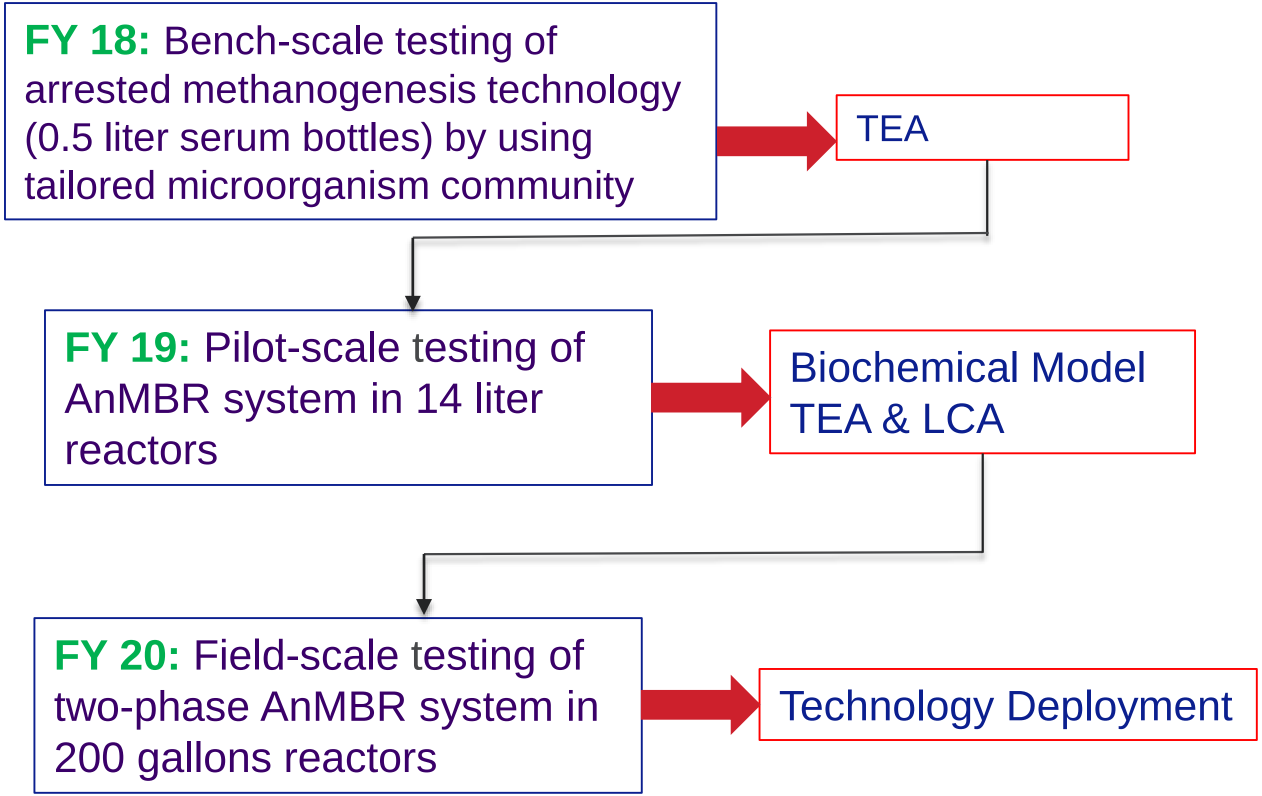
PROJECT OVERVIEW

- Potential to upend the current wastewater treatment paradigm “the minimum needed to meet the discharge criteria” into “reuse of high-strength organic wastewater and solid waste in the US to produce renewable chemicals
- Current State of the Art: Low titer, yield and productivity; product toxicity and separation; robustness and resiliency of microbial consortium
- ***Objective:*** Rewire dark fermentation process to produce VFAs and alcohols via arrested methanogenesis sustainably
    - Resilient, robust and productive microbial consortium
    - High conversion and separation efficiencies and organic loading capacity

Specific Project Goals:

- Define concepts and develop tools to transform low value/negative value high-strength organic waste streams into high value short chain carboxylic acids
- Establish highly efficient, robust and productive community structure for VFA production;
- Develop a new cost effective arrested in situ organic acid production and separation technology (a.k.a. Carboxylate Platform) at TRL 4
- Produce C1-C6 organic acids (12.5 g/l) continuously in AnMBR (200 gal) on a sustainable basis

PROJECT OVEVIEW



FY 18: Bench-scale testing of arrested methanogenesis technology (0.5 liter serum bottles) by using tailored microorganism community

TEA

FY 19: Pilot-scale testing of AnMBR system in 14 liter reactors

Biochemical Model
TEA & LCA

FY 20: Field-scale testing of two-phase AnMBR system in 200 gallons reactors

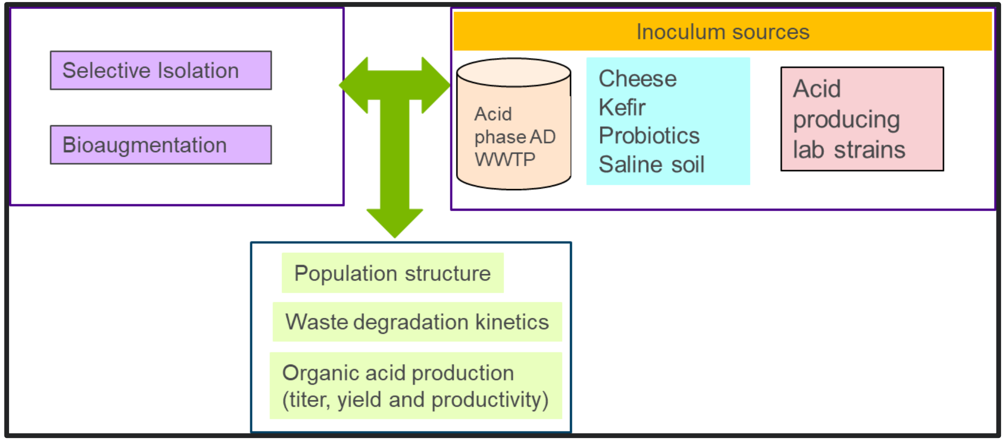
Technology Deployment

PROJECT OVERVIEW- TASKS

(1) Tailoring Microbial Consortia and Dynamics for Organic Acid Production

(2) Development of New Arrested AD technologies

(3) Techno-economic Assessment of New Technologies: process model, TEA and LCA



Selective Isolation

Bioaugmentation

Inoculum sources

Acid phase AD WWTP

Cheese
Kefir
Probiotics
Saline soil

Acid producing lab strains

Population structure

Waste degradation kinetics

Organic acid production (titer, yield and productivity)

Tailoring Microbial Consortia for Organic Acid Production

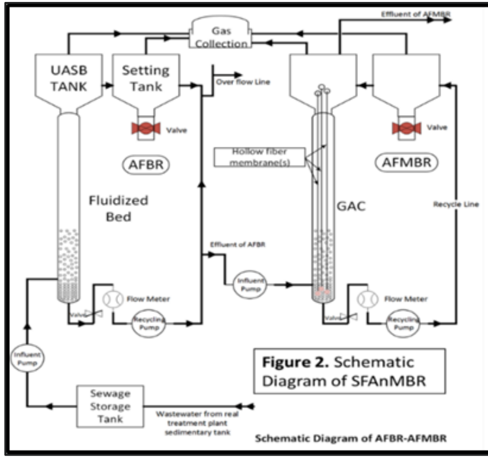


Figure 2. Schematic Diagram of SFAnMBR

Schematic Diagram of AFBR-AFMBR

Table 2. Operational conditions of the bench-scale SFAnMBRs

SFAnMBR Parameter	Test conditions
Temperature (°C)	30 and 42
Organic loading (kg/m³ d)	2-12
Gas sparging rate (lpm)	0.30-0.75
HRT (hr)	3-6

