# BETO 2021 Peer Review: CAP Process Research

*WBS 1.3.4.201*

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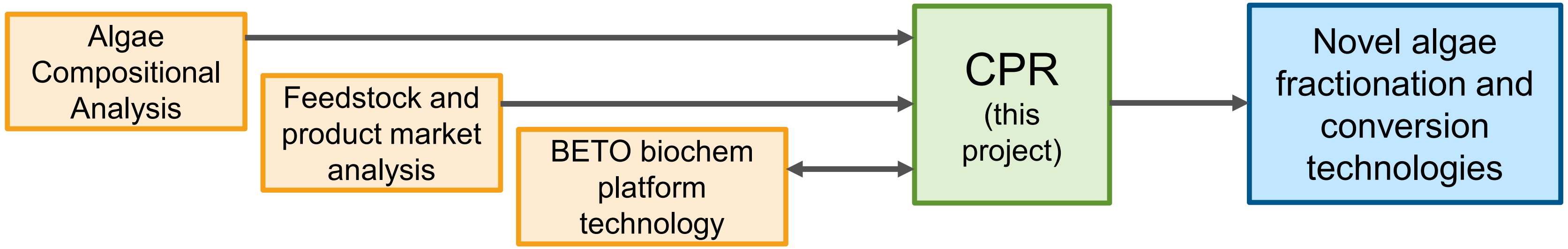
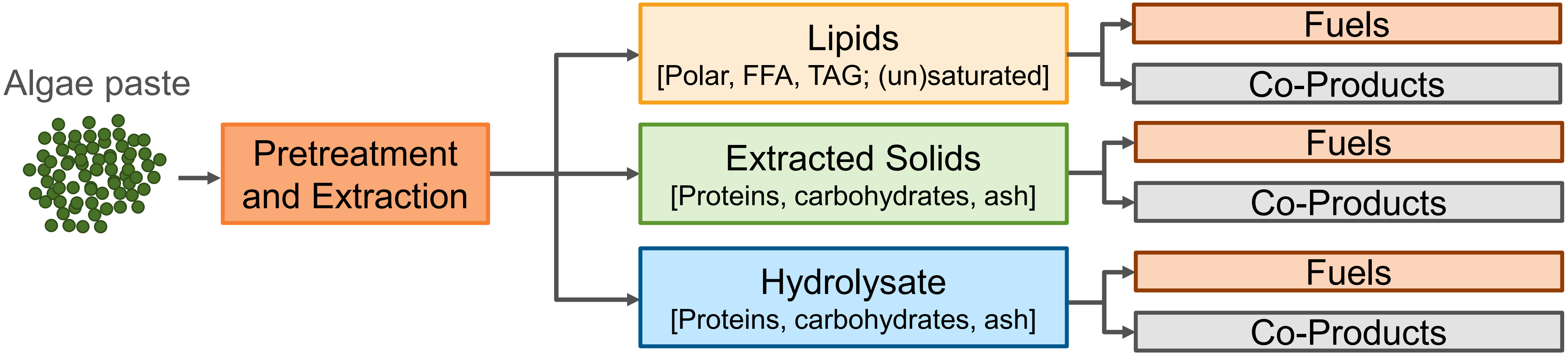
Advanced Algal Systems
March 24, 2021

# Project Overview

- **Aim:** Develop biorefinery concepts that enable economically-viable biofuel production from algae of variable composition




- **Today:** Algal biofuel production is not conducted at large scale, only high-value products, such as nutraceuticals
- **Importance:** Lignocellulose cannot fully replace petroleum; algae needed for energy independence. Large-scale algae cultivation will also create jobs.
- **Risks:** Cost of algae cultivation is main cost driver; handling low-cost algae with variable/complex composition critical to economics



## Market Trends

| | |
|---|---|
| Product | Gasoline/ethanol demand decreasing, diesel demand steady |
| Product | Increasing demand for aviation and marine fuel |
| Product | Demand for higher-performance products |
| Product | Increasing demand for renewable/recyclable materials |
| Feedstock | Sustained low oil prices |
| Feedstock | Decreasing cost of renewable electricity |
| Feedstock | Sustainable waste management |
| Feedstock | Expanding availability of green $H_2$ |
| Feedstock | Closing the carbon cycle |
| Capital | Risk of greenfield investments |
| Capital | Challenges and costs of biorefinery start-up |
| Capital | Availability of depreciated and underutilized capital equipment |
| Social Responsibility | Carbon intensity reduction |
| Social Responsibility | Access to clean air and water |
| Social Responsibility | Environmental equity |

# NREL's Bioenergy Program Is Enabling a Sustainable Energy Future by Responding to Key Market Needs

## Value Proposition

- CAP approach allows path to $2.50/GGE hydrocarbon algal biofuels in the diesel and jet range from $400+/ton algae biomass via generation of high-value co-products and TEA-guided research.

## Key Differentiators

- Co-developing fractionation and conversion technology for lowest-cost biomass to both fuels and coproducts.
- Feedback/validation loop with TEA and LCA teams via SOT and Design Reports.
- Industry outreach informs co-product development.

# Management

**PI: Jake Kruger**

**Task 1: SOT Support (Eric Knoshaug)**
Generate data for SOT and Design Reports

**Task 2: CAP Expansion (Jake Kruger)**
Identify new process and co-product opportunities

**Task 3: Algae-Based Polymers (Tao Dong)**
Novel polymer-based co-products

- **Algae Compositional and Product Analysis**
  - Stefanie Van Wychen, Bonnie Panczak, Hannah Alt
- **Algae Pretreatment**
  - Nick Nagle, Matt Fowler, Tao Dong
- **Hydrolysate Fermentation**
  - Eric Knoshaug, Ryan Spiller
- **Catalytic Upgrading**
  - Jake Kruger, Tobias Hull, Earl Christensen
- **Product Formulation and Characterization**
  - Tao Dong, Lieve Laurens, Phil Pienkos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Algal Biomass Conversion to Fuels via Combined Algae Processing (CAP): 2019 State of Technology and Future Research

Ryan Davis and Matthew Wiatrowski


NREL

Conceptual Basis and Techno-Economic Modeling for Integrated Algal Biorefinery Conversion of Microalgae to Fuels and Products

2019 NREL TEA Update: Highlighting Paths to Future Cost Goals via a New Pathway for Combined Algal Processing

Ryan Davis,[1] Matthew Wiatrowski,[1] Christopher Kinchin,[1] and David Humbird[2]

