DOE Bioenergy Technologies Office (BETO) 2019 Project Peer Review

WBS 1.3.4.201 CAP Process Research

Advanced Algal Systems

March, 2019

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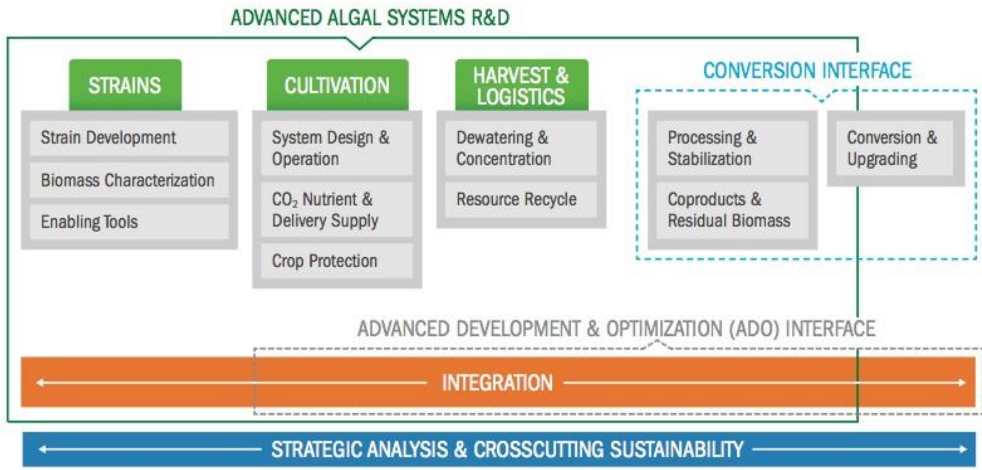
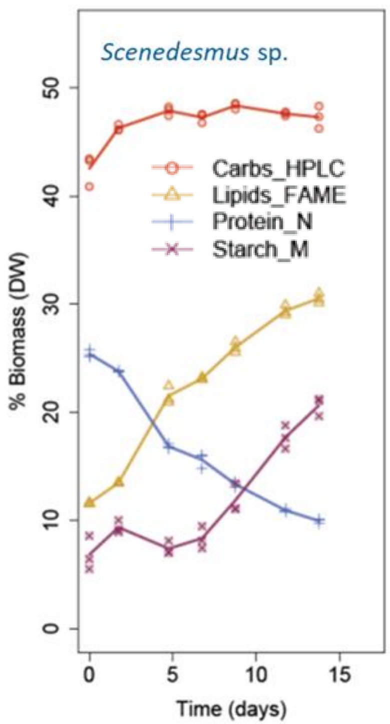
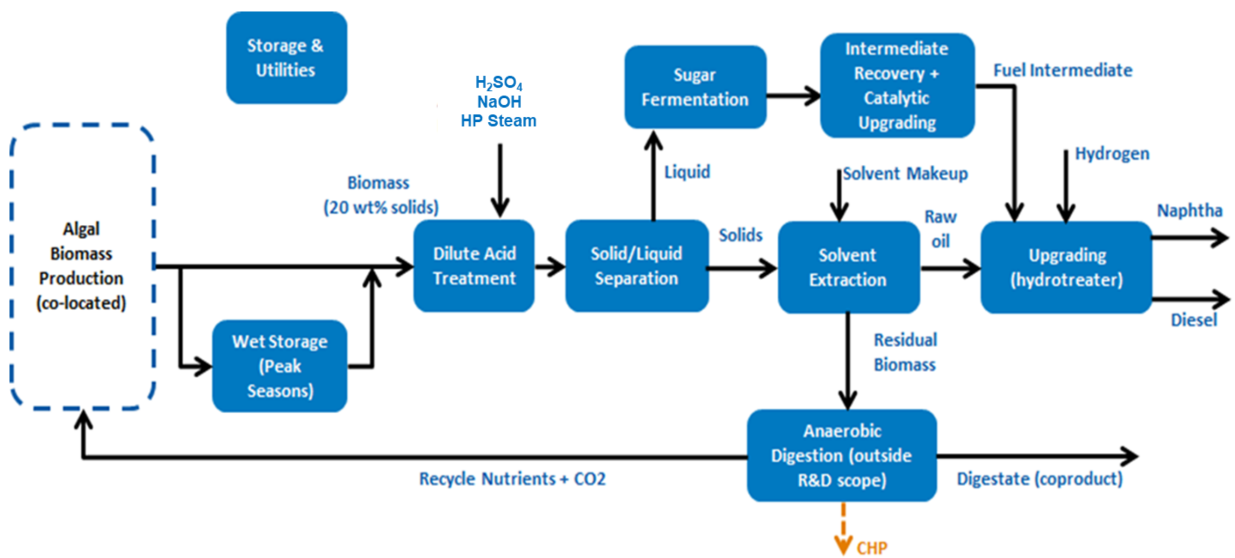
National Renewable Energy Laboratory

Background



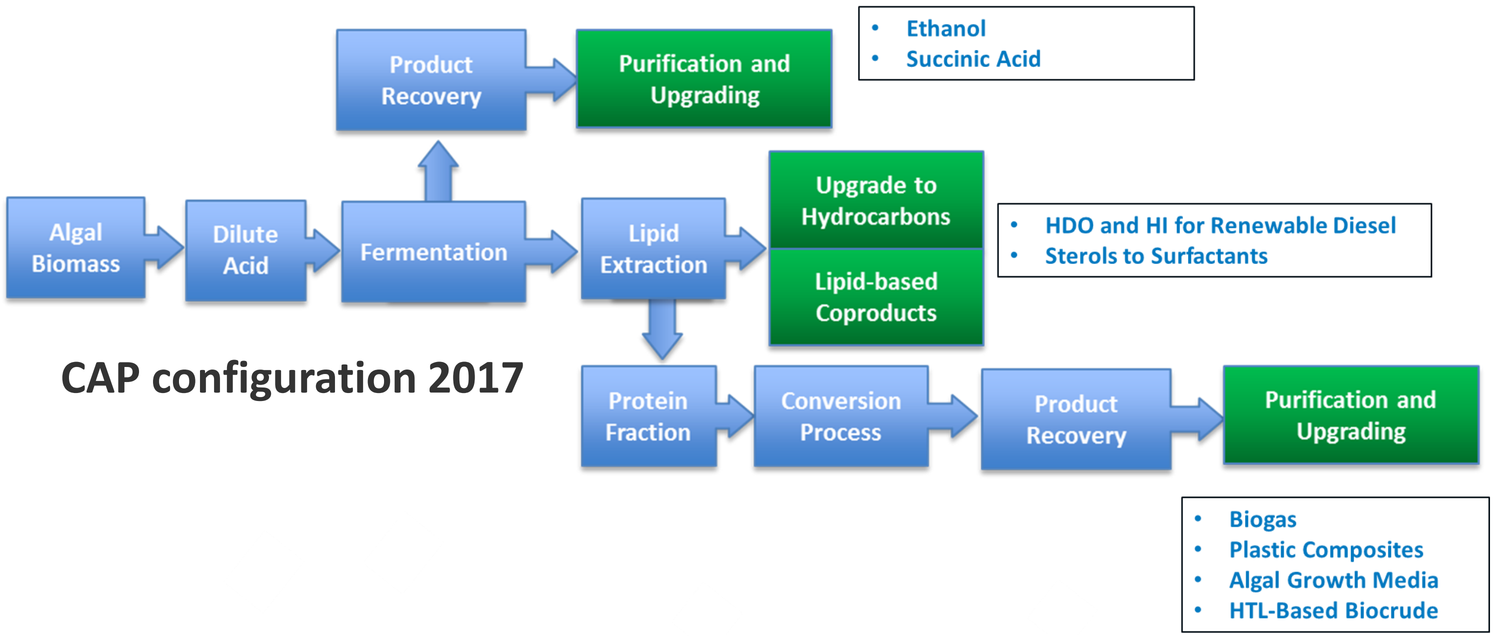




Combined Algal Processing (CAP)

Goal Statement

Goals: *Reduce algal biofuel production cost* by integrating advanced process options for the conversion of algal biomass into fuels along with *scalable, higher value bioproducts* based on *detailed knowledge of algal biomass composition* using *novel conversion pathways* leveraged with *technologies developed by the BETO Biochem Conversion Program.*



Relevance: TEA modeling for algal biofuels indicate that *algal biofuels cannot achieve economic viability without coproducts.*

Outcome: *Complement work on improved cultivation productivity* to *accelerate commercialization* of algal biorefineries, leading to *expansion of 21st century agriculture*, high quality *job creation*, and *energy independence*.

Quad Chart Overview

Timeline

- Start date: 1/30/13
- Merit Review: FY18
- End date: 9/30/21
- Percent complete: 17%

	Total Costs Pre FY17**	FY 17 Costs	FY 18 Costs	Total Planned Funding (FY 19-Project End Date)
DOE Funded	$2.0M	$500K	$500K	$1.5M
Cost Share	NA			
Partners	None			

Barriers addressed

Aft-E. Algal Biomass Characterization, Quality, and Monitoring

Aft-F. Algae Storage Systems

Aft-I. Algal Feedstock On-Farm Preprocessing

Aft-J. Resource Recapture and Recycle

Objective

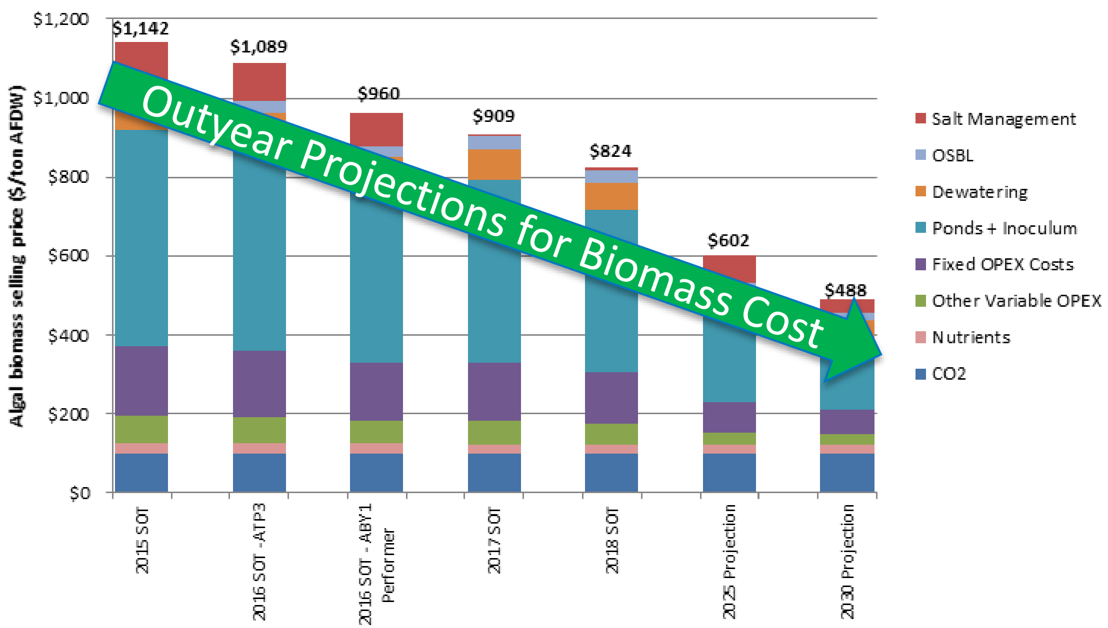
Reduce biofuel production costs through development of multiproduct biorefinery concept involving integrated conversion of all major algal components

End of Project Goal

Demonstrate integrated high protein biomass CAP process with data supporting <$3/GGE, with path to <$2/GGE

Project Overview

- *Context:* Leveraging Biochem Conversion Program processes for biomass with very different composition. Acid pretreatment enables wet lipid extraction and also efficiently hydrolyzes algal carbohydrates with no need for enzymes. Though verified cultivation productivity is increasing and cost of biomass production decreasing, the long term targeted cost for biomass will not allow economic production of algal biofuels without coproducts. Combined Algal Processing serves as basis for multiproduct biorefinery concept using lipids, carbs and proteins able to achieve MFSP goals despite high biomass cost.