AnMBR Parameter	Test conditions
Flux (l/m²h)	2-10
TMP (kPa)	<10

Two different reactor configurations due to waste stream characteristics and application point and size of the new AD at the utilities and facilities

PROJECT MANAGEMENT

- *Project Team:* Highly diverse project team with different but complementary expertise
    - NREL: TEA
    - Roeslein Alternative Energy (RAE) (process scale up, pilot-scale demonstration)
- *Team Interaction:* Site visits, monthly project meetings, weekly task meetings
- *Progress measurement:* Milestones, industry partners guidance, BETO TMs feedback
- *Data Sharing and Storage:* BlueJeans meetings and Secured Box storage

TECHNICAL APPROACH

- *Approach:* Integrate highly efficient, robust and productive community structure, and anaerobic membrane reactors coupled with separation technology with process modelling and TEA driven new bioproducts production technology development strategies
- *Major challenges: (i) lack of resiliency and robustness of microbial community structures for conversion of highly complex organic waste streams (ii) low titer, yield and productivity of organic acids, (iii) product toxicity and separation, iv) clogging and fouling of membranes*
- *Critical success factors:*
  - Establish robust and resilient microbial community structure for targeted VFA production (12.5 g/l) continuously
  - Develop and demonstrate a viable pathway to commercialization of new arrested AnMBR technology at TRL 4 (200 gal)
  - Develop a new *in situ* organic acid production and separation technology for AD industry

TAILORING MICROBIAL CONSORTIA AND DYNAMICS

- **FY18 Target**: Isolation and establishment of resilient microbial consortium

FY18 Efforts:

- Ecology Barriers
  - Directing metabolic processes to generate target carboxylates at high productivity and titer
  - Toxicity of high concentrations of carboxylates and their undissociated forms
  - Toxicity of high concentrations of salts
- Inhibit methanogenesis
  - Acid and Heat Treatment
  - Increase organic loading rate
  - Reduce HRT/SRT
  - Run digesters at pH≤ 6.0
- Find Best Inocula for Lactic and Acetic Acid production
  - Yogurt, Kefir, Cheese and Probiotics
  - Augmentation of acetic acid producing strains
- Find salt tolerant inocula

TAILORING MICROBIAL CONSORTIA AND DYNAMICS

- Selectively isolated strains from sludge samples taken from the acidogenic digester of two stage sludge digester facility located in Illinois, and soil samples collected from highly saline environments
- Enriched acidogenic consortia further by selective strategies to regulate acidogenic metabolism towards sustainable VFA production.
  - Pretreatment of anaerobic consortia is very crucial in the selective enrichment of resilient acidogenic consortia.
  - Acid shock (pH=2 for 6 hr)
  - Heat (105 ^{o}C for 6 hr)
  - Chemical pretreatment (Acid + heat)
  - Pretreatment of organic waste stream such as aeration to washout methanogens from the consortia
  - Operating digester with short SRT (HRT) (5-7 days)

COMMUNITY STRUCTURE AND DYNAMICS

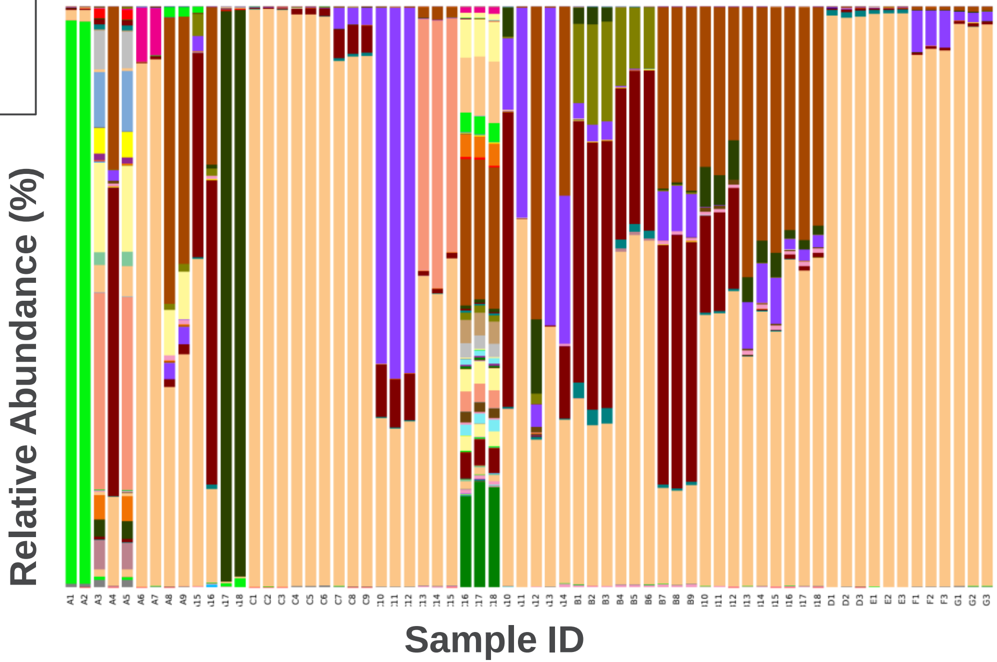
16S rRNA based Metagenomic Analysis for over 24 different reactor operating conditions

- 10 Different inoculum sources
- 8 Different operating conditions (SRT/HRT, organic loading rate)
- 6 Different wastewater composition (COD and mixing ratio)

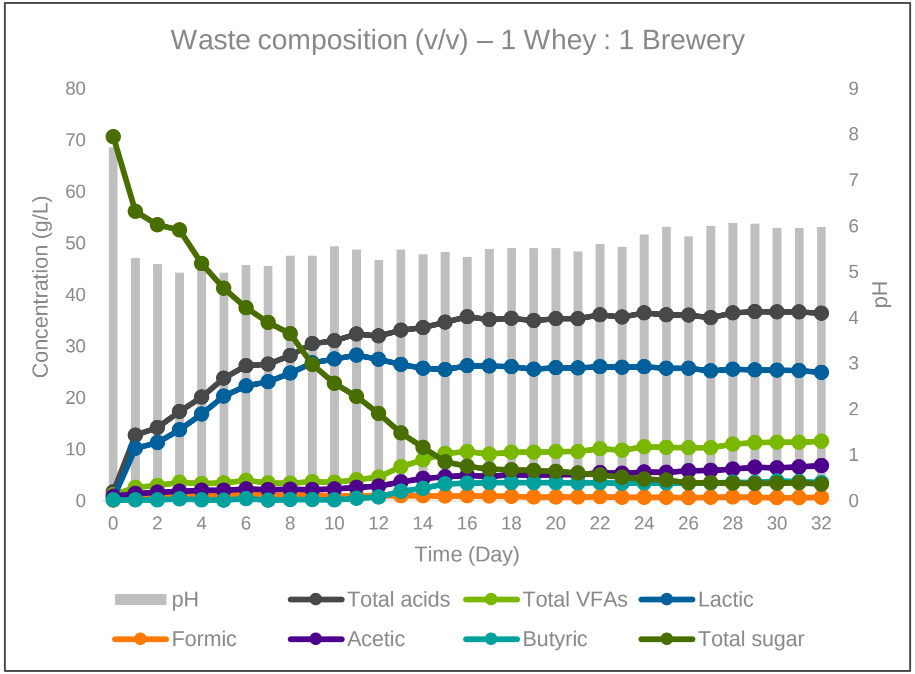
- The family *Bacillaceae* was found in all samples
    - Facultative anaerobe
    - Certain strains breaks down complex carbohydrates
    - Others produce lactic acid