1 National Renewable Energy Laboratory
2 DWH Process Consulting LLC

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5100-75168
September 2020

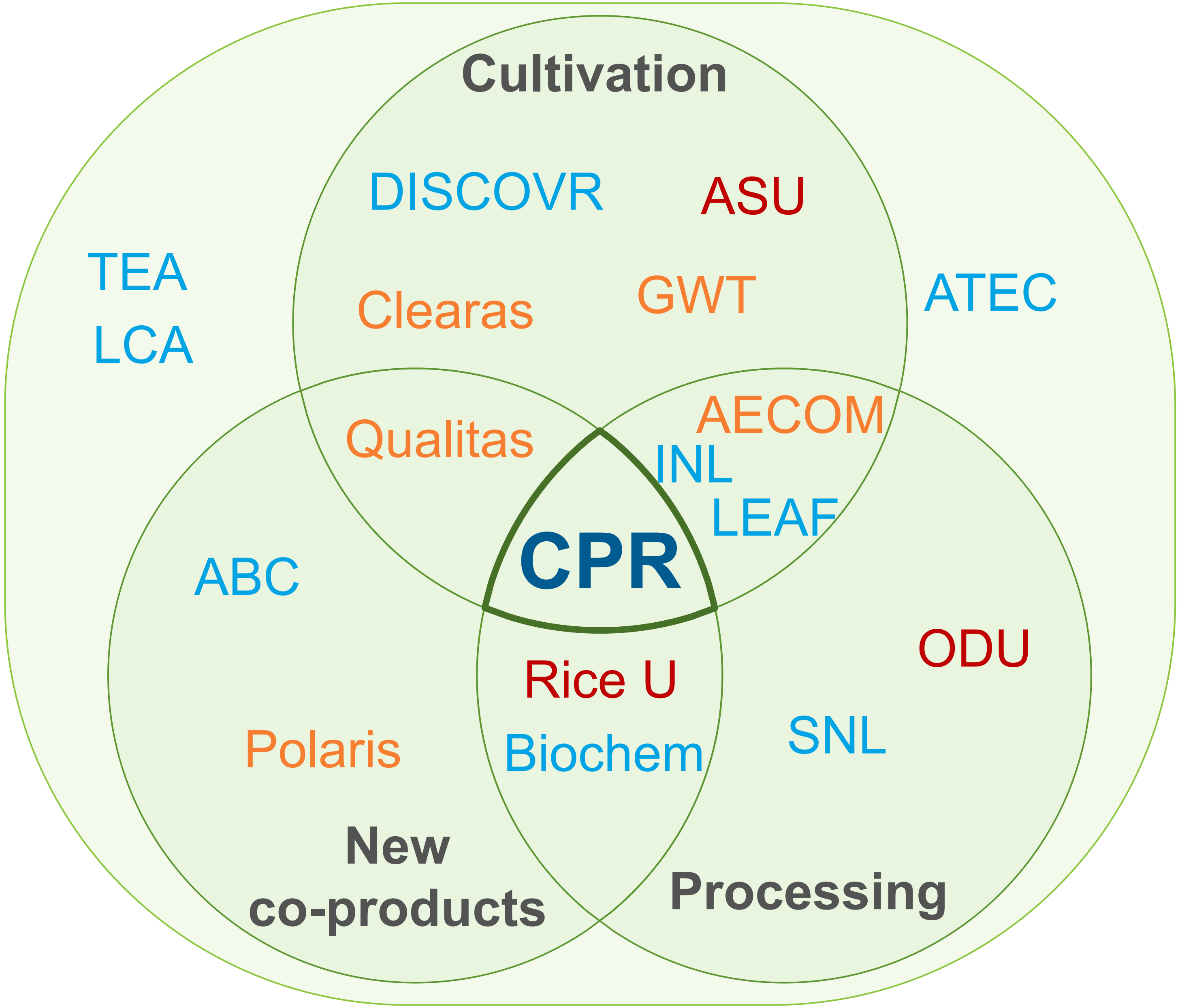
## Management Approach

- Bi-weekly meetings with project team, 1-on-1 meetings with team members as needed
- Milestones structured to enable TEA, which quantifies project success via reduction in MFSP **(success metric #1)**
- Disseminate results via publications, presentations, patent applications, technical reports **(success metric #2)**
- Leverage expertise of collaborating partners and projects to develop new concepts

## Risks

- Steps in biorefinery are interdependent – flexibility in valorization of each fraction allows strategic pivot points if one operation underperforms
- Simultaneous development of new co-products from changing algae compositions can challenge quantification of project progress – ongoing dialogue with TEA enables timely feedback on new concepts

# Management




**Collaboration and coordination with other national lab research, industry, academia**

- Understand algae composition via coordination with DISCOVR, ABC, RACER, industry
- Guide product development via industry outreach
- Guide process development via collaboration with TEA and LCA teams

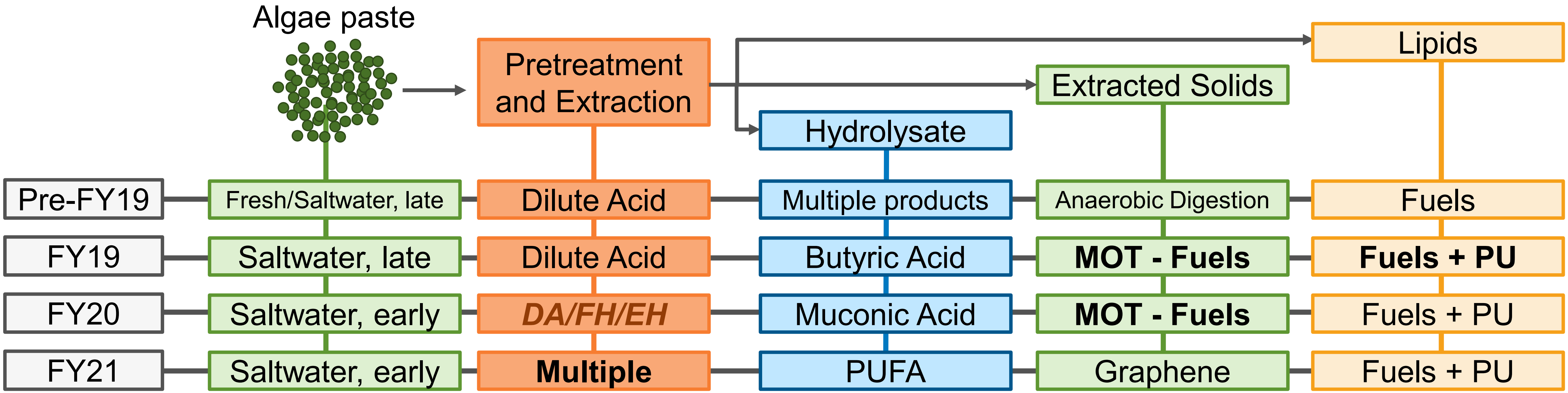
# Approach

## Technical Approach

- Develop and adapt robust technology to fractionate and valorize lowest-cost algae
- Use TEA to establish yield targets and quantify improvements in MFSP

## Potential Challenges

- Developing technology for changing and complex compositions
- Managing complexity of multiple pathways and products




Major Decision Points to Reduce MFSP: ***Go/No Go Milestone***
**Annual Milestone**