Project Overview

Project Goals:

- Demonstrate integrated pathway for conversion of high lipid/carb algal biomass to a product portfolio with modeled MFSP <$2.50 per GGE.
  - Identify novel coproduct options
  - Mitigate feedstock costs by blending algal biomass with high lipid waste streams.
  - Mitigate cultivation challenges by adapting CAP process for use with high protein biomass.

Creative Advantage:

- Leverage work in Cellulosic Biochem Program to integrate conversion technologies for fuel and coproduct development to reduce MFSP.
  - The CAP multiproduct biorefinery concept is the only technology in BETO portfolio that has identified a path to reduce algal MFSP<$2.50/GGE.
  - Continued development of novel conversion operations for broad portfolio of products and inclusion of lower cost feedstocks can accelerate algal biofuel commercialization).

See Additional Slides 36-38

Approach - Management

Phil Pienkos, Project Lead

Biomass Deconstruction and Biological Upgrading

- Nick Nagle, Task Lead
- Tao Dong
- Lieve Laurens
- Eric Knoshaug
- Stefanie Van Wychen
- Ryan Spiller
- Bonnie Panczak

Thermochemical Upgrading

- Jake Kruger, Task Lead
- Earl Christensen
- Tobias Hull

- Biweekly progress update meetings
- Quarterly milestones to track progress
- Merit Review in FY18
- Go/no go scheduled for FY20
- Close Coordination with Algal Biomass Composition, RACER, Polyurethane TCF, TEA, DISCOVR, INL and SNL personnel
- Regular outreach to stakeholders

See Additional Slide 29

Approach - Technical

<u>Technical Approach:</u>

- Coordinate with other BETO projects to **identify and develop processes** for **algal biofuels and bioproducts** that can **utilize all algal components**, can be **scaled to multiple unit farms**, and can **generate significant revenue** to mitigate high cost of algal biomass.
  - Identify, develop and integrate new unit operations to expand product portfolio and evaluate TEA potential
  - Improve upon core unit operations (pretreatment, extraction, and lipid upgrading) to increase performance metrics and reduce MFSP

Approach - Technical

Potential Challenges:

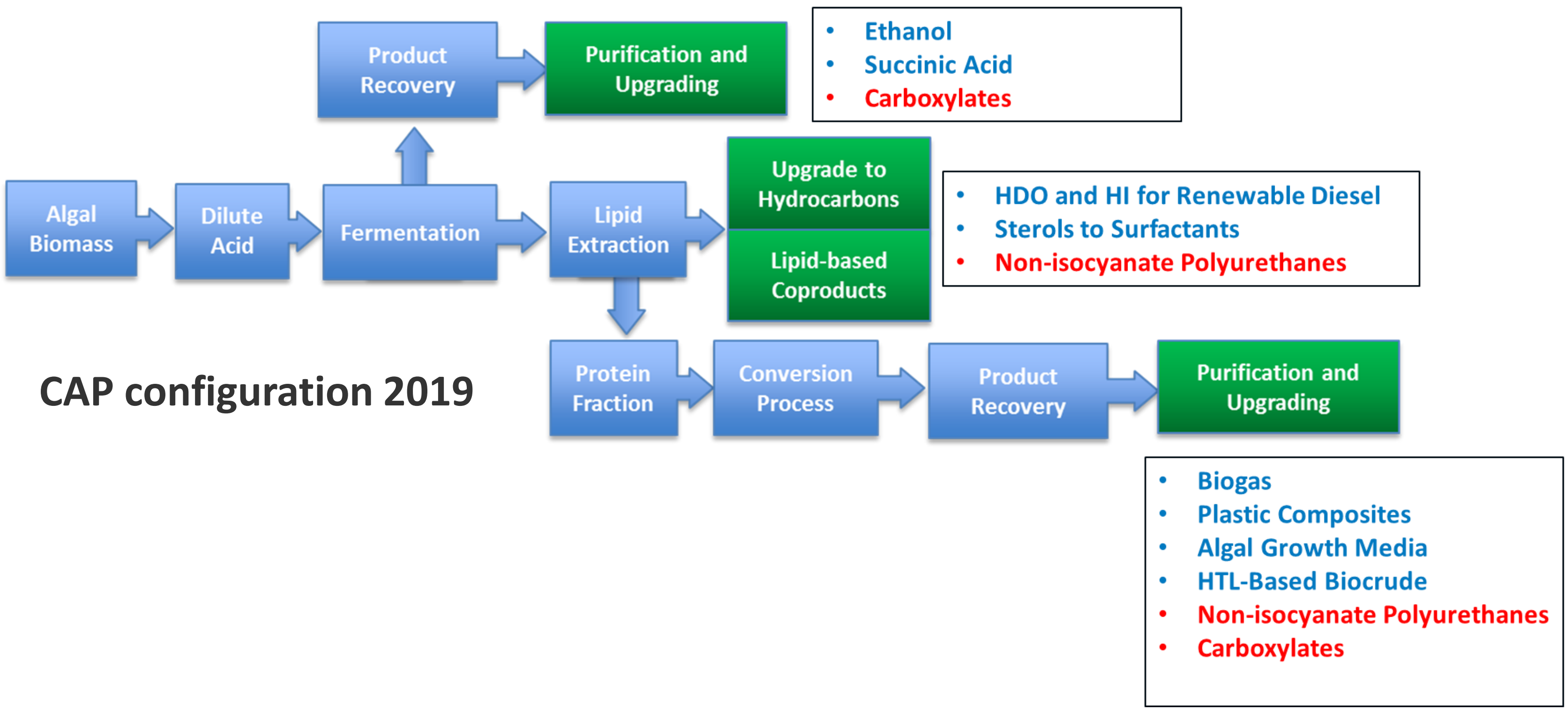
- Establishment of coproduct options with significant TEA impact
- Development of unit operations for multiple products that can plug and play within CAP process
- Build a credible concept that requires simultaneous development of technology for multiple products
- Expansion of CAP process to include options for high protein biomass (FY20 Go/No Go)

Critical Success Factors:

- Bridge gap between business strategies involving high-value, small-market products and low-value, large-market products
- Engage companies interested in coproduct market opportunities
- Reduce risks for biorefinery startups through extensive portfolio of coproducts offering breadth of opportunities

Accomplishments

- *New products for the CAP portfolio*
- *Improved efficiency of lipid extraction upgrading*
- *Modeled cost reductions to achieve <$2.50/GGE*
- *CAP process with biomass from halotolerant algae*
- *High protein biomass*