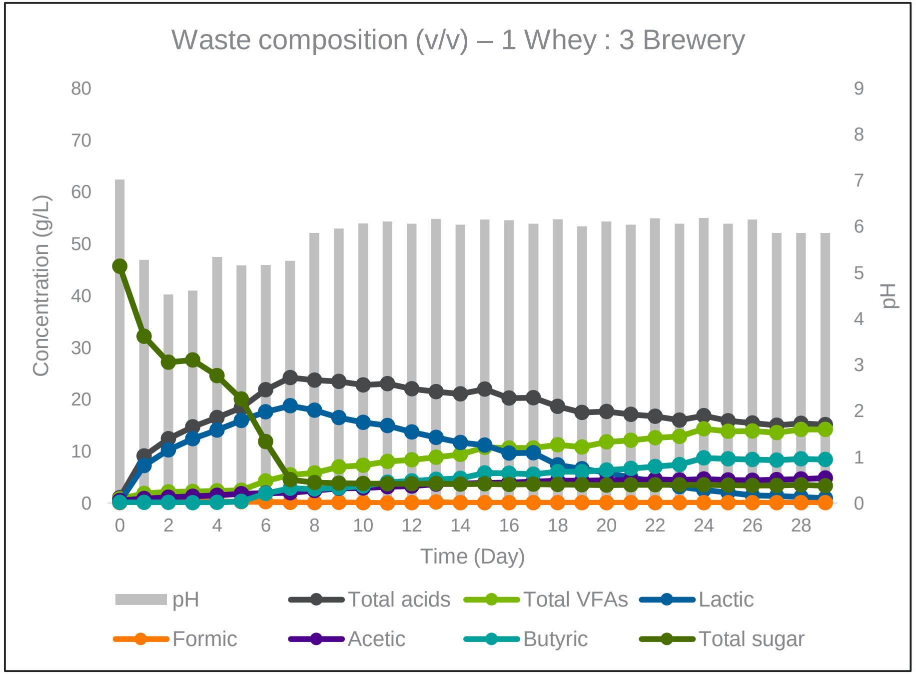
- The family *Clostridiaceae* was also identified
    - Obligate anaerobes
    - Break down simple sugars to produce acetic and butyric acid

Family Taxa Plot



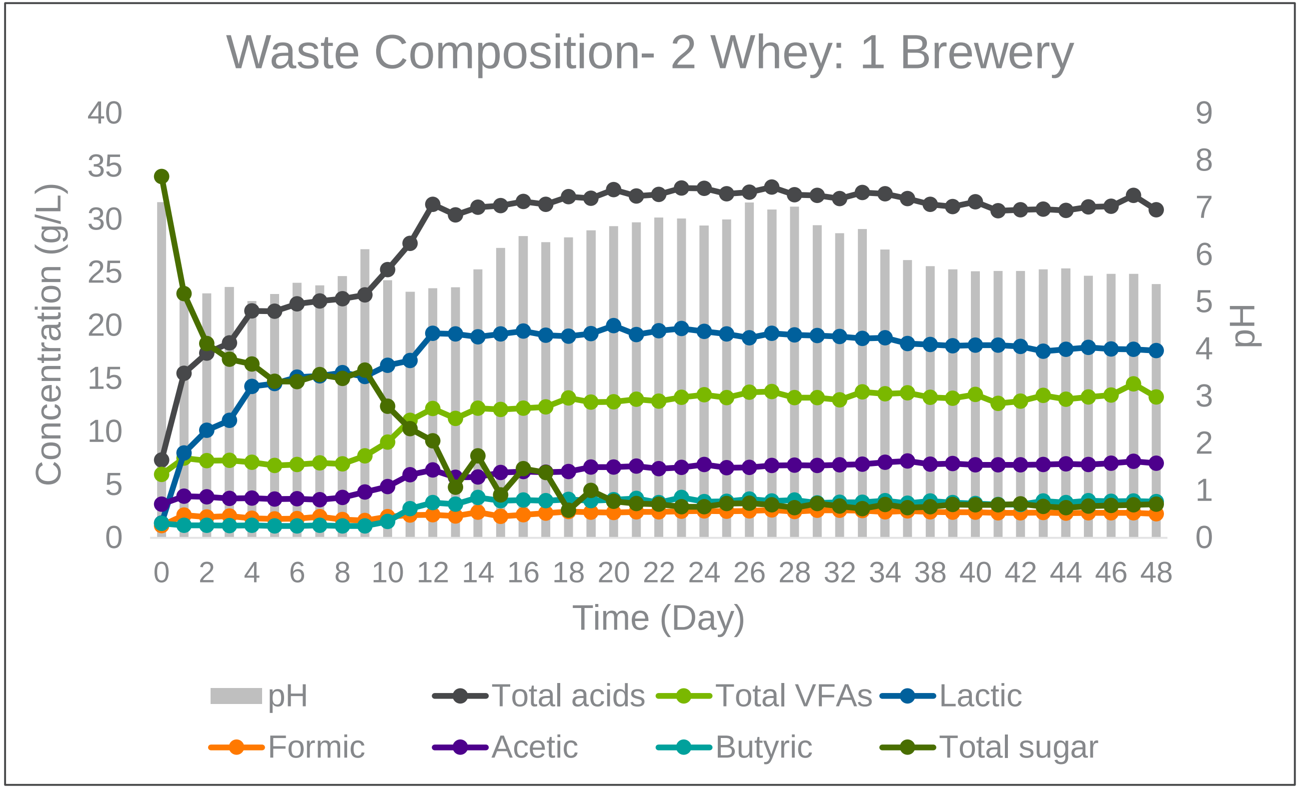
IMPACT OF WASTEWATER COMPOSITION ON PRODUCT PROFILE





Batch Mode Operation

IMPACT OF WASTEWATER COMPOSITION ON PRODUCT PROFILE



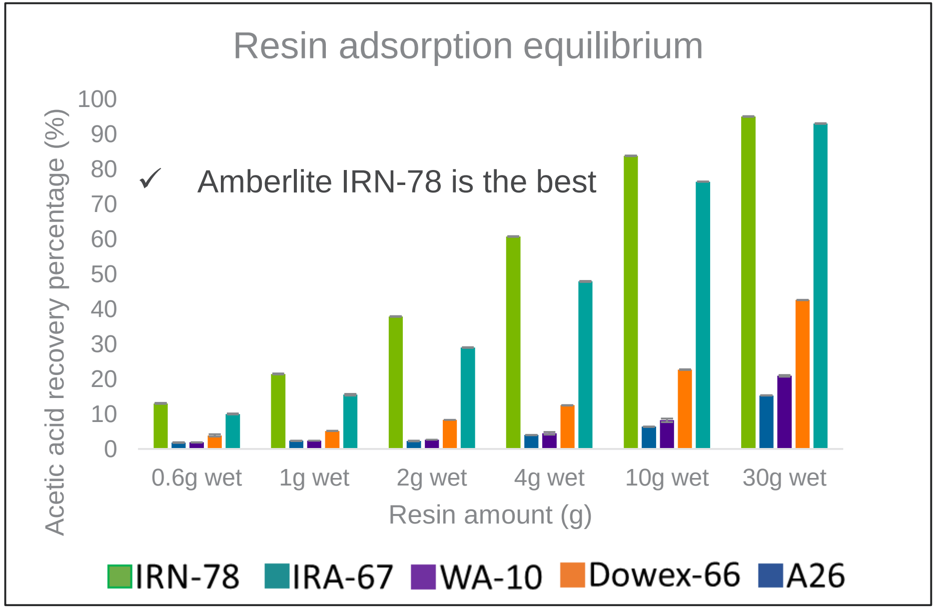
COD conversion efficiency to organic acids: 75-79%