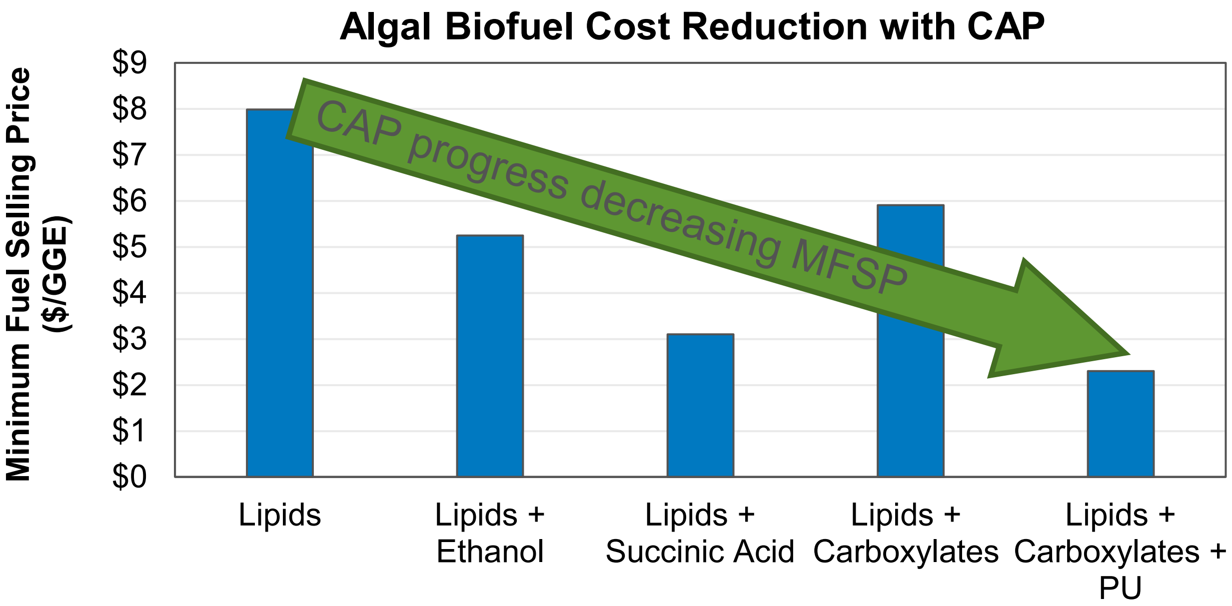
# Impact

## Economic and Market Impact

- TEA suggests pathway to produce $2.50/GGE fuels from $400+/ton biomass
- Increasing market demand for renewable fuels and products

## Environmental Impact

- Algae are powerful carbon capture tool
- Multiple co-products that fix $CO_2$ long-term




## Industrial Impact

- NIPU technology basis for TCF projects, licensing agreements, R&D 100 award
- Development of robust, high-protein processing concept enables use of “secondary product” algae from WWT, algal blooms
- TEA at early stage makes project technology more attractive to scale-up partners

## Technical and Science Impact

- Fractionation technology is necessary and must work on low-cost biomass
- Publications, presentations, patents detailing promise of integrated process

# Progress and Outcomes

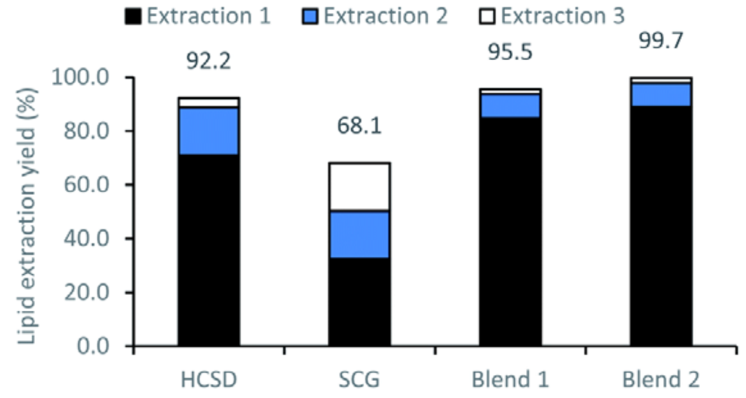
Pretreatment and Extraction

## "Leveling the Load"

- Demonstrated multiple options to mitigate up to 3-fold seasonal variability in algae production
  - Blend with brown grease or coffee grounds
  - Store excess summer biomass for use in winter
- Lipid extraction yields maintained in each case
  - Monomeric sugar yields depend on algae
- These approaches can reduce capital cost contributions to MFSP

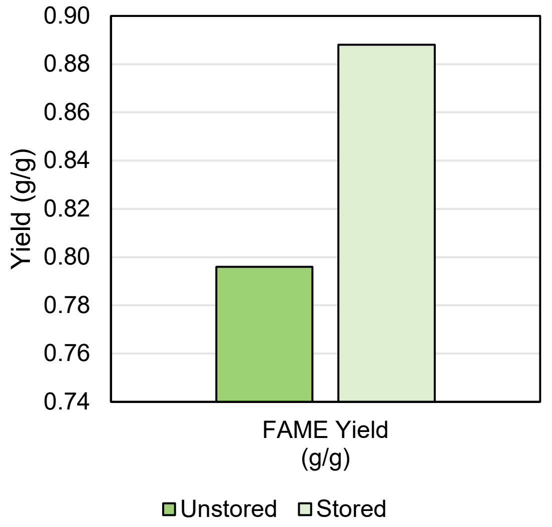
### Spent coffee grounds study

Prates Pereira et al., *Sus Energy Fuels*, **2020**, 4:3400-3408



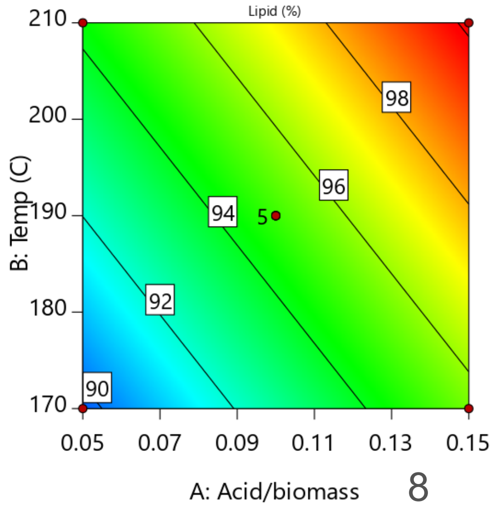

### Ensilage study

Wendt et al., ACS *Sus Chem Eng*, **2020**, 8:13310-13317

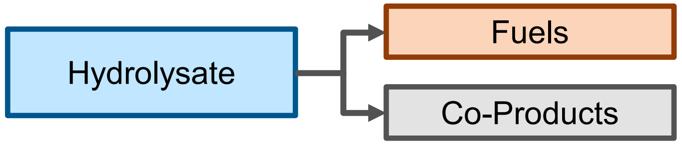



### Brown grease study

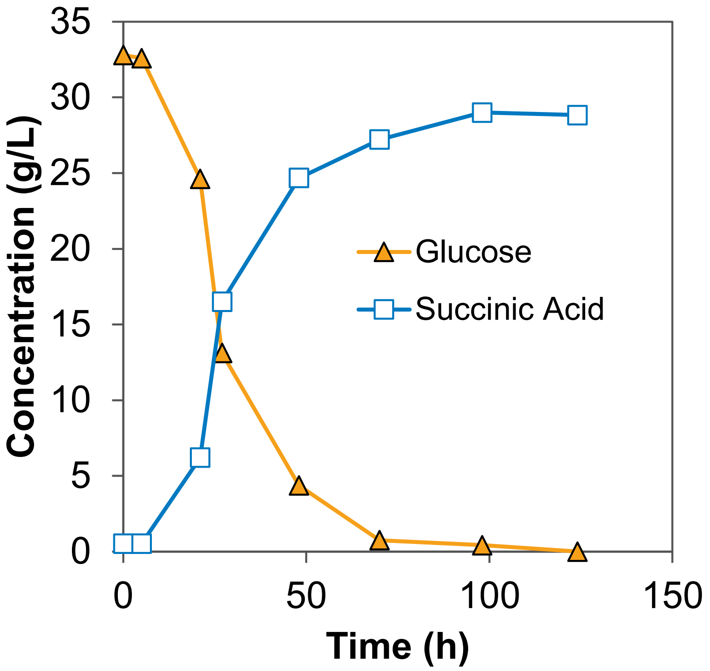
Spiller et al., *Biores Technol Reports*, **2020**, 100344