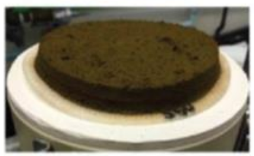


CAP configuration 2019

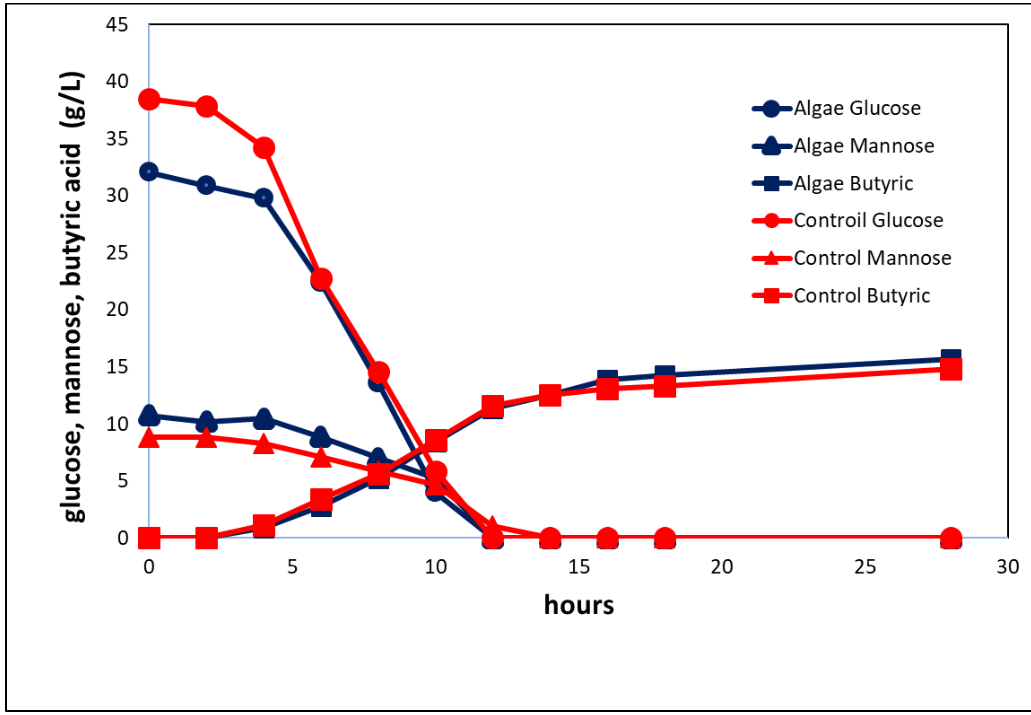
Carboxylate-Based Fuel Coproduct

Pretreated Algae Hydrolysate

Filtered liquor with algal sugars



Flocculated and vacuumed algal solids



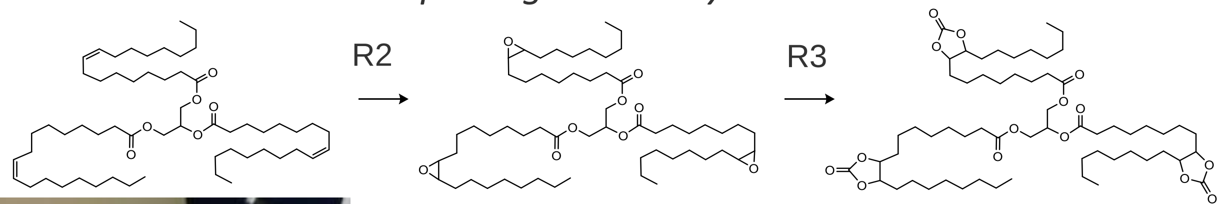
Clostridium butyricum

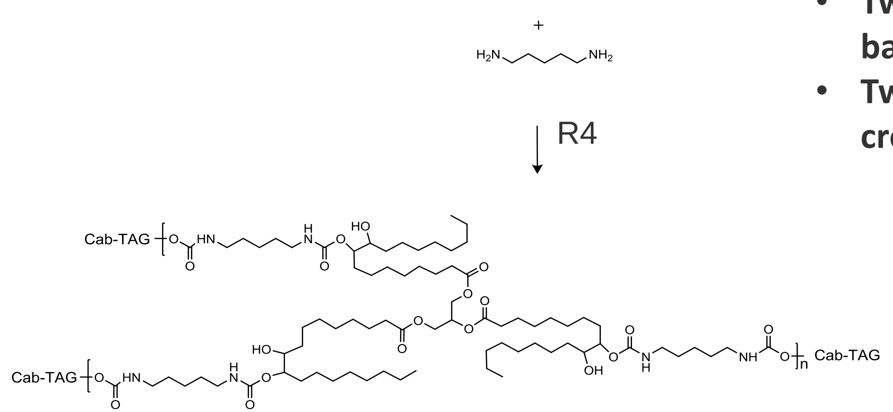
Media	Time (h)	Butyric Acid		
		Titer (g/L)	Productivity (g/L/h)	Yield (g/g sugar)
Algae Liquor	12	12.15 ± 1.21	1.01 ± 0.10	0.29 ± 0.03
	56	17.23 ± 1.05	0.31 ± 0.02	0.41 ± 0.03
Control	12	11.62	0.97	0.25
	56	15.07	0.27	0.32

Productivity and yields comparable to that seen with cellulosic hydrolysate

NREL Proprietary Non-Isocyanate Polyurethane Technology

Fully Renewable **Polyurethane Plastics** from unsaturated lipids and protein-derived amine cross linkers - *replacing toxic isocyanates*





Resins prepared from:

- **Soybean oil**
- **Linseed oil**
- **Fish oil**
- **Two algal oils**
- **Two different amino acid based crosslinkers**
- **Two peptide based crosslinkers**

Dong et al. USPTO provisional patent: 62/482238

Subject of Technology Commercialization Fund project FY19

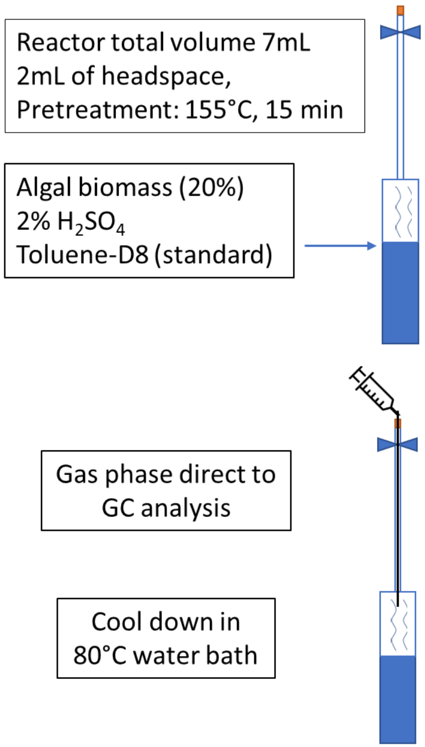
See Poster #64 March 5 for more information about Technology Commercialization Fund Project NL00TCF1 (6.6.0.1), "Fully Renewable Polyurethane Resins Produced from Algae and other Feedstocks"

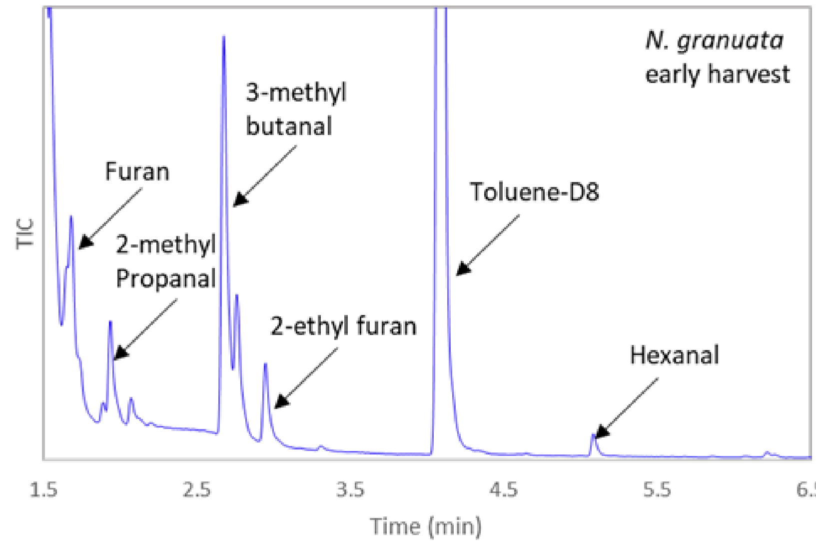
Polymer properties linked to level of unsaturation of initial oil and nature of amine-cross linker. The potential number of possible polymers is nearly limitless

See Additional Slide 32

Volatile Compounds in Algal Biomass

Determine if high value coproducts can be recovered from pretreatment vapor phase





Compounds	*Nannochloropsis granulata* Early harvest	Middle harvest	Late harvest
	Concentrations in ppm		
Acetaldehyde	0	0	7.99
Ethanol	0	0	0
Furan	5.46	0.97	0
2-methyl propanal	1.42	0.59	2.04
3-methyl butanal	7.44	2.67	4.16
2-ethyl furan,	1.04	2.61	0
Hexanal	0.3	0.29	0.83

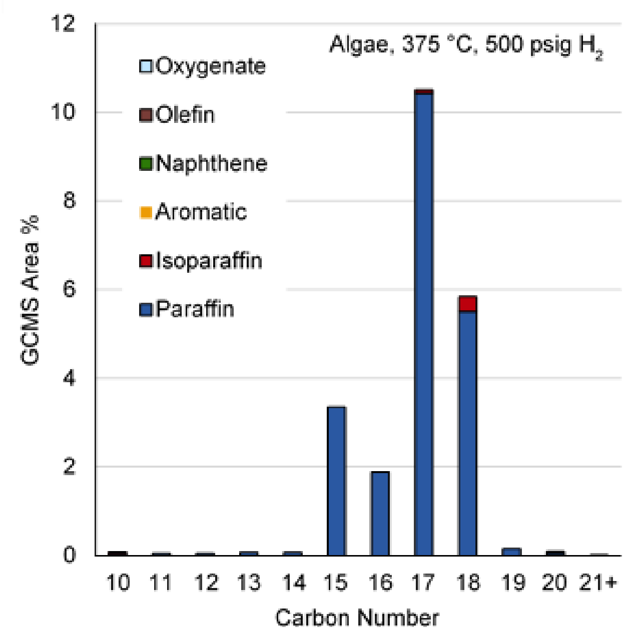
Interesting compounds identified but concentrations too low to warrant further work.

Progress in Lipid Extraction and Upgrading

Solvent System	Total FAME Recovery (%)
Hexane	87.4 ± 6.0
Hexane/EtOH	96.0 ± 0.4
Naphtha/EtOH	95.7 ± 1.7

Substrate	Temp (°C)	Pressure (PSIG)	Liquid Yield (wt%)	Conversion (%)	Fuel Range Hydrocarbon Yield (%)
10% Oleic Acid	325	300	88.4	100	88.4
11% Algae Oil	325	300	80.1	44.2	5.8
11% Algae Oil	375	500	94.6	95.3	89.6

Lipid Upgrading with Pt/SAPO-11 catalyst

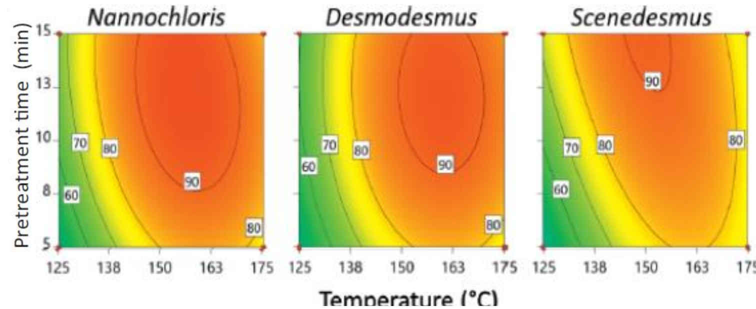


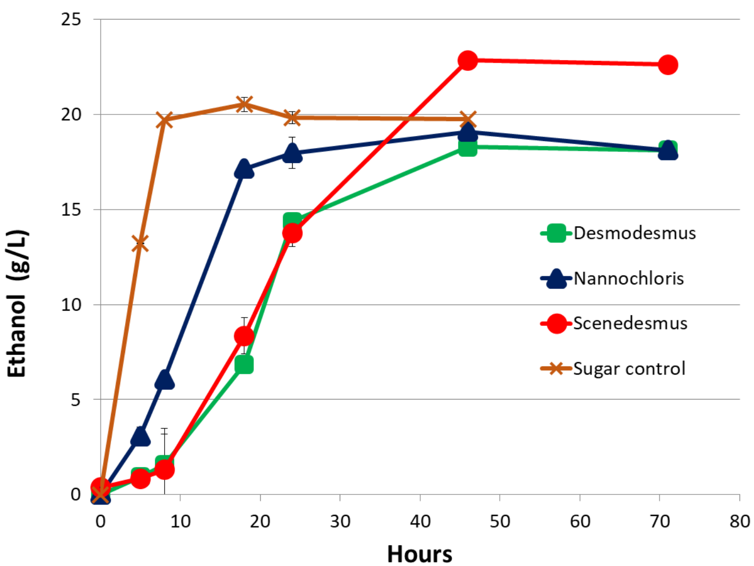
Improvements in lipid extraction and upgrading included in FY18 SOT resulted in 12% improvement in MFSP