Batch Mode Operation

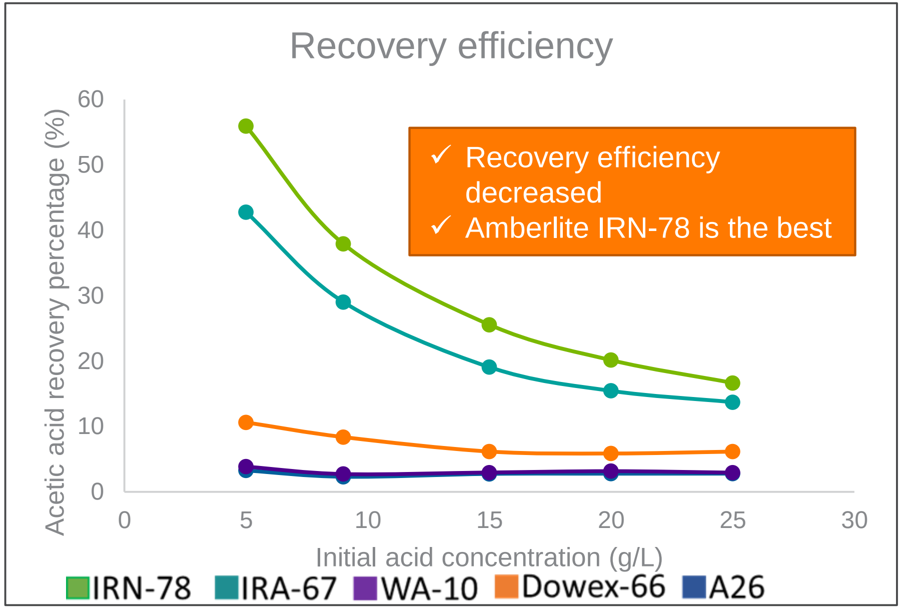
SOLVING CHALLENGING SEPARATIONS ISSUES

Performance Testing of Ion-Exchange Resins

- Effect of initial acid concentration



✓ Amberlite IRN-78 is the best

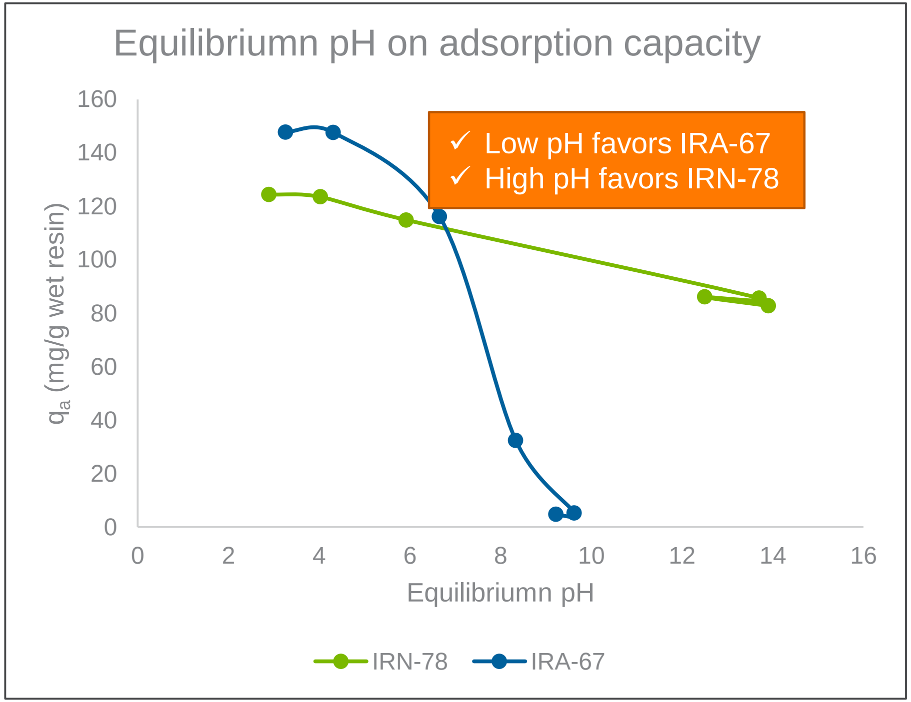


- ✓ Recovery efficiency decreased
- ✓ Amberlite IRN-78 is the best

SOLVING CHALLENGING SEPARATIONS ISSUES

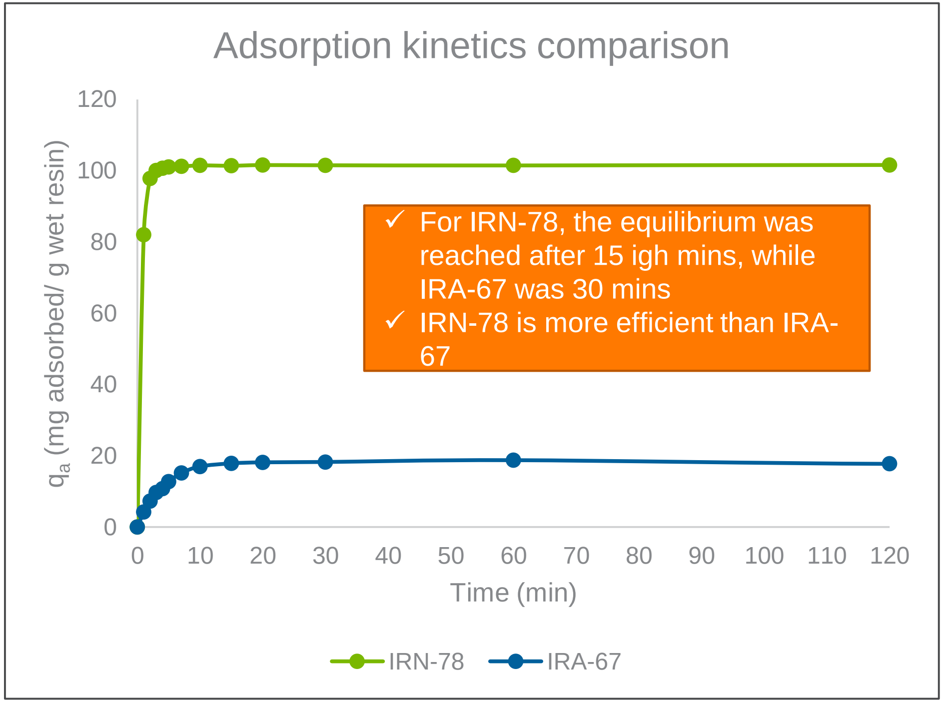
Performance Testing of Ion-Exchange Resins