# Progress and Outcomes

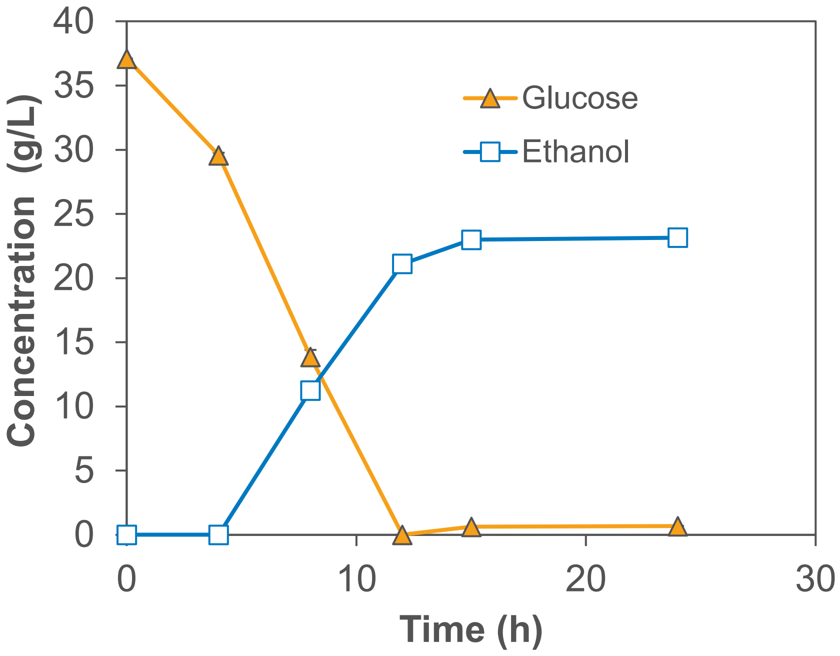



**High-carb, freshwater**
**Pre-FY19**



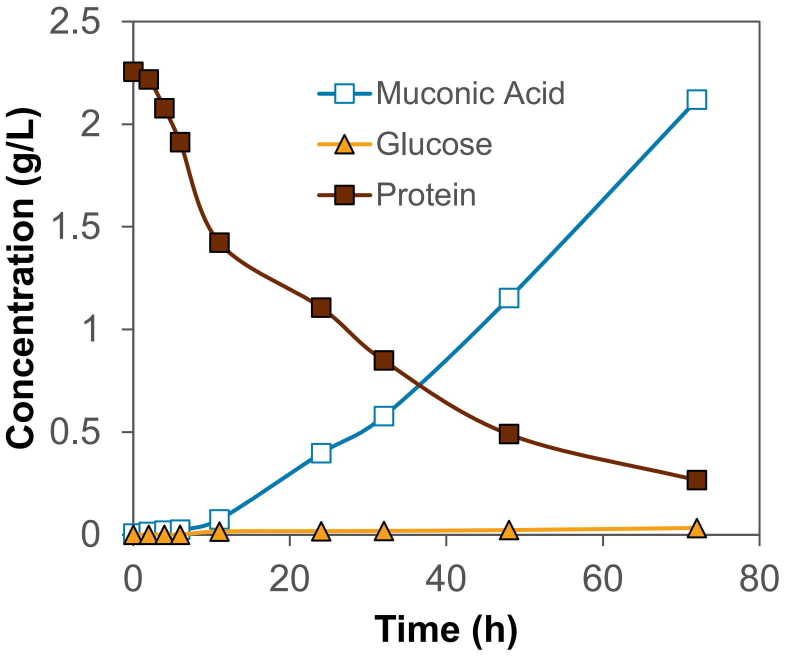

Knoshaug et al., *Green Chem*, **2018**, 20:457-468

**High-carb, saltwater**
**Pre-FY19**




Knoshaug et al., *Algal Res*, **2018**, 36:239-248

**High-protein, saltwater**
**FY20-21**

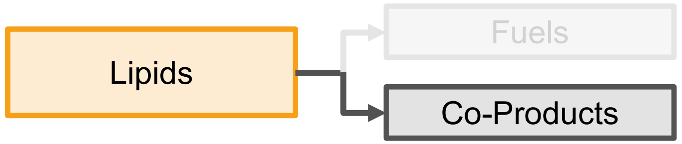



Knoshaug et al., **2021**, *in preparation*

## Flexible hydrolysate fermentation

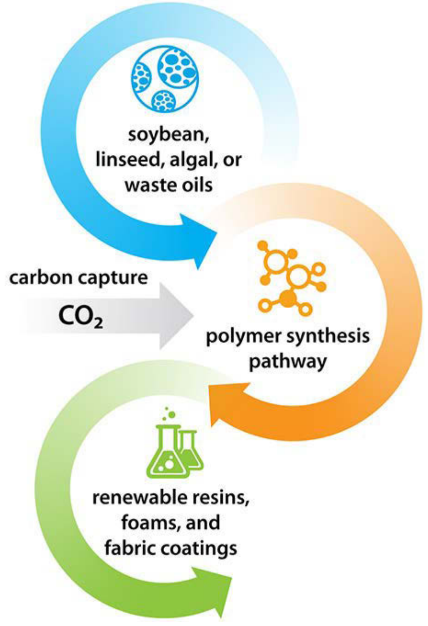
- Transition toward halotolerant and high-protein biomass necessitates salt tolerant and protein-utilizing organisms
- CAP hydrolysates support fermentation to multiple products and fuel precursors
  - Ethanol, succinic acid, butyric acid, muconic acid

# Progress and Outcomes




## Non-Isocyanate Polyurethanes

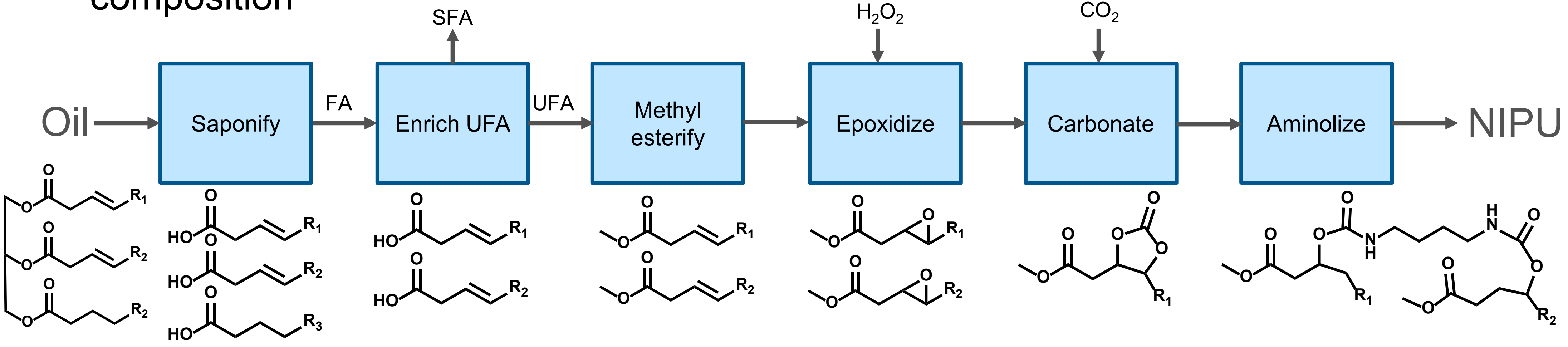
- Leverage high degree of unsaturation in algal lipids to replace toxic isocyanate crosslinkers with bio-based amines
  - Also fixes $CO_2$
- Subject of two TCF projects, *R&D 100* Special Recognition "market disruptor" award
  - Patagonia, Tempur-Sealy, Algix as partners
  - Negotiating license arrangement with Polaris Renewables
- Potential to reduce MFSP by more than $5/GGE with algae oils of favorable composition




| Fatty acid feedstock | Young's Modulus (Mpa) | Tensile strength (Mpa) | Tg (°C) |
|---|---|---|---|
| Soybean (TAG) | 3 | 1 | 1 |
| Linseed (TAG) | 590 | 16 | 40 |
| Qualitas (FAME)* | 371 | 12 | 89 |