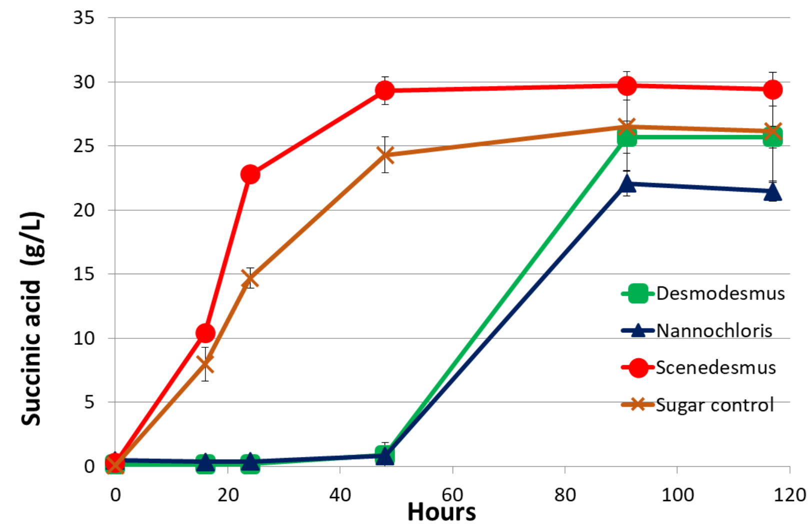
Halotolerant Strains

Improve sustainability of algal biofuel process by reducing freshwater usage

	FAME (%)	Total Carb (%)	Glucose (%)	Mannose (%)	Protein (%)	Ash (%)
Desmodesmus	30	37.7	24.8	12.1	10.2	7.6
Nannochloris	16.5	38.3	27.2	3.4	15.6	12.5
Scenedesmus (freshwater benchmark)	30.8	44.3	34.9	8.8	10.9	1.6

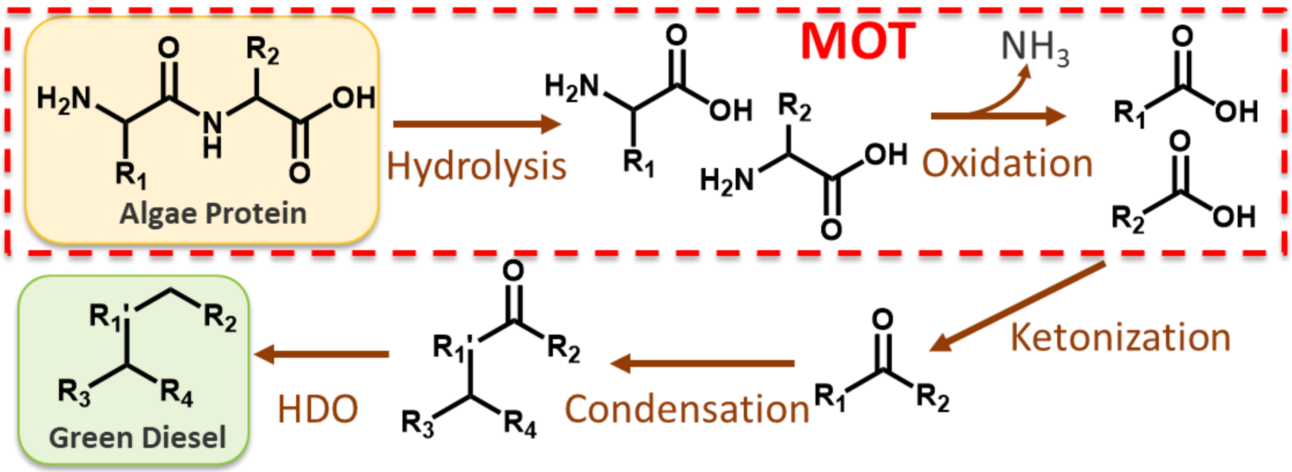






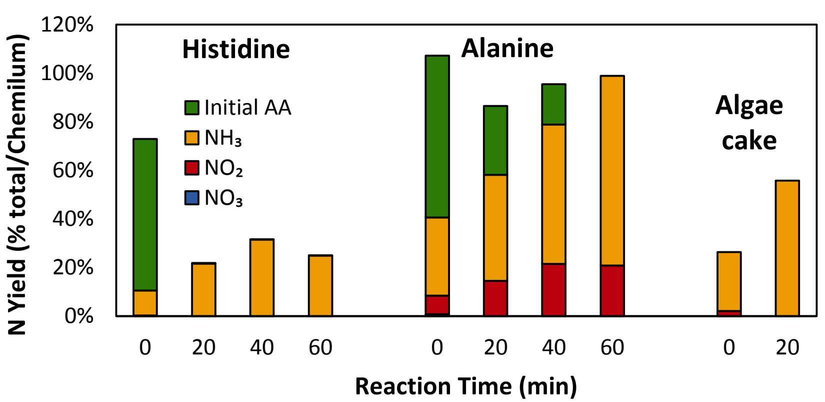
	FAME Yield	FAME Purity
Desmodesmus	82.6 +/- 6.8	101.6 +/- 1.0
Nannochloris	104.2 +/- 4.7	90.5 +/- 0.3
Scenedesmus	96.7 +/- 14.1	101.4 +/- 0.3

Mild Oxidative Treatment (MOT)

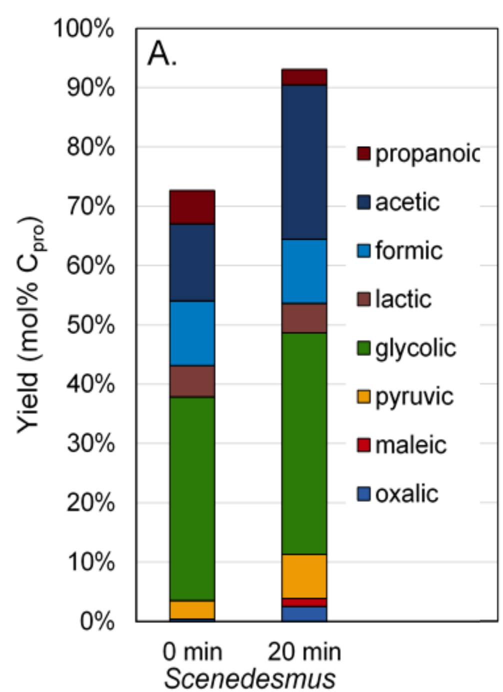


Algae cake

Oxidized Algae cake



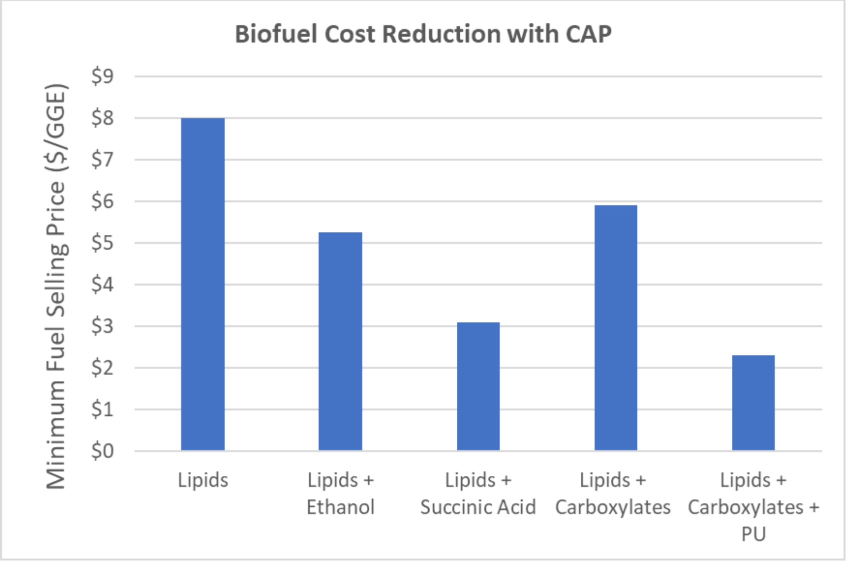
- Focus on conversion of carboxylates to hydrocarbons
- Yields to hydrocarbons will be critical metric



Mild Oxidative Treatment (MOT) is promising pathway for conversion of CAP residuals to biofuels and ammonia for recycle to algae ponds

Relevance

- **Goals:** Reduce biofuel production costs through development of multiproduct biorefinery concept with integrated conversion of all major algal components.
- **Importance and Alignment with BETO Goals:** This project supports the MYP Goals for 2019, 2020, 2024, and 2030 regarding biofuel and bioproduct in support of BETO's goals for mature modeled MFSP of $2.5/GGE for biofuels.
- **Relevance to the bioenergy industry:** The algae industry has largely shifted away from biofuels in favor of higher value products. However the coproducts generated by CAP process options, especially our novel polyurethane chemistry can significantly reduce MFSP and is gaining traction with industry as noted by TCF partnership with Patagonia and Algix.
- **State of technology and commercial viability:** Advances in biomass conversion play a key role in BETO's annual SOT analysis, and CAP process improvements are integrated into that analysis. By advancing the state of technology, this project could and positively impact the commercial viability of algal biomass technologies.
- **Tech transfer:** Both Patagonia and Algix received licensing rights for NREL novel polyurethane chemistry.