- Effect of equilibrium pH



✓ Low pH favors IRA-67
✓ High pH favors IRN-78

- Kinetics experiment

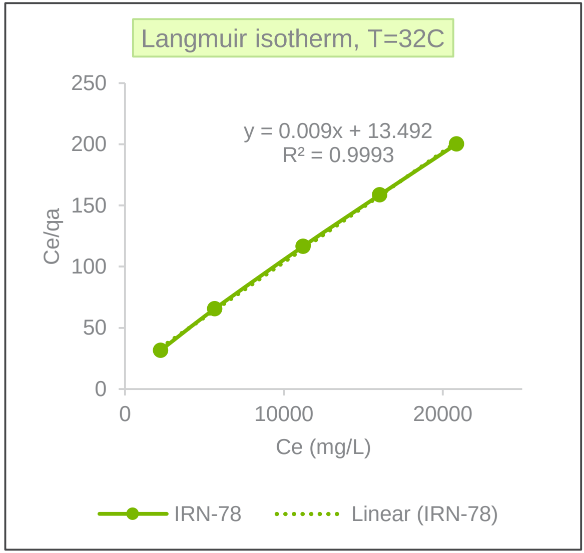


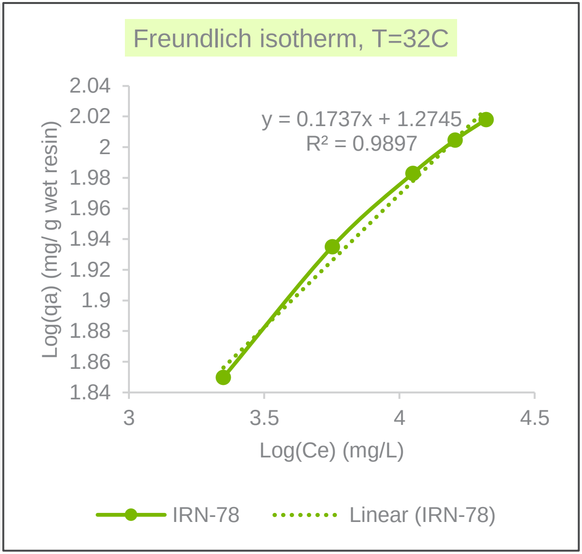
✓ For IRN-78, the equilibrium was reached after 15 igh mins, while IRA-67 was 30 mins
✓ IRN-78 is more efficient than IRA-67

SOLVING CHALLENGING SEPARATIONS ISSUES

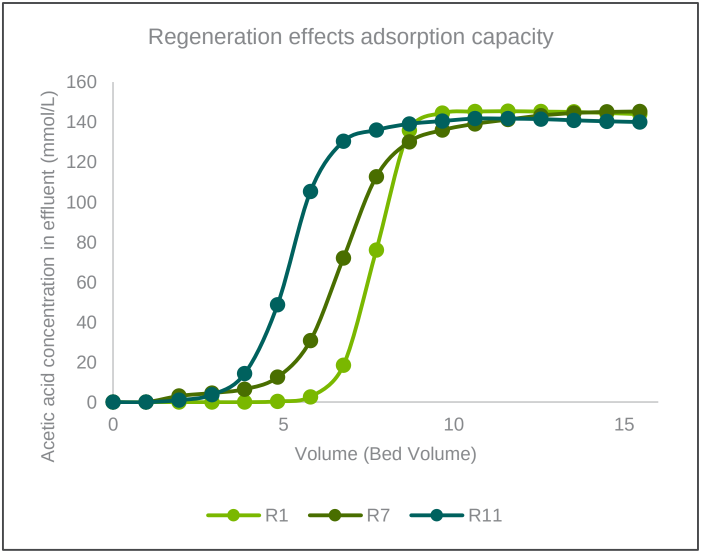
Performance Testing of Ion-Exchange Resins

- Adsorption isotherm


Langmuir isotherm, T=32C

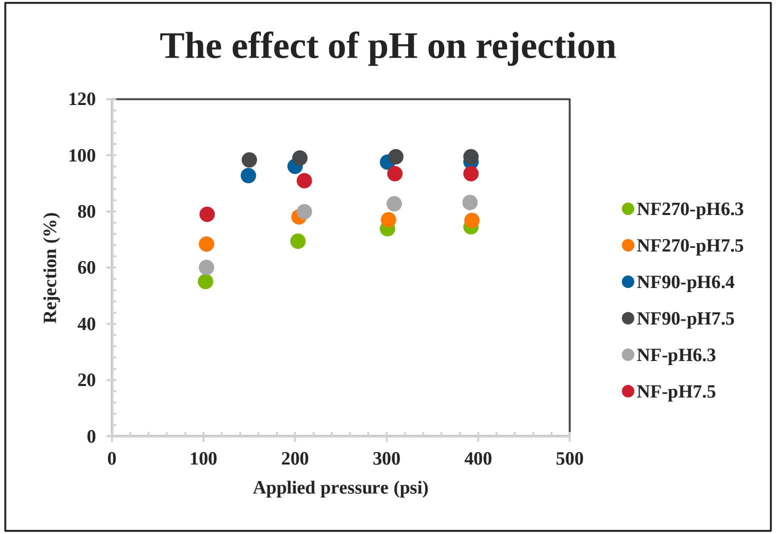

Freundlich isotherm, T=32C

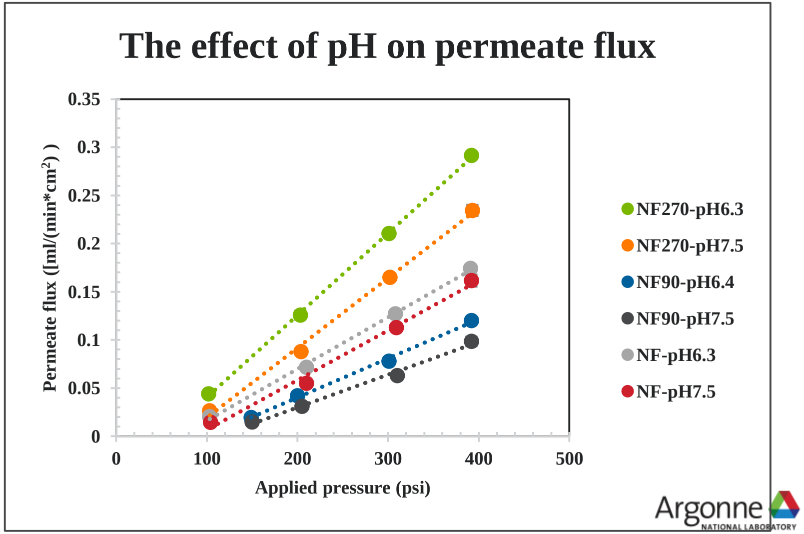
- Breakthrough curve


Regeneration effects adsorption capacity

Performance Testing of Membrane Technologies

	Pore size/ MWCO	Polymer	Feed	pH	Flux (GFD/TMPpsi)	Rejection	Maximun Pressure
Ultrafiltration	10,000 Da	Polyethersulfone	Process/Ultrapure	1-11	85/30	10K-Dextran	200
Nanofiltration	~200-400 Da	Polyamide-TFC	Surface/Groundwater	2-11	72-98/130	99.2% MgSO4	600
	~200-400 Da	Polyamide-TFC	Industrial/Commercial Water	2-11	46-60/130	99.0% MgSO4	600
	~200-400 Da	Polyamide-TFC	Foods/Beverages	2-11	26.5-39.5/130	99.0% MgSO4	600
Reverse Osmosis	~100 Da	Polyamide-TFC	Seawater	2-11	17-24/800	99.6% MgSO4	1,200
	~100 Da	Polyamide-TFC	Brackish Water	2-12	28-33/225	99.7% MgSO4	600





RELEVANCE

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

- A novel scalable AnMBR technology enriches robustness and resiliency of microbial consortium, enhances product titer, yield and productivity, and overcomes product separation challenges

- Tech transfer/Marketability: New AnMBR technology at TRL 4 opens door for poorly valorized organic waste streams generated in the US and provides an alternative to biogas production
    - Renewable precursors would have energy content of ~150 trillion Btu (NREL, 2013) which corresponds to displacing the equivalent of 1.1 x 10^7 gallons of diesel per year
    - Address the challenges and barriers in renewable chemical production
    - Encourage development of new AD industry towards chemical production