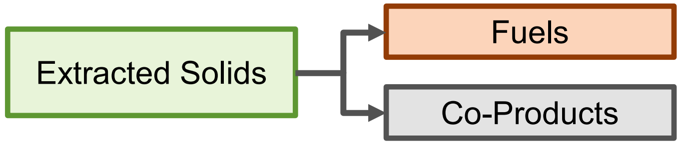
*Lower viscosity than other lipid, easier for processing

Dong et al., **2020**, US Patent App. 16/483,844, 63/063,666



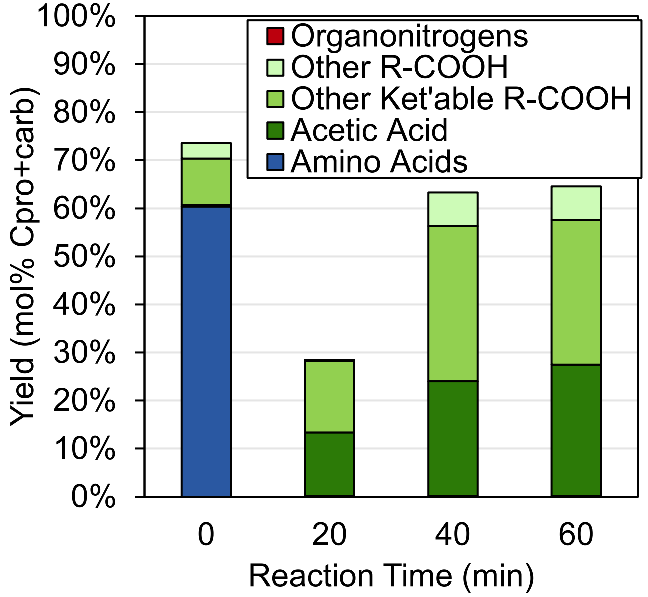

SPECIAL RECOGNITION 2020 R&D 100 BRONZE

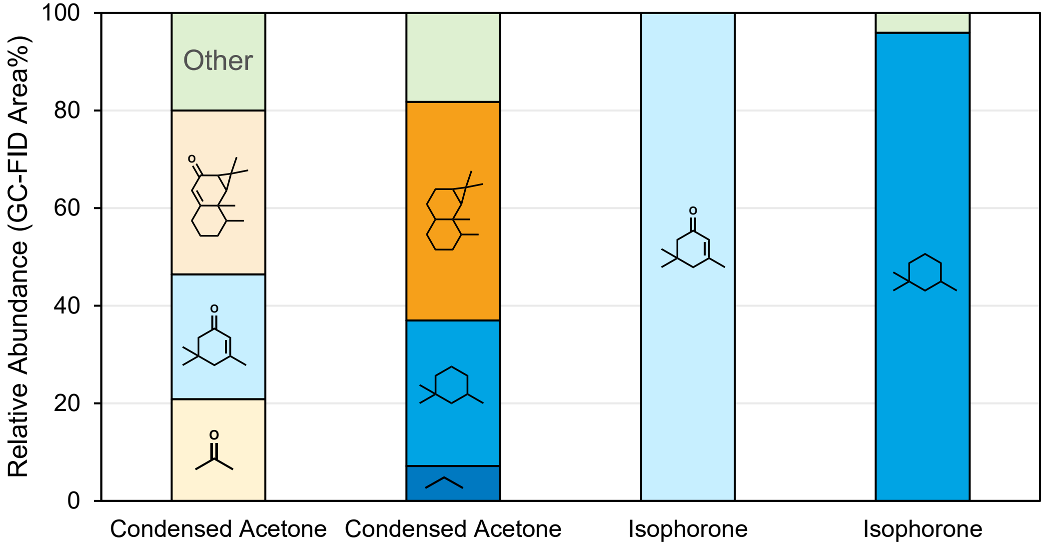
# Progress and Outcomes

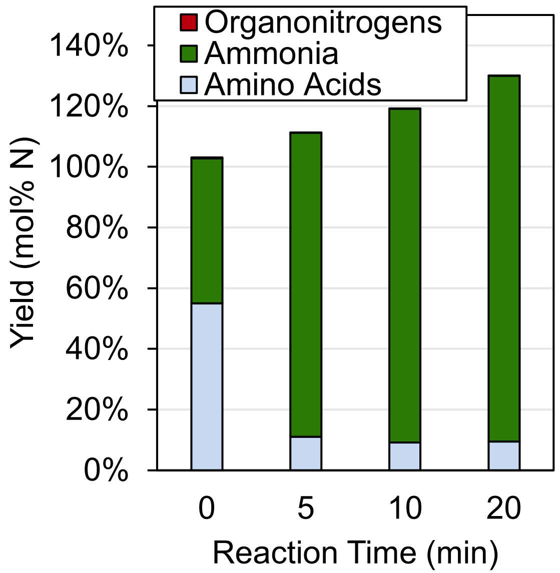



## Integrated CAP Processing

- Leverage wet oxidation (Mild Oxidative Treatment, MOT) for carboxylate production and nutrient recycle
- Carboxylic acids converted to ketones, ketones condensed to jet and diesel range