Future Work

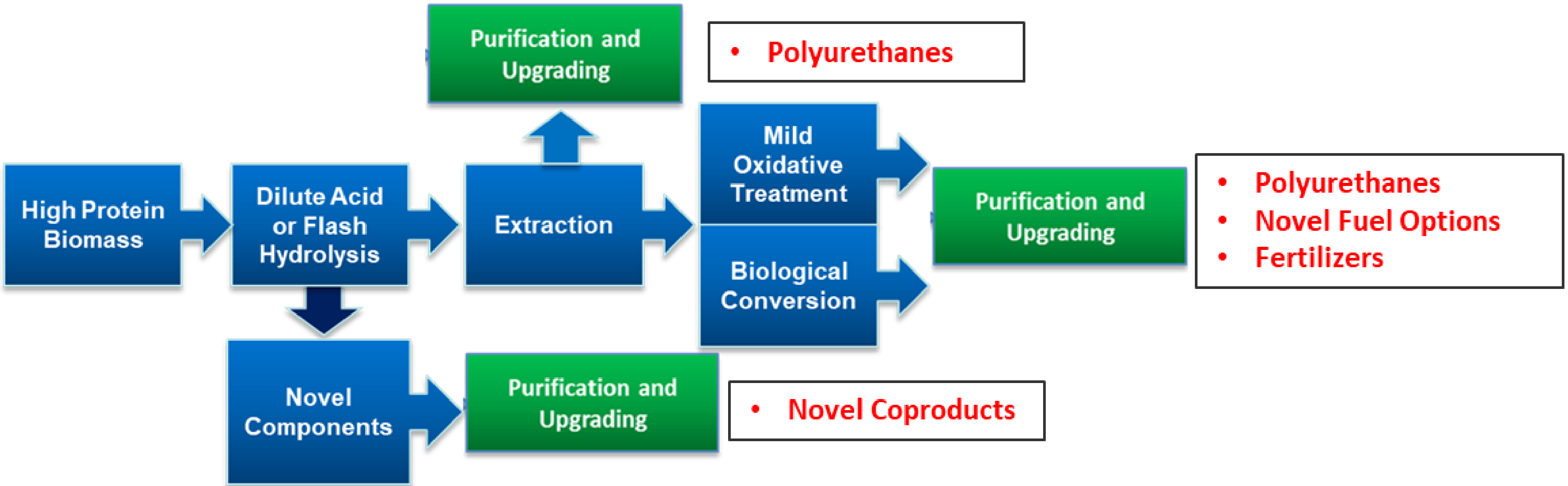
FY19 (Begin transition to high protein biomass)

- Integrated CAP processing of halotolerant algal biomass and biomass/brown grease blend pretreated in Q2 to provide data for FY19 SOT
- Evaluate process options for conversion of high protein biomass to establish modified CAP process focusing on high carbon conversion efficiency of proteins to biofuels

FY20 (Focus on high protein biomass)

- Integrate at least one new fuel/coproduct option for high protein biomass based on new information from detailed compositional analysis and provide data for TEA.
- Work with Old Dominion University to compare efficacy of flash hydrolysis vs. dilute acid pretreatment for disruption of high protein biomass.
- Go/No Go: Compare modeled MFSP for high protein biomass conversion approaches under development at NREL and SNL based on projected feedstock costs, processing costs, biofuel intermediate yields, and coproduct contributions.
- Establish basecase biofuel production cost of <$5/GGE from high protein algal biomass using validated aspirational MBSP (for open ponds, $490/ton AFDW) with >50% of algal carbon slated for biofuels

High Protein CAP Process



See Additional Slide 29

Summary

1. **Overview:** Combined Algal Processing provides a flexible approach to identifying low cost/energy routes to a wide portfolio of biofuels and bioproducts using all main algal components.
2. **Approach:** CPR works closely with other BETO projects to integrate with multiple stakeholders providing synergies across the project portfolio.
3. **Technical Accomplishments:** Several new product options were identified since last peer review and critical path operations such as lipid extraction and upgrading have been improved. The biomass feedstocks have been expanded to include halotolerant algal strains as well as algal/wet waste blends.
4. **Relevance:** CPR is critical to the AAS portfolio providing process options and data for SOT analyses. TEA modeling has identified a set of CAP product options with potential for MFSP<$2.50/GGE.
5. **Future work:** Complete CAP process development with high carb/lipid biomass with integrated production run to provide data for production of fuels and coproducts using lipids, carbs, and proteins. Incorporate waste streams such as brown grease to mitigate seasonal cultivation variation. Adapt CAP process for use with high protein biomass to mitigate the challenges of providing consistent high carb/lipid biomass.

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

BIOMASS TECHNOLOGIES OFFICE

Thank You

www.nrel.gov
www.nrel.gov/bioenergy/algal-biofuels.html

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Additional Slides

Responses to Previous Reviewers' Comments

Comment	Response
Identification of potential algal species in order to meet commercial relevance could be a challenge.	Future work will involve biomass from high productivity strains identified by DISCOVR
Market sensitivity for potential co-products not considered.	This has become a more important role for TEA group; their guidance on market size for coproducts is a critical path element in evaluation.
I would have liked to hear more information on how the project envisioned controlling the culture to optimize their intended composition.	Though other projects are addressing this issue in a variety of ways, the CPR project will be focusing adapting the CAP process for high protein biomass.
Demonstration of pretreatment process with fresh and salt water species will help to provide clarity on the ability to achieve target goals.	The preliminary demonstration of the CAP process with saltwater biomass was competed in FY18 and a fully integrated process demonstration is planned for FY19.
It is not clear what if anything will be done in protein valorization under this project	Protein valorization became a key element in FY18 with the implementation of Mild Oxidative Treatment. This operation and additional biochemical conversion approaches are planned for FY19 and beyond.
It is unclear whether the fermentation portions of the CAP process will be competitive in the marketplace with competing technologies that utilize concentrated glucose feedstocks.	The fermentation processes were never meant to compete with pure sugars but rather to valorize the sugars made available by pretreatment, which would otherwise be sent to anaerobic digestion. The impact of this is reflected in reduced MFSP seen with integration of sugar-based coproducts along with lipid-based RDB.

Publications

- Arora, N., L. ML. Laurens, N. Sweeney, V. Pruthi, K. M. Mohan, and P. T. Pienkos. 2018. Elucidating the unique physiological responses of halotolerant Scenedesmus sp. cultivated in sea water. Algal Research 37:260-268.
- E. P. Knoshaug, T. Dong, R. Spiller, N. Nagle, and P. Pienkos. 2018. Pretreatment and fermentation of salt tolerant algal biomass as a feedstock for biofuels and high-value biochemicals. Algal Research 36:239-248.
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- Pienkos, P. T. 2018. “New Algae Biofuel Production Method Could Someday Compete with Petroleum”. R&D Magazine. https://www.rdmag.com/article/2018/06/new-algae-biofuel-production-method-could-someday-compete-petroleum.
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- Knoshaug, E.P., A. Mohagheghi, N. Nagle J. J. Stickel, T. Dong, E. M. Karp, J. S. Kruger, D. G. Brandner, L. P. Manker, N. A. Rorrer, D. Hyman, E. Christensen and P. T. Pienkos. 2017. Demonstration of Parallel Algal Processing: Production of renewable diesel blendstock and a high-value chemical intermediate. Green Chem. 20:457-468.
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- E. P. Knoshaug, R. Spiller, N. Nagle, T. Dong, and P. Pienkos. Algal biomass and brown grease as fermentation feedstocks for advanced biofuels and biochemicals. In preparation.
- L. M. Wendt, B. D. Whalen, E. P. Knoshaug, R. Spiller, N. Nagle, T. Dong, P. Pienkos. Fermentation of ensiled algal biomass. In preparation.
- Samaratung, A, A. Teymouri, M. Martin, T. Dong, N. Nagle, P. T. Pienkos, R. W. Davis, and S. Kumar. Acid-assisted flash hydrolysis of Scenedesmus acutus for recovery of sugars and lipids. In preparation.
- R. Spiller,, E. P. Knoshaug, N. Nagle, T. Dong, A. Milbrandt, J. Clippinger, and P. T. Pienkos. Butyric acid and lipid production from raw municipal brown grease. In preparation
- A. Pereira, R. Spiller, E. P. Knoshaug, N. Nagle, T. Dong, and P. T. Pienkos. Blending of algal biomass with spent coffee grounds for reduced cost production of biofuels and bioproducts. In preparation
- J. S. Kruger, E. D. Christensen, T. Dong, T. C. Hull, and P. T. Pienkos. One-Step Upgrading of Algal Lipids to Renewable Diesel Fuel. In preparation.
- J. S. Kruger, E. D. Christensen, T. Dong, T. C. Hull, and P. T. Pienkos. Mild Oxidative Treatment of Algae Residues. In preparation.

Patents and Records of Invention

- T. Dong, L. M. L. Laurens, and P. T. Pienkos. Renewable Polymers and Resins and Making of Same. International Patent Application 2018.
- P. Pienkos. Novel polyurethanes by esterification of free fatty acids with polyols. Provisional Patent Application 2018.
- P. Pienkos. Novel food-grade surfactants from algal components. Record of Invention. 2018
- P. Pienkos, P Ciesielski, L. M. L. Laurens, and T. Dong. High performance polymer formulations. Record of Invention. 2018
- J. Kruger. E. Christensen, G. Beckham, P. T. Pienkos, and T. Dong. Mild oxidative treatment of Biomass. Record of Invention. 2018

Presentations

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- J. S. Kruger, E. D. Christensen, T. Dong, R. L. McCormick, P. T. Pienkos. Catalytic Upgrading of Algae Oils to Hydrocarbon Fuels. American Oil Chemists Society Annual Meeting. Minneapolis. 2018
- J. S. Kruger, E. Christensen, T. Dong, R. L. McCormick, P. T. Pienkos. Catalytic Upgrading of Algae Oils to Hydrocarbon Fuels. American Chemical Society Fall Meeting, Boston. 2018
- J. S. Kruger, E. Christensen, T. Dong, R. L. McCormick, P. T. Pienkos. Catalytic Upgrading of Algal Lipids to Hydrocarbon Fuels. American Institute of Chemical Engineers Annual Meeting. Pittsburgh. 2018
- P. T. Pienkos. Outside the Box Thinking at NREL—New Feedstocks, New Targets, New Processes. ABLC Next. San Francisco. 2017
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- P. T. Pienkos. A Biorefinery Concept for the for Accelerated Commercialization of Algal Biofuel Production. Asia Oceania Algae International Summit. Wuhan. 2017
- P. T. Pienkos. Identification of Halotolerant Algal Strains Suitable for Conversion to Biofuels and Bioproducts. Algae Biomass Summit. Orlando. 2017

Posters

- E. P. Knoshaug, R. Spiller, N. Nagle, T. Dong, L. Laurens, D. Peterson, and P. T. Pienkos. Fermentation of Salt Water Grown Algal Biomass through Combined Algal Processing Provides a Variety of Co-product Options. Seattle 2018.
- J. S. Kruger, T. Dong, E. Christensen, G. M. Fioroni, R. L. McCormick, P. T. Pienkos. Hydroprocessing Algal Lipids to Renewable Diesel Blend Stock. ABO Algae Biomass Summit. Salt Lake City, UT. 2017.
- T. Dong, L. Laurens, P. T. Pienkos. Fully Renewable Polyurethane Produced From Microalgal Lipids and Amino Acids-derived Diamines. Algae Biomass Summit. Houston. 2018
- T. Dong, N. Sweeney, W. Xiong, J. Yu, P. T. Pienkos. Improving biofuel intermediate yield and quality by tuning algal composition. Algae Biomass Summit. Houston. 2018