FUTURE WORK

- *FY19 Target:* Develop novel arrested technologies at TRL3 in 14 liter fermenters under batch mode
    - Complete development of scalable stable arrested methanogenesis processes in 0.5 liter fermenters by varying organic loading rate (2-12 g/l/d), hydraulic retention time (3-24 hr), sludge retention time (3-20 days) and operating temperatures
    - Produce C1-C6 organic acids at a titer of 12.5 g/l under batch mode in AnMBR (14 liter)
    - Determine community structure and dynamics in reactors based on 16S RNA analysis methods (qPCR and metagenomic analysis)
    - Reevaluate and modify process and TEA models with experimental data from 14 liter fermenter operations

- *FY20 Target:* A scalable, high performance, low-cost arrested AnMBR technology (200 gallons) at TRL 4
    - Complete arrested AnMBR process development in 14 liter fermenters under continuous mode
    - Test the best performing arrested AD technology and conditions at 200 gal fermenters in RAE’s pilot complex

FUTURE WORK

- *FY20 Target:* A scalable, high performance, low-cost arrested AnMBR technology (200 gallons) at TRL 4 (*continued*)
  - Determine proper cleaning protocols for AnMBR systems to prevent membrane fouling
  - Complete development of process and TEA models

- *Go/No-Go Points (3-31-2019):* Produce C1-C6 organic acids in AnMBR (0.5 liter) on a sustainable basis under batch mode at a titer of 12.5 g/L for 100 hours

SUMMARY

- Conventional AD operations are challenged by slow degradation rate, incomplete biodegradation, large footprints and high cost of biogas production and upgrading
  - There is a need for development of cost effective bioproducts production technologies

- Develop scalable, high performance, low-cost, arrested AnMBR technology (200 gal) at TRL 4
  - Establish highly efficient, robust and productive community structure for VFA production
  - > 2 fold increase in organic loading capacity
  - > 2 fold increase in product titer
  - Develop new arrested in situ AD technologies where both production and separation take place (a.k.a. Carboxylate Platform) at TRL 4

- Future work will include the integrated highly efficient, robust and productive community structure, and anaerobic membrane reactor engineering coupled with separation technology with process modelling and TEA driven new bioproducts production technology development strategies

Q&A

THANK YOU!!!

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- RAE: Hassan Loutfi

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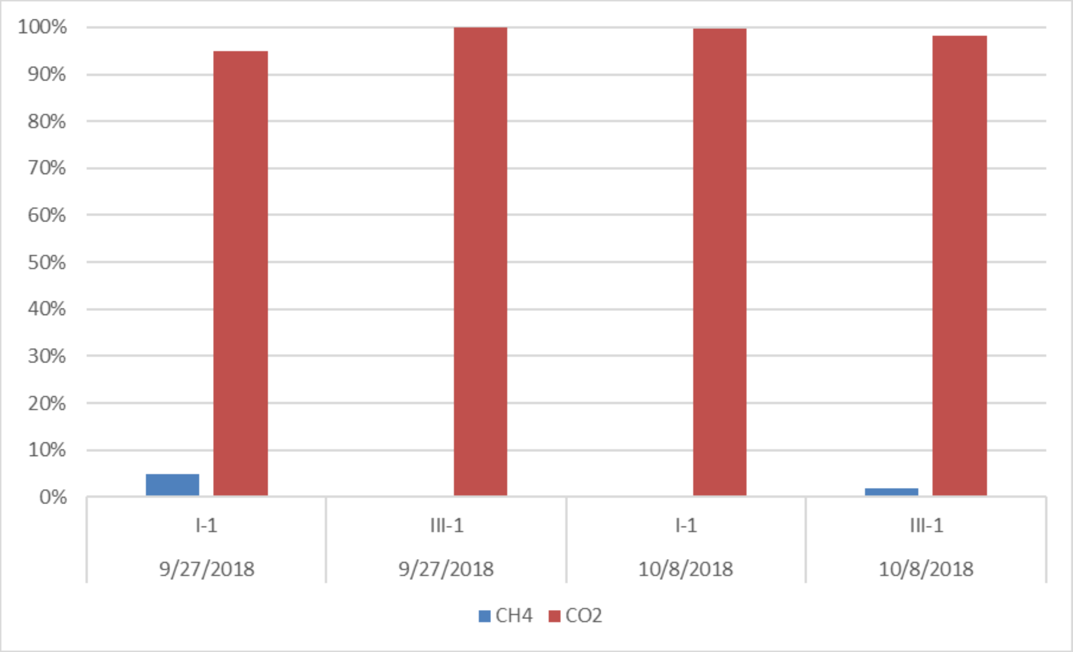
ADDITIONAL SLIDES

NOMENCLATURE

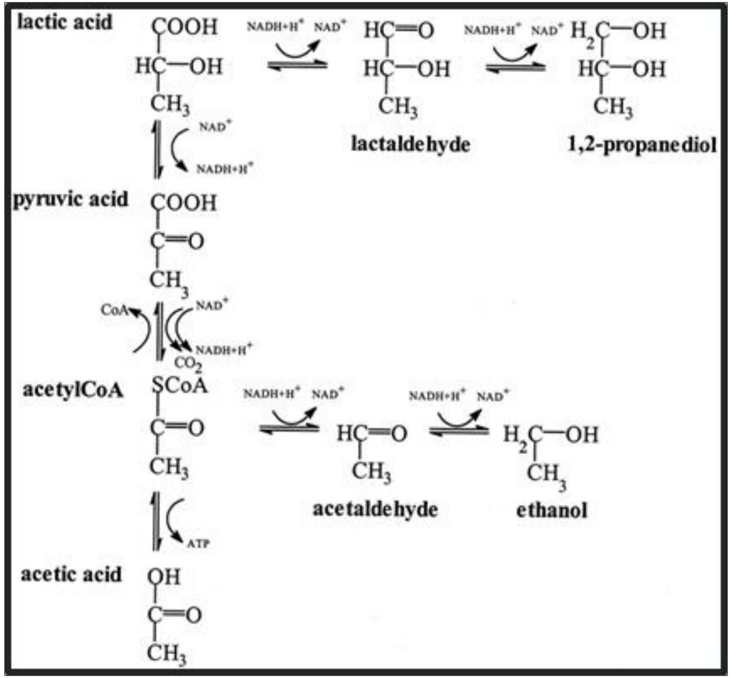
AD: Anaerobic Digestion or Anaerobic Digester
AnMBR: Anaerobic Membrane Bioreactor
HRT: Hydraulic Retention Time
OLR: Organic Loading Rate
SRT: Sludge Retention Time
TEA: Techno-economic Analysis
TRL: Technology Readiness Level
VFA: Volatile Fatty Acids