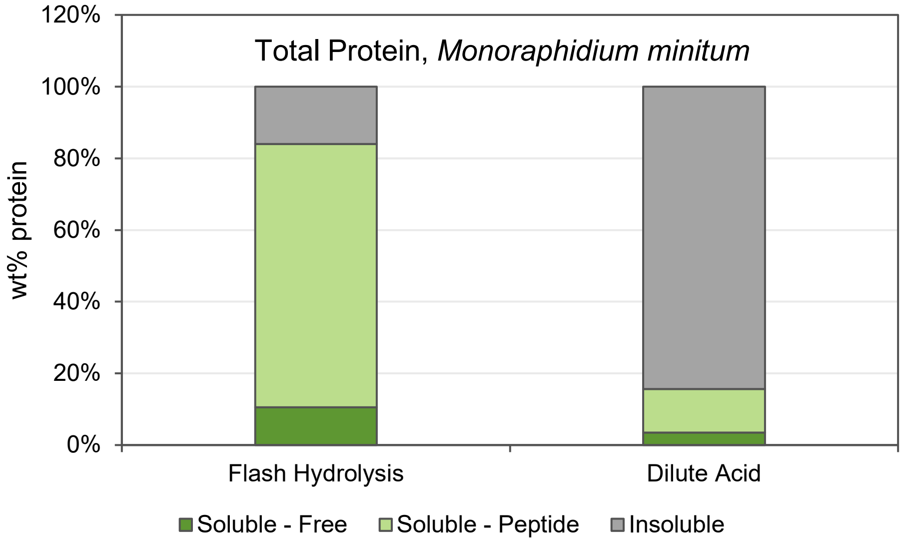

Kruger et al., **2021** *in preparation*

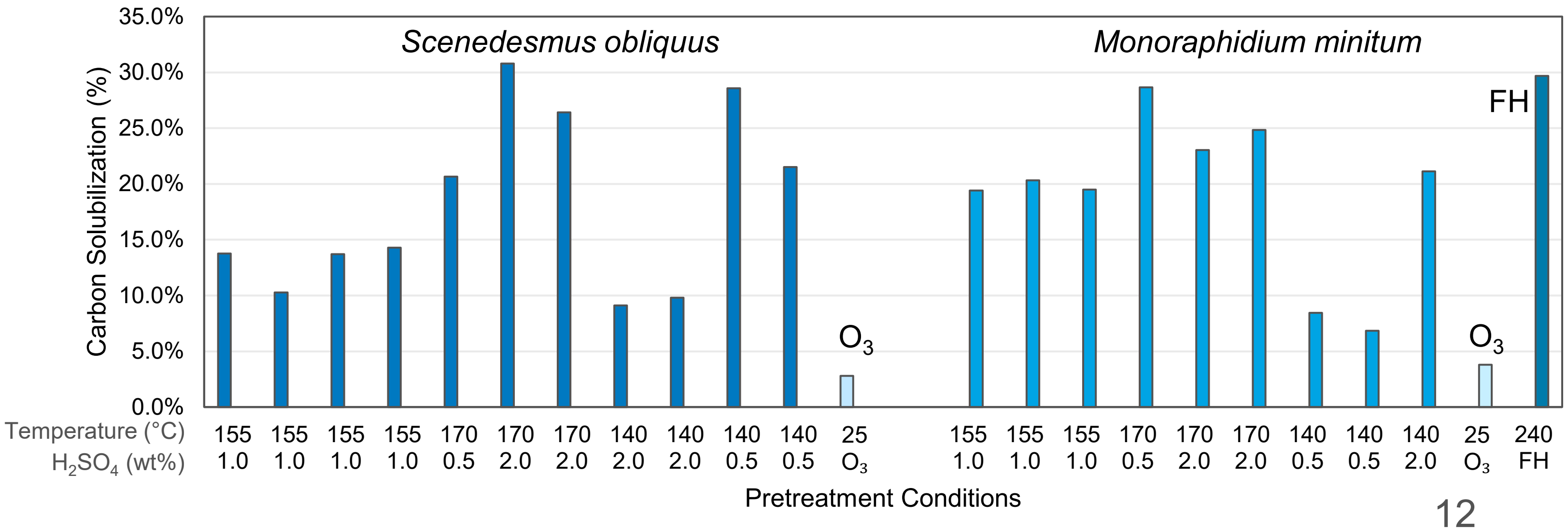
# Progress and Outcomes

Pretreatment and Extraction

## Focus on Pretreatment

- Solubilization of algal biomass to fermentable intermediates is critical metric for fuel yields
- Transition to halotolerant and high-protein algae have revealed limitations to dilute acid pretreatment
- Flash Hydrolysis competitive with Dilute Acid
  - Selective for protein solubilization



# Summary and Future Work

**Overview:** CPR aims to generate drop-in algal jet- and diesel-range biofuels at modeled cost of < $2.50/GGE.

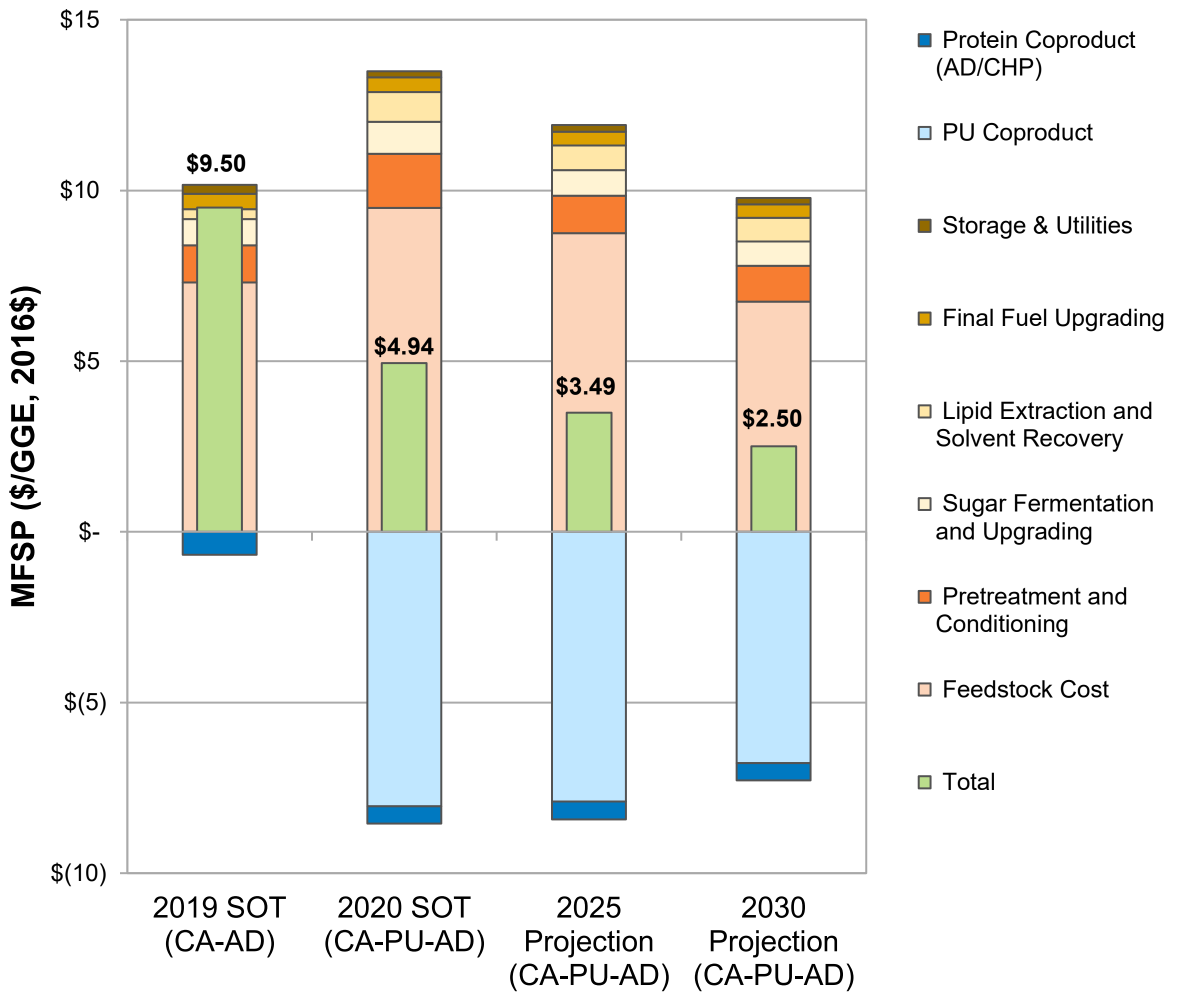
**Management:** Provide quantitative data to analysis teams to measure improvements in modeled MFSP via SOT and Design Reports.

**Approach:** Leverage network of collaborators to define lowest cost and most sustainable algae compositions, develop and adapt fuel and co-product technology to optimize valorization.

**Impact:** TEA models suggest pathway from $400+/ton biomass to $2.50/GGE fuels and market-competitive co-products. Environmental benefits from $CO_2$-fixing co-products.