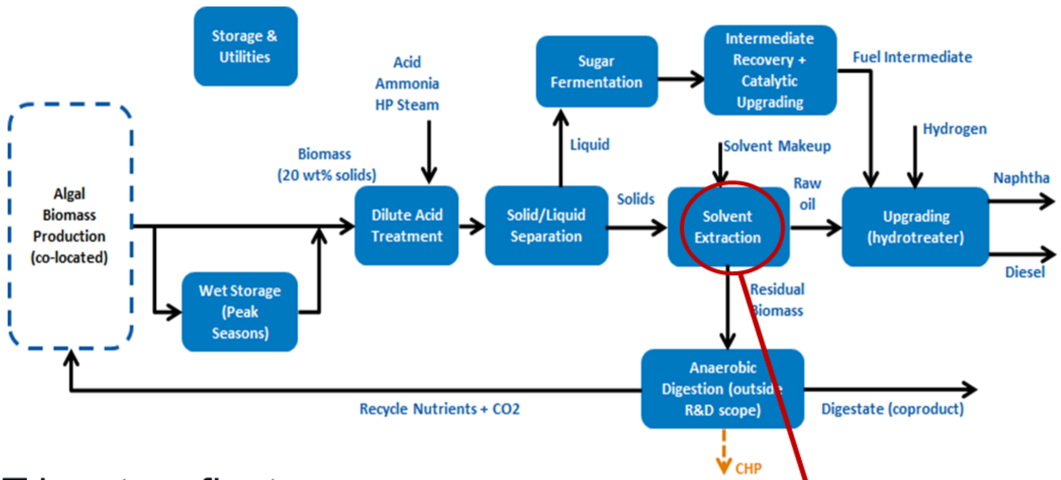
BETO Project Interactions

CAP Process Research (NREL)

Interaction	Project
Identify novel coproducts and composition-conversion interactions	Algal Biomass Composition (NREL)
Identify critical cost elements and key process opportunities	Algal Biofuels TEA (NREL)
Develop high-value coproducts from lipid and protein fractions	Polyurethanes TCF (NREL)
Evaluate storage and blending effects on conversion processes	Algal Feedstock Logistics (INL)
Coordinate work with other algae project operating in same space	Bioconversion of Algal Carbs and Proteins (SNL)
Obtain biomass samples from highest productivity strains cultivated for SOT runs	DISCOVR (PNNL, LANL, SNL, NREL)

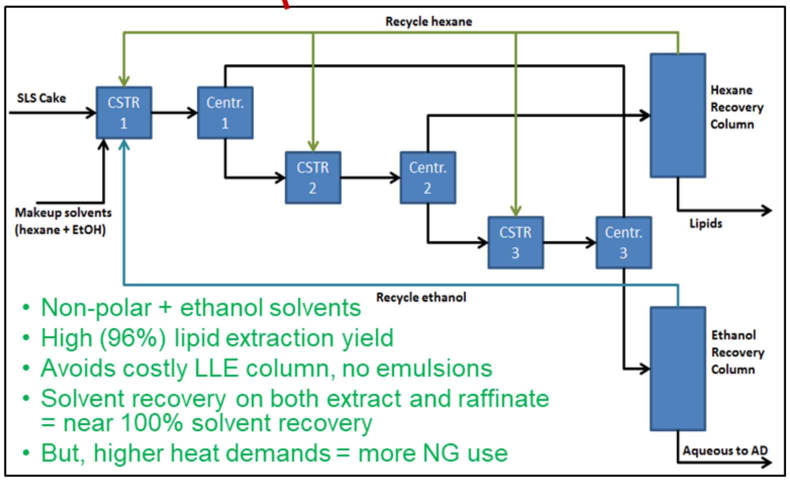
Project	Interaction
Biological Upgrading of Sugars (NREL)	Leverage carboxylate-producing organisms and upgrading catalysts/ conditions
Bench Scale Integration (NREL)	Share cultivation and separations strategies for upgrading unit operations
Targeted Microbial Development (NREL)	Develop co-products and organisms/ organism engineering approaches
Lignin First Biorefinery Development (NREL)	Inform solvolysis and hydrogenolysis catalysts and conditions
Biological Lignin Valorization (NREL)	Leverage novel coproduct processes
Lignin Utilization (NREL)	Develop oxidation catalysts and conditions

FY18 SOT: CAP Conversion (From TEA Presentation)



FY18 SOT inputs reflect:

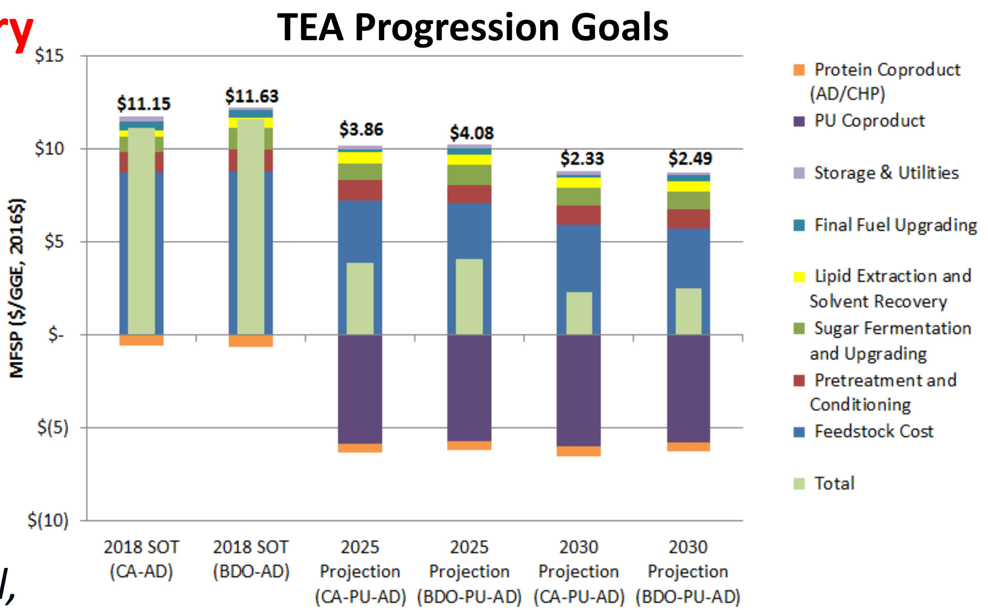
- Wet seasonal storage of biomass (inputs from INL)
- New 2-solvent extraction with light naphtha product + ethanol (from CPR) → **96% extraction yield**
- Sugars-to-HC fuels via acid fermentation (from CPR)
- Sugars-to-HC fuels via BDO fermentation (from RACER)



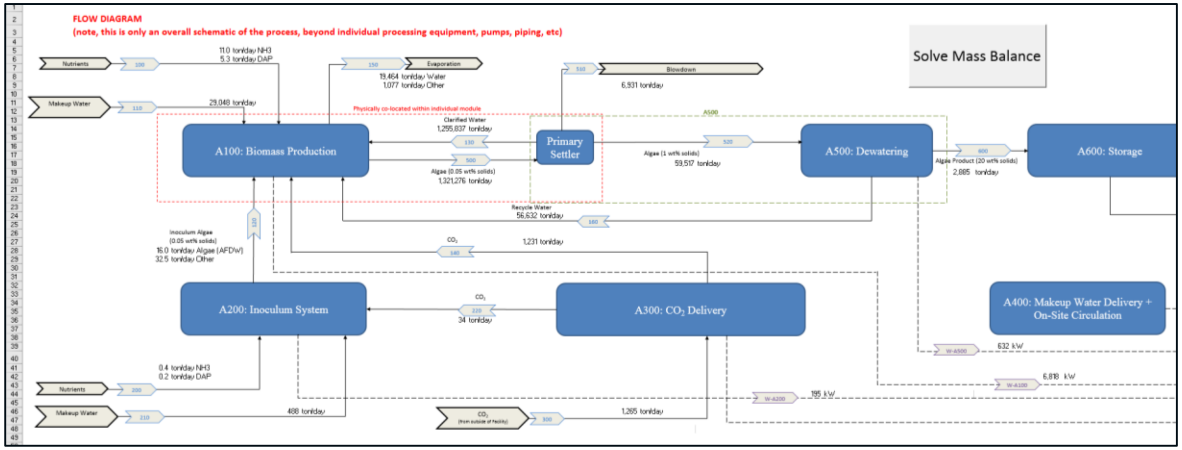
TEA Modeling for CAP Process

TEA modeling is highly relevant to industry and BETO goals:

- **Guides R&D/DOE decisions, sets targets**
  - Technical targets (yields, process performance)
  - Cost targets (basis for BETO MYPP goals)
- Identifies key R&D directions (pathways, coproduct opportunities, etc.)
- Facilitate interaction between stakeholders in industry, research, DOE
  - *Example: Outreach to GAI, MicroBio, Algenol, Clearas, Algenesis for TEA discussions*



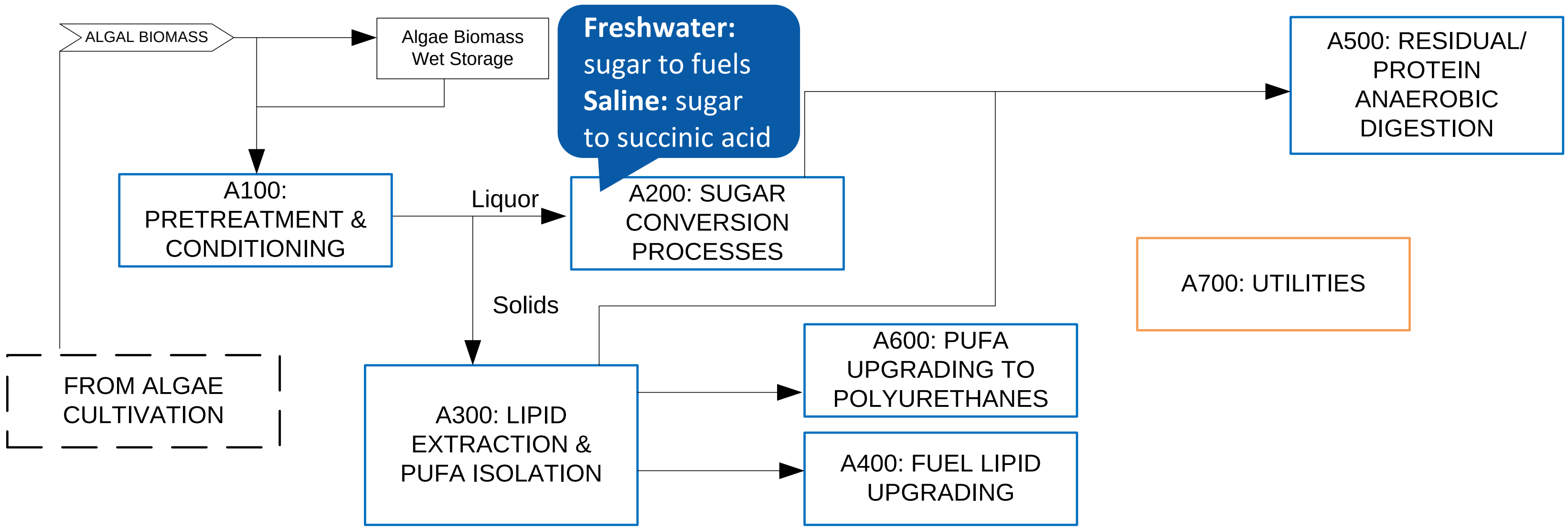
- **Foster collaboration** with other modeling groups (ANL, PNNL, ORNL, INL), BETO consortia (ATP3, DISCOVR, Sep-Con)