ARRESTED METHANOGENESIS AND H_2 PRODUCTION



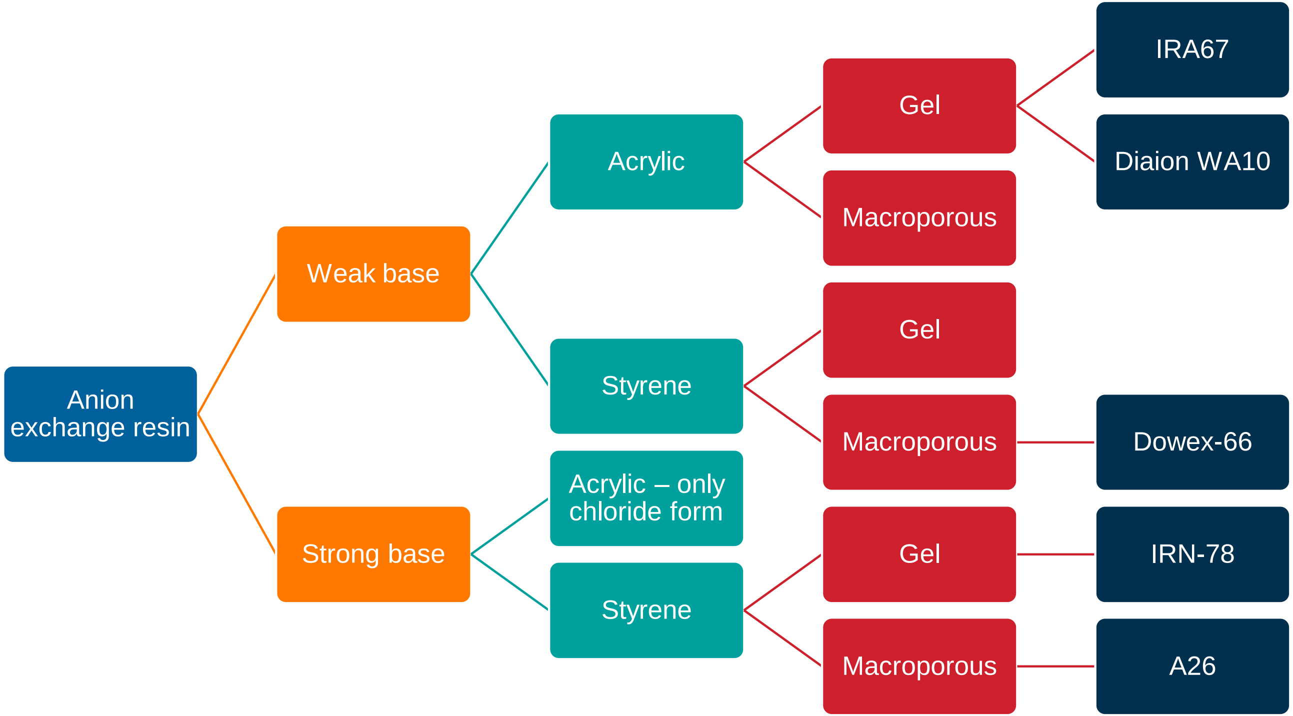
- Analysis of more than 100 gas samples showed that
- CH_4 <5% (mostly 1-2%)
- H_2 <1 %
- CO_2 > 95%

PATHWAY FOR CONVERSION OF LACTIC ACID TO ACETIC ACID



Appl. Environ. Microbiol., **2001** vol. 67 no. 1 **125-132**

SEPARATIONS OF VFAS BY IX RESINS



Anion exchange resin
- Weak base
  - Acrylic
    - Gel
      - IRA67
      - Diaion WA10
    - Macroporous
  - Styrene
    - Gel
    - Macroporous
      - Dowex-66
- Strong base
  - Acrylic – only chloride form
  - Styrene
    - Gel
      - IRN-78
    - Macroporous
      - A26

PROPERTIS OF SELECTED IX RESINS

	IRN-78	**IRA-67**	**WA-10**	**Dowex-66**	**A26**
Type	Strong base	Weak base	weak base	Weak base	Strong base
Matrix	Styrene divinylbenzene copolymer, gel type	Crosslinked acrylic gel structure	Acrylic-DVB, gel type	Styrene-DVB, macroporous	crosslinked styrene divinylbenzene copolymer, macroporous
Functional group	Trimethyl ammonium	Tertiary amine	Tertiary Amine	Tertiary amine	quaternary ammonium
Ionic form	OH^-	Free base	Free base	Free base	OH^-
Total exchange capacity	≥ 1.20 eq/L	≥ 1.60 eq/L	≥ 1.20 eq/L	≥ 1.60 eq/L	≥ 0.80 eq/L
Moisture content	54 to 60 %	56 to 64 %	63 to 69 %	40 to 46 %	66 to 75%
Density	690 g/L	700 g/L	690 g/L	640 g/L	675 g/L

AN OVERVIEW OF VFA PRODUCTION

VFA	Microorganism	Substrate	Fermentation Condition	Reactor Scale	Yield (g/g)	Titer (g/L)	Dilution Rate (1/h)	Productivity (g/L/h)	References
Acetic Acid	Acetobacter aceti	Date extract	Continuous CSTR		0.46-0.50	0.9-0.96	1.92-6.09[c]	2.8-11	Mehaia and Cheryan (1991)
		Cheese way - yeast extract supplement	Continuous membrane-integrated hybrid process	30 L capacity fermentor	0.96	96.9	0.102	4.14	Nayak and Pal (2013)
	Clostridium aceticum	CO - used mixed gas (H2, Ar, CO) as sole carbon source	Batch fermentation	163 mL glass serum bottle		1.28	0.0167	0.021	Sim and Kamaruddin (2008)
	Clostridium lentocellum SG6	Paddy straw - yeast extract supplement	Vials level	120 mL serum vials	0.44	30.98	0.03	0.1[c]	Ravinder et al. (2000)
	Clostridium thermoaceticum	Glucose - yeast extract supplement	Batch CSTR	5 L fermenter	0.39	39	0.0128	0.5	Witjitra et al. (1996)
	Moorella thermoacetica	Sugarcane straw hydrosylate - yeast extract, glucose, and xylose supplement	Flask fermentation	100 mL Wheaton serum bottles	0.71	17.2	0.0139	0.238[c]	Ehsanipour et al. (2016)
	Streptococcus lactis and Clostridium formicoaceticum	Whey lactose - resazurin, trypticase, yeast extract, sodium lactate supplement	Coculture at 35 C	5 L fermenter		30	0.1250	0.375[c]	Tang et al. (1988)
	Sacharomyces cerevisiae and Acetobac	Glucose - glucose, yeast extract, peptone, sodium glutamate supplement	Fed batch w/ coculture	10 L fermenter		66			Wang et al. (2013)
	Kluyveromyces fragilis	Whey - yeast extract 3, malt extract 3, peptone 5, glucose 10, agar 15 supplement	Shake flask	1 L centrifuge bottle (200 mL working volume)	0.322	16.12	0.0052	0.108[c]	Mostafa (2001)
Propionic Acid	Propionibacterium acidipropionici	Lactate - yeast extract and sodium lactate supplement	Batch fermentation	1 L customized flasks		15.06	0.00750[c]	0.113	Coral et al. (2008)
		Glycerol - yeast extract and sodium lactate supplement	Batch fermentation	1 L customized flasks		6.77	0.00739[c]	0.05	Coral et al. (2008)
		Glycerol - yeast extract, tryptic soy supplement	Fed-batch	7 L fermenter, 10 m3 scale up bioreactor		44.62	0.0045	0.2	Zhu et al. (2010)
		Glycerol/glucose/lactate - yeast extract with glucose as carbon source	Fibrous bed bioreactor	5 L fermenter	0.35-0.54	100	0.0022-0.0041[c]	0.22-0.41	Zhang and Yang (2009a)
		Sugarcane molasses - yeast extract and sodium lactate supplement	Batch fermentation	1 L customized flasks		8.23	0.0074[c]	0.061	Coral et al. (2008)
		Lignocellulose hydrolysate - proteose peptone and yeast extract supplement	Batch fermentation	2 L batch reactor		18	0.0280	0.514	Ramsay et al. (1998)
		Cheese way - yeast extract supplement	Continuous fermentation	6 L fermenter	0.7	19.7	0.0500	0.98	Gupta and Srivastava (2001)