**Progress and Outcomes:** Identified pretreatment as key step requiring further study as algae composition changes. Demonstrated benefits of:

- Mitigating seasonality
- Flexible fermentation of hydrolysates
- Incorporating high-value NIPU co-product
- Proof-of-concept for production of fuels and nutrient recycle from protein- and carbohydrate-derived carboxylic acids.



# Quad Chart Overview

## Timeline

- Active Project Duration: 10/1/2019 – 9/30/2021
- Total Project Duration: 10/1/2013 – 9/30/2021

| | FY20 | Active Project |
|---|---|---|
| **DOE Funding** | $612,000 | $1,812,000 |

## Project Partners

- **National Labs:** Sandia National Lab, Los Alamos National Lab, Idaho National Lab, DISCOVR, Algal Biomass Composition, Algal Biofuels TEA
- **Universities:** Arizona State University, Old Dominion University

## 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

## Project Goal

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

## End of Project Milestone

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

## Funding Mechanism

BETO AOP

**Acknowledgements:**

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Christy Sterner

**NREL Contributors:**

Lieve Laurens, Philip Pienkos, Nick Nagle, Eric Knoshaug, Tao Dong, Bonnie Panczak, Stefanie Van Wychen, Hannah Alt, Ryan Spiller, Tobias Hull, Ryan E. Davis, Matt Wiatrowski, Matt Fowler, Earl Christensen, Cameron Hays

**External Collaborators:**

John McGowen (ASU), Sandeep Kumar (ODU), Jakob Nalley (Qualitas), Dan Levy (AECOM), Martin Gross (GWT), Jordan Lind (Clearas), Lynn Wendt (INL), Amanda Barry (SNL), Jenna Schaumbach (LANL), Ryan W. Davis (SNL), Kevin Wyss (Rice U)

# Thank You!

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NREL/PR-2800-79437

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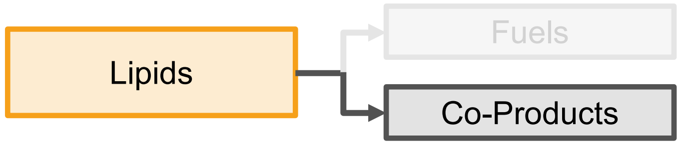
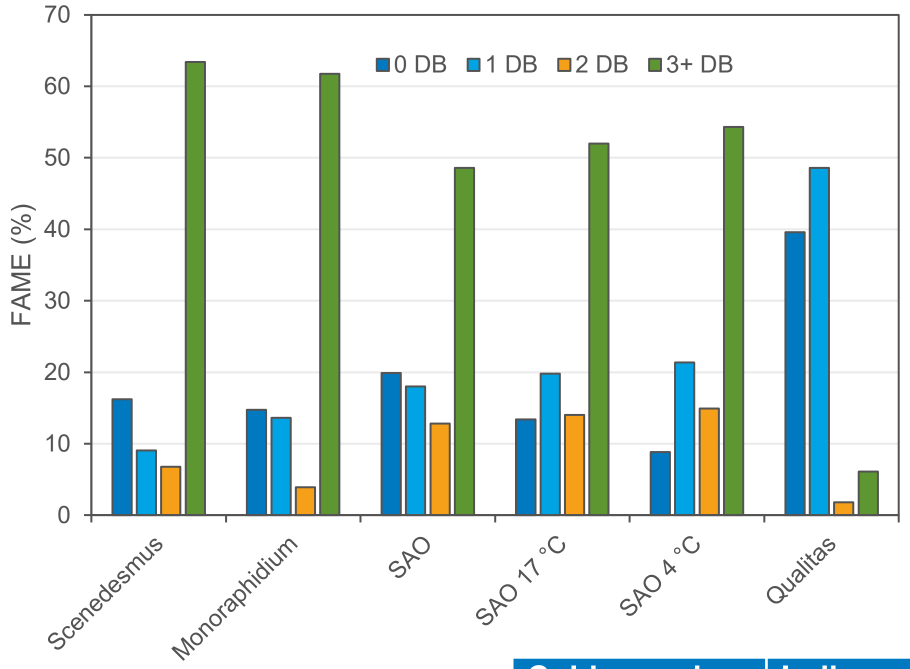
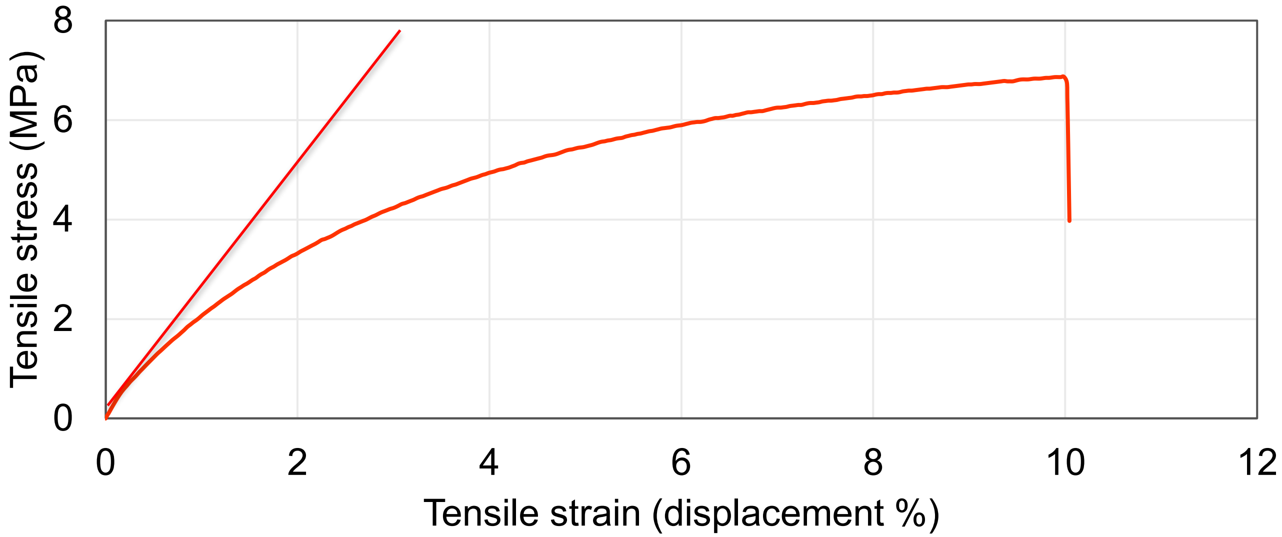
# Additional Slides

# Progress and Outcomes



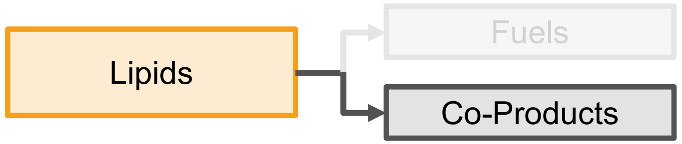

| Cold pressing | Iodine value |
|---|---|
| SAO | 160 |
| UFA_17 °C | 183 |
| UFA_4 °C | 197 |