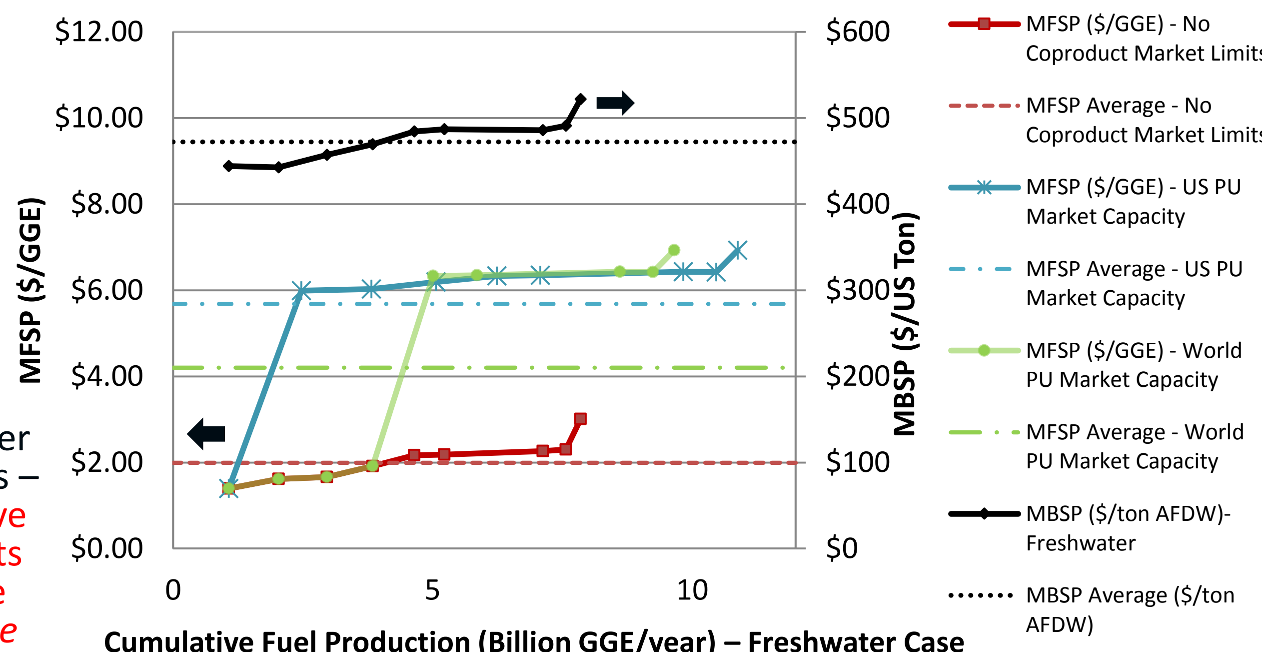
- **Public dissemination** of models: e.g. Excel-based algae farm TEA tool now available publicly:

https://www.nrel.gov/extranet/biorefinery/aspen-models/

Harmonization: Conversion to Fuels/Products via CAP



- Evaluated CAP conversion potential to achieve <$2.5/GGE for selected coproduct examples
- Evaluated over various market limit scenarios (reverted back to fuels after reaching saturation)
- ~1-4 BGGE/yr fuel potential is possible while supporting MFSP goals (for freshwater example) based on market scenarios
- Other coproduct options may further alleviate market limitation concerns – key point highlights ability to achieve MFSP goals with scalable coproducts beyond "niche" markets for a single *proof-of-concept coproduct example*

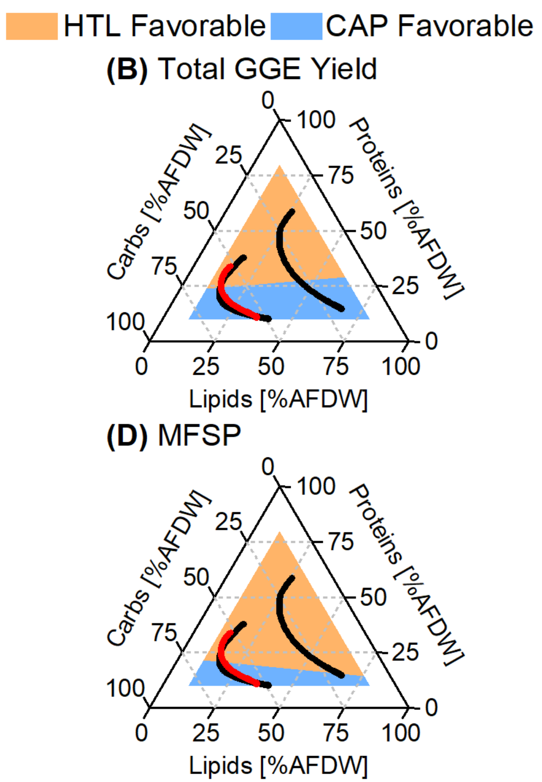


New Coproducts Can Provide Significant Revenue Relative to Biofuel Options

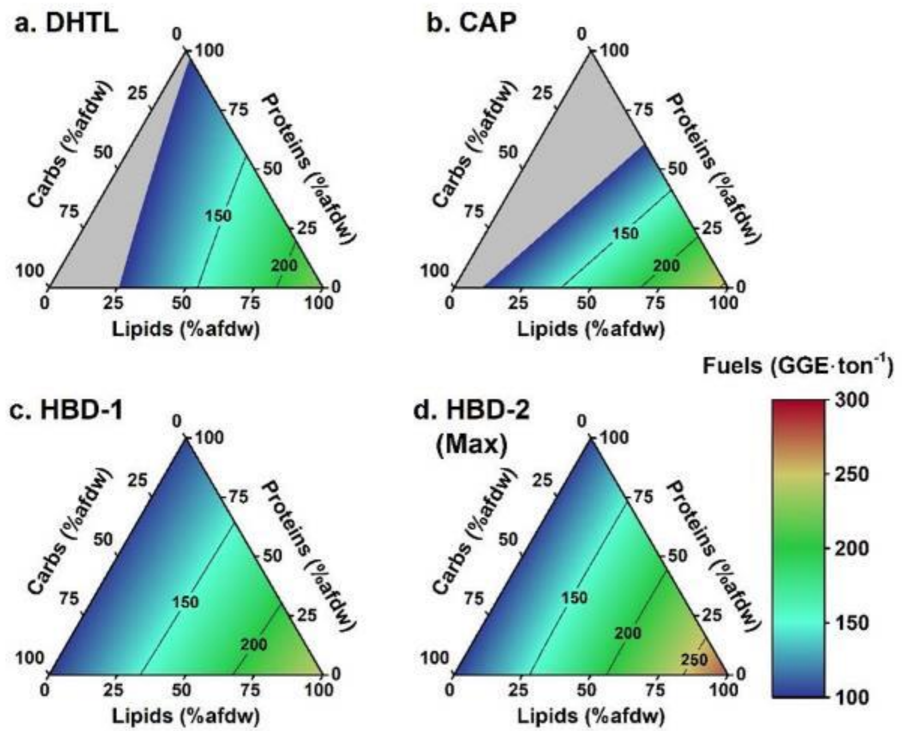
Protein-rich extracted stillage from CAP-ethanol go/no go provided to stakeholders for conversion feasibility studies

Fraction	Product	Volume Product Per Unit Farm Per Year	Revenue Per Unit Farm Per Year
Lipid	RDB from Lipids (NREL)	16M GGE	$47M
Carbohydrate	Ethanol (NREL)	5.5M GGE	$16M
Extracted stillage	Biogas (NRC)	12,500 tonnes methane	$4.3M
Extracted stillage	Cultivation medium for G. sulphuraria (ASU)	65,000 tonnes biomass	$34M
Extracted stillage	RDB from HTL biocrude (CSM)	9.3M GGE	$28M
Extracted stillage solids	Bioplastic blendstock (Algix)	32,000 tonnes	$23M–$39M

CAP or HTL or Both?



Leow et al. A Unified Modeling Framework to Advance Biofuel Production from Microalgae. Env. Sci. Technol 2018



Li et al. Demonstration and Evaluation of Hybrid Microalgae Aqueous Conversion Systems for Biofuel Production. Submitted

Cost Reduction Scenarios

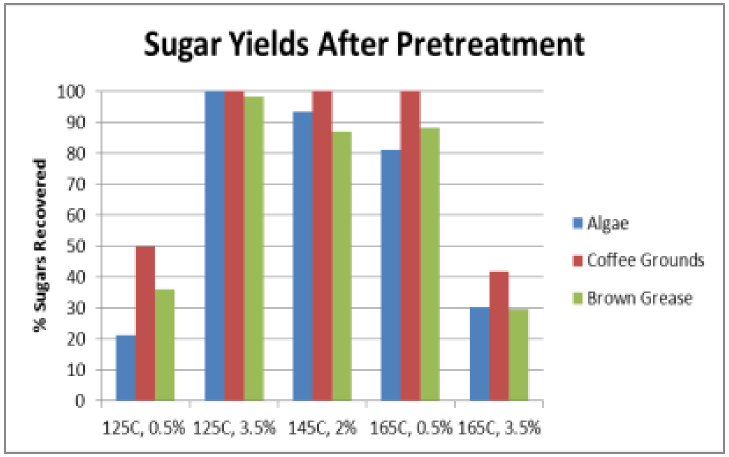
Scenario	Algae Farms Supported	Tons of Biomass Supported
Utilize 50% of US Spent coffee grounds as biomass blendstock	6	1.1M
Utilize 50% of US brown grease as biomass blendstock	11	2.0M
Capture 50% of US market for succinic acid as coproduct	13	2.4M
Capture 50% of US market for polyurethane as coproduct	38	7.1M