AN OVERVIEW OF VFA PRODUCTION

Propionic Acid		Jerusalem artichoke hydrolysate - yeast extract, trypticase, glucose, fructose supplement	Free cell fibrous fed bioreactor	5 L fermenter	0.379	40.6	0.0047[c]	0.19	Liang et al. (2012)
		Jerusalem artichoke hydrolysate - yeast extract, trypticase, glucose, fructose	Immobilized cell fibrous fed bioreactor	5 L stirred tank fermenter	0.434	68.5	0.0226[c]	1.55	Liang et al. (2012)
	Propionibacterium freudenreichii	Glucose - glucose, peptone, yeast extract, and NaCl supplement	Multi-point fibrous-bed bioreactor (fed-batch)	7.5 L bioreactor	0.7828	67.05	0.0020	0.14	Feng et al. (2010)
	Propionibacterium shermanii	Glucose/glycerol - yeast extract, tryptic soy broth supplement	Batch	1.2 L glass reactors	0.4/0.58	6.4/9	0.0109[c]/0.02[c]	0.07/0.18	Himmi et al. (2000)
Butyric acid	Clostridium butyricum	Sucrose	Fed batch	225 mL double-walled cylinder (extractive), two 500 mL tanks (pertractive)	0.19 (extractive), 0.3 (pertractive)	10 (extractive), 20 (pertractive)	0.023[c] (extractive), 0.0105[c] (pertractive)	0.23 (extractive), 0.21 (pertractive)	Zigova et al. (1999)
	Clostridium butyricum (ZJUCB)	Glucose- corn steep flour supplement	Fed batch	5 L bioreactor		16.74	0.03125[c]	0.524	He et al. (2005)
	Clostridium thermobutyricum	Glucose - yeast extract supplement	Continuous culture	500 mL rotary fermenter		18.4	0.1304[c]	2.4	Canganella and Wiegel (2000)
	Clostridium tyrobutyricum	Xylose	Immobilized cell fibrous fed bioreactor	0.5 L fibrous bed bioreactor connected to 5 L stirred tank fermenter	0.38-0.59	57.9	0.0551[c]	3.19	Zhu and Yang (2004)
		Glucose	Immobilized cell fibrous fed bioreactor	5 L stirred tank fermenter connected to 0.5 L FBB	0.46	86.9	0.0127[c]	1.1	Jiang et al. (2011)
		Cane molasses - gluose supplement	Batch fermentation	5 L stirred tank fermenter connected to 0.5 L FBB	0.47	26.2	0.1576[c]	4.13	Jiang et al. (2009)
		Sugarcane bagasse - CMCase, glucosidase, xylanase, protein, B-glucosidase supplement	Batch fermentation	2 L stirred tank fermenter and 0.5 L FBB	0.48	20.9	0.0244[c]	0.51	Wei et al. (2013)
Isobutyric acid	Propionibacterium freudenreichii	Complex media - contained lactic starters and propionibacteria starters	Fermentation			0.005-0.013			Thierry et al. (2004)

AN OVERVIEW OF VFA SEPARATION-MEMBRANE

Fermentation Products	Process Name	Operating Condition	Configuration	Performance	Reference
Lactic Acid	Microfiltration	1-4 bar, pore size 50 nm-5 um, pH 7-8	ex situ, cross-flow membrane filtration	90.4 g/L ammonium lactate	Milcent and Carrere (2001)
Acetic Acid	Microfiltration	4.0+ pH	in situ	60% acetic acid rejection	Grzenia et al (2008)
Acetic Acid	Microfiltration	pH 8.5	in situ membrane recycle bioreactor	25.84 g/L acetic acid, 0.497 g/g acetic acid	Mostafa (2001)
Acetic Acid	Ultrafiltration	5-9 bar, pore size 2-50 nm	in situ	75-84% acetic acid rejection	Lakra et al (2013)
Lactic Acid	Ultrafiltration	30 C, 0.8 bar	in situ, cross flow ultrafiltration	140-160 g/L lactic acid from wheat hydrolysis	Torang et al (1999)
Acetic Acid	Nanofiltration	10-20 bar, pore size 1 nm			Pal and Nayak (2016)
Acetic Acid	Nanofiltration	3.7 isoelectric point, 0.83 nm pore size, pH 2.9, 24.5 bar	spiral wound	acetic acid retention -6.8-90% , 28-81% xylose retention	Weng et al (2009)
Furans/Carboxylic acids	Nanofiltration	pH 2.9, 24.5-34.3 bar	in situ, spiral wound, with MW cutoff	acetic acid retention -19-14.9% at 24.5 bar, -31.8-27.7% at 34.3 bar	Weng et al (2010)
Acetate	Nanofiltration w/ RO	pH 5.6, 50 C, 250 psig	in situ	40% acetate rejection	Han and Cheryan (1995)
Acetate	Nanofiltration	pH 5.6, 200 psig, 30 C	ex situ - fermentation, clarification, purification, concentration (downstream)	60% acetate rejection	Han and Cheryan (1995)
Acetic Acid	Reverse Osmosis	15-45 bar	in situ	47% acetic acid rejection	Hausmanns et al (1996)
Acetic Acid	Reverse Osmosis	17 bar, 21 C	ex situ	70%+ acetic acid rejection	Ragaini et al (2004)
Acetic Acid	Reverse Osmosis	55 bar	spiral wound single-pass	90.3% acetic acid rejection	Diltz et al (2007)
Acetic Acid	Electrodialysis			93.1% efficiency, 77% acetic acid yield, lowest energy consumption 3.14kWh/kg acetic acid	Pal and Nayak (2016)
Acetic Acid	Electrodialysis	pH 6.8	ex situ, side streams: fermentation, clarification, electrodialysis, evaporation/drying	134 g/L acetic acid	Chukwu and Cheryan (1999)
Acetic Acid	Electrodialysis	pH 4	in situ; further treatment by extraction and distillation in side streams	70 wt% acetic acid	Yu et al (2000)
Acetic Acid	Membrane-Integrated Hybrid Reactor		in situ, hollow fiber microfiltration filter	40 g/L acetic acid, 160 g/Lh productivity	Park et al (1989)
Acetic Acid	Membrane-Integrated Hybrid Reactor		ex situ, 2-stage recycle system	150 g/Lh productivity, 3.7 L/h volume rate	Nishiwaki (1997)
Acetic Acid	Membrane-Integrated Hybrid Reactor	303 K, 1 bar	in situ, flat sheet cross flow modules	4.06 g/Lh productivity, 96.9 g/L acetic acid, 98% purity	Nayak and Pal (2013)

RESPONSES TO PREVIOUS REVIEWERS' COMMENTS

This project was not subjected to prior review

PUBLICATIONS, PATENTS, PRESENTATIONS, AWARDS, AND COMMERCIALIZATION

- Paper titled “Bring it All Back to Nature: A New Paradigm in Environment-Energy-Nutrient Nexus” was presented at 2018 AIChE Midwest Regional Conference, March 13-14, 2018, Chicago, IL
- Paper titled “New Perspectives for Biochar Utilization under Food-Water-Energy Nexus” was presented at 255th ACS National Meeting & Exposition, March 18-22, 2018, New Orleans, LA
- Presentation titled “Dry Fermentation of Organic Wastes” at BETO and NREL Anaerobic Digestion Workshop, April 24, 2018
- Arrested Methanogenesis for Volatile Fatty Acid Production: Valorization of Industrial Wastewaters Beyond Biogas” at WEFTEC Conference Sep 29-Oct 3, 2018 in a session dedicated an “Overview of the DOE’s Integrated Efforts to Advance Resource Recovery and Energy Efficiency in the Nation’s Water Systems“
- Ecosystem services of livestock waste based energy generation” accepted for a podium presentation at ACES 2018 Conference, Dec 3-6, 2018. The conference is organized by The University of Florida’s Institute of Food and Agricultural Sciences (UF/IFAS)

PUBLICATIONS, PATENTS, PRESENTATIONS, AWARDS, AND COMMERCIALIZATION

- Waste to Bioproducts and Biofuels: Challenges and Opportunities in Driving Bioeconomy (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