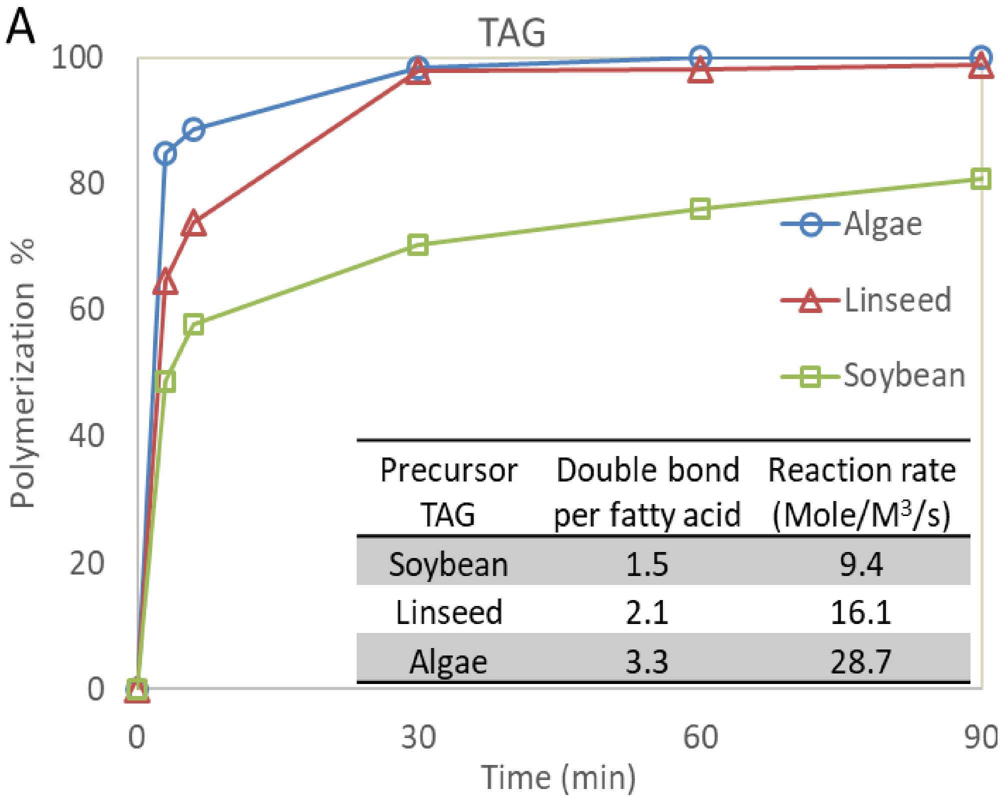
| Young's Modulus (MPa) | Tensile stress (MPa) | Elongation (%) |
|---|---|---|
| 221.2 | 6.8 | 9.4 |

## Simulated Algae Oil (SAO) produces novel polymers

- Simulated composition similar to oils observed from high-protein algae allows enrichment of unsaturated fatty acids
- Amine crosslinker reacts with both carbonate and methyl ester bonds to form both urethane and amide bonds

# Progress and Outcomes




| Precursor TAG | Double bond per fatty acid | Reaction rate (Mole/M³/s) |
|---|---|---|
| Soybean | 1.5 | 9.4 |
| Linseed | 2.1 | 16.1 |
| Algae | 3.3 | 28.7 |

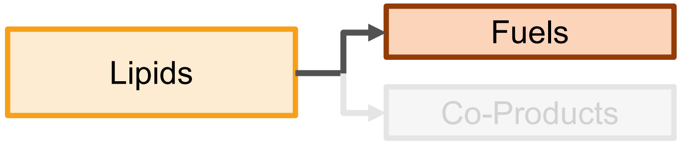
**Figure 1.** Polymerization kinetics of A) triglyceride oil; and B) fatty acid methyl esters

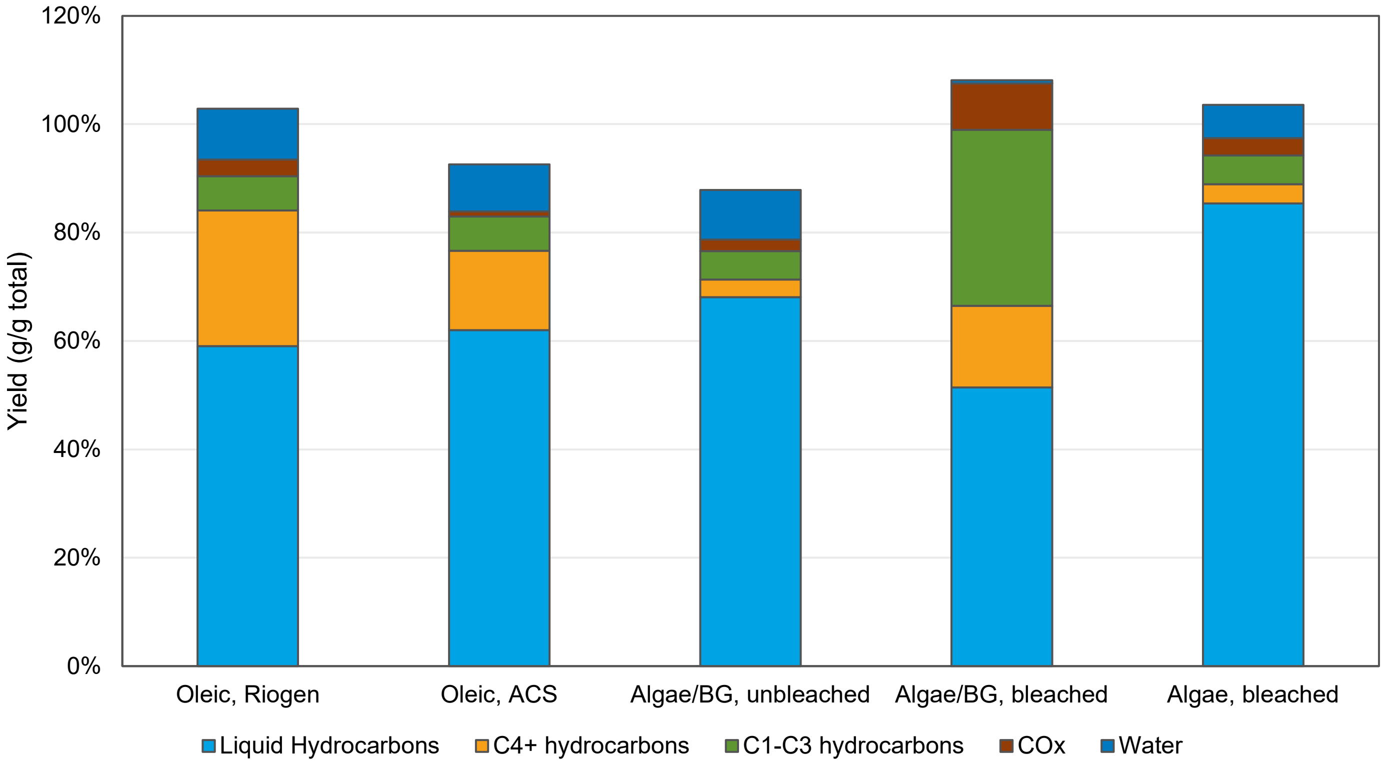
NREL foaming technology
(U.S. 63/063,666)

## Algae oil is versatile NIPU feedstock

- Faster polymerization than linseed oil; higher conversion than soybean oil
- NIPU process compatible with foaming technology

# Progress and Outcomes



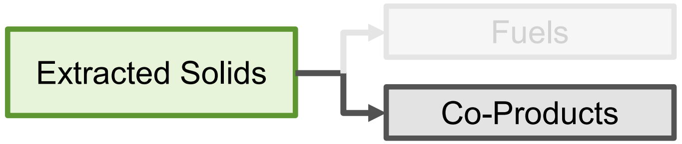

## Integrated CAP Processing