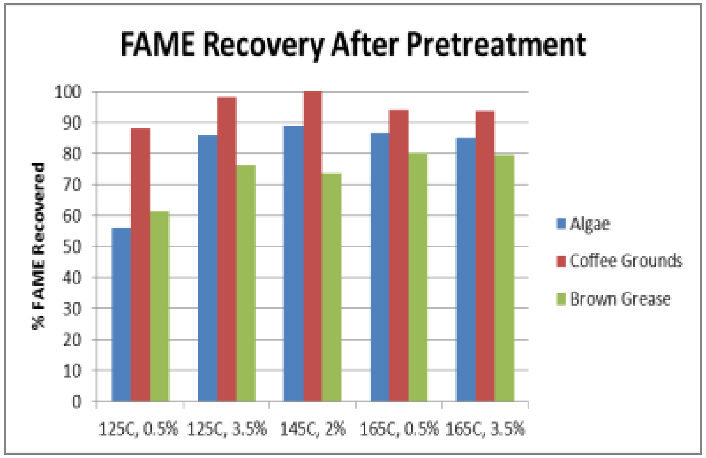
Source: R. Davis and J. Markham. National scale potential for algal coproducts to achieve $2/GGE. Go/No Go Milestone. June, 2018

Wet Wastes As Substitute for Algal Biomass

Compositional analysis of fresh and spent coffee grounds (NREL unpublished data)

Sample	% Total Ash	% Total Protein	% Lignin	% Fermentable Sugars	% FAMEs	% Sterols
Algal Biomass	2.4	13.2	0.0	47.8	27.4	1-2
Fresh Coffee Grounds	4.4	11.5	15.9	29.2	14.9	0.12
Spent Coffee Grounds	1.6	10	22.6	38.8	18.1	0.15
Brown Grease	1.6	11	ND	7.7	63.2	ND





- **Potential to use waste streams to generate portfolio of fuels and coproducts at a fraction of the feedstock costs.**
- **Keep waste streams from entering landfills**

CAP Process Applied to Brown Grease

Table 2. Lipid and monomeric sugar recovery from the original brown grease samples without pretreatment.

Sample ID	FAME yield %	Monomeric sugar yield %
BG #1	91.9 ± 2.2	6.3 ± 0.3
BG #2	84.2 ± 3.0	27.3 ± 0.6

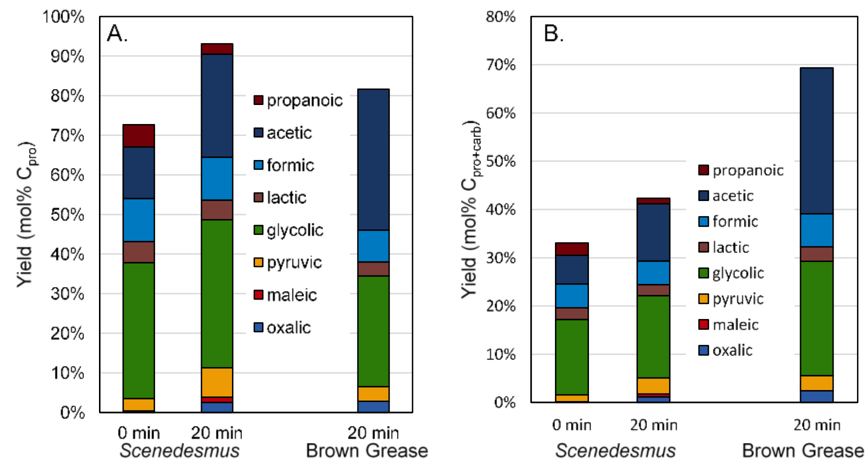
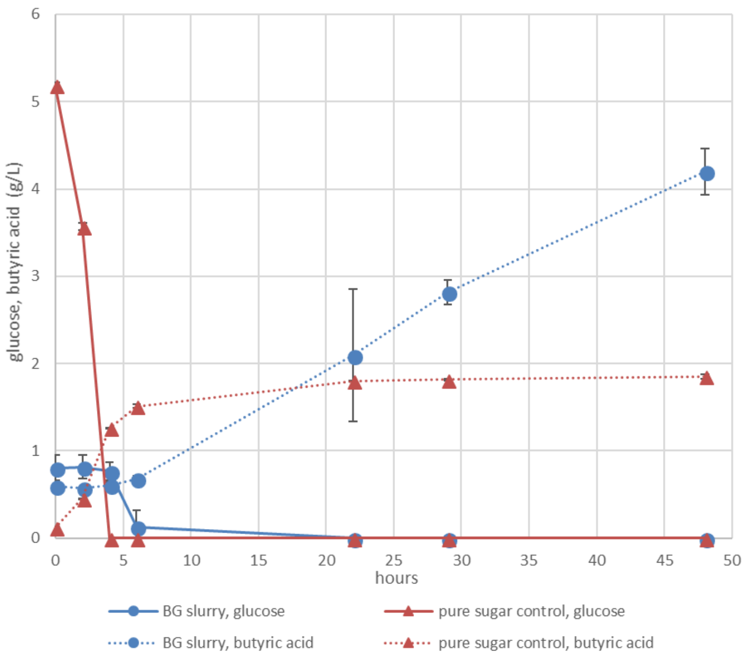
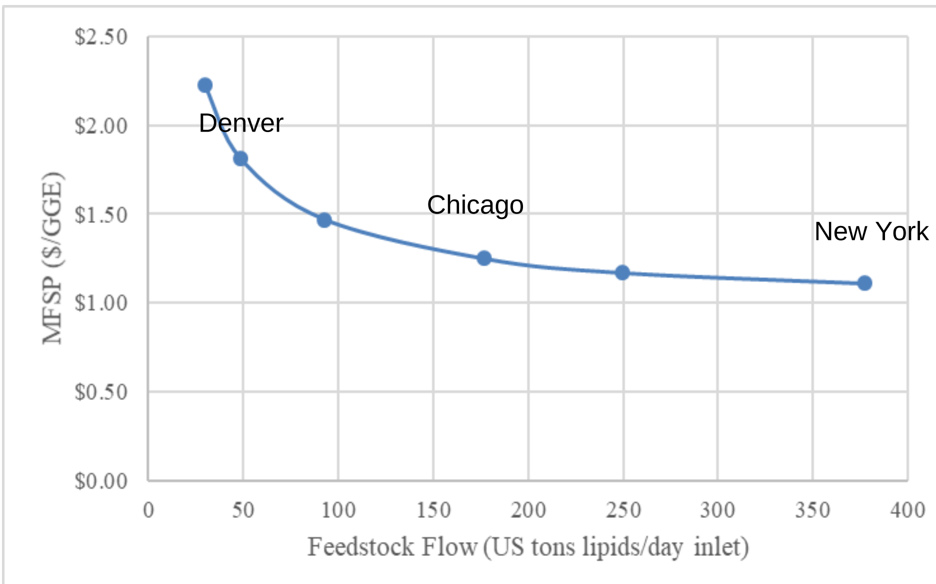
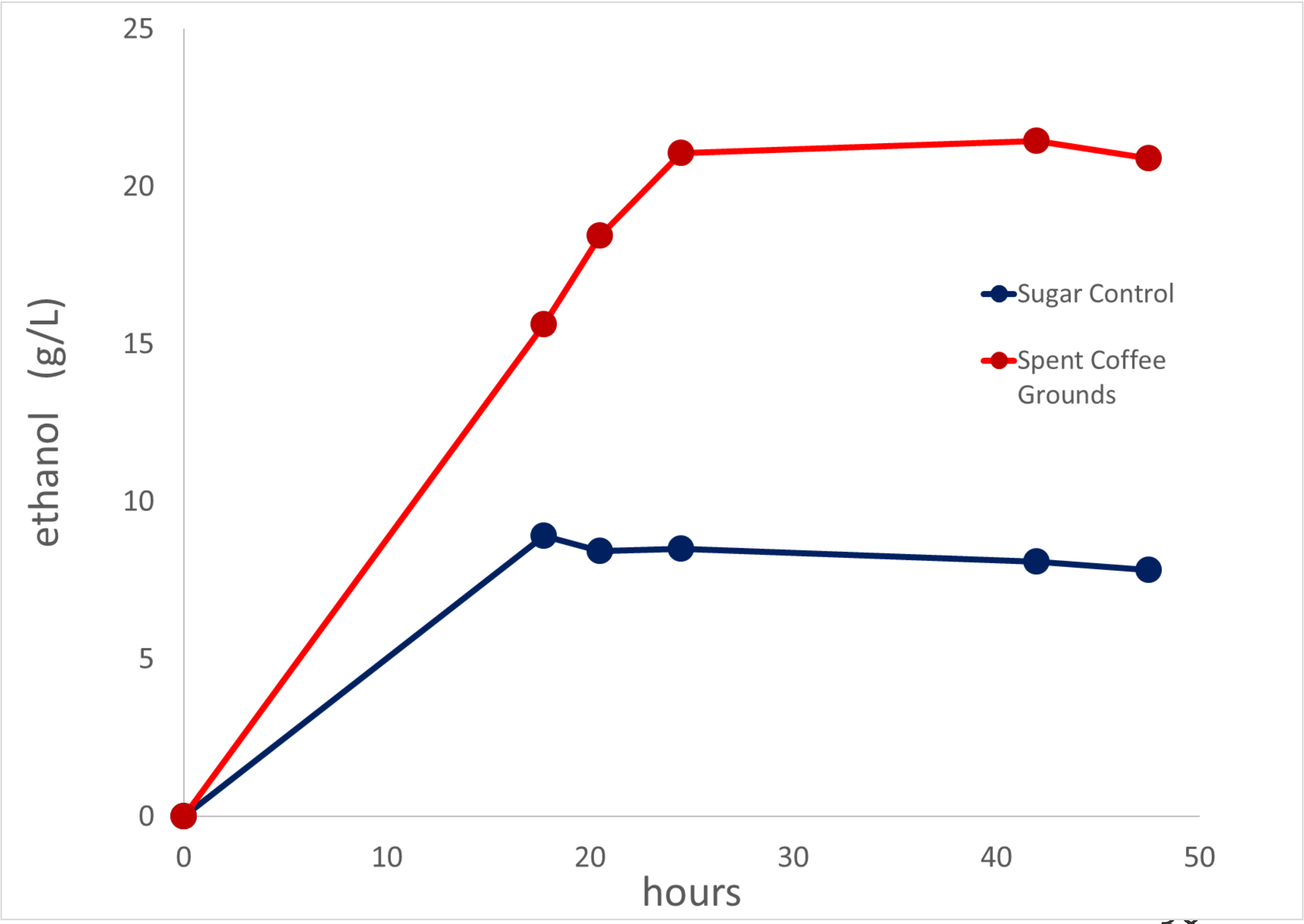


Figure 1. Carboxylic acid yield from *Scenedesmus* and brown grease extracted solids on mol% C basis.





Fermentation of Sugars from Spent Coffee Grounds



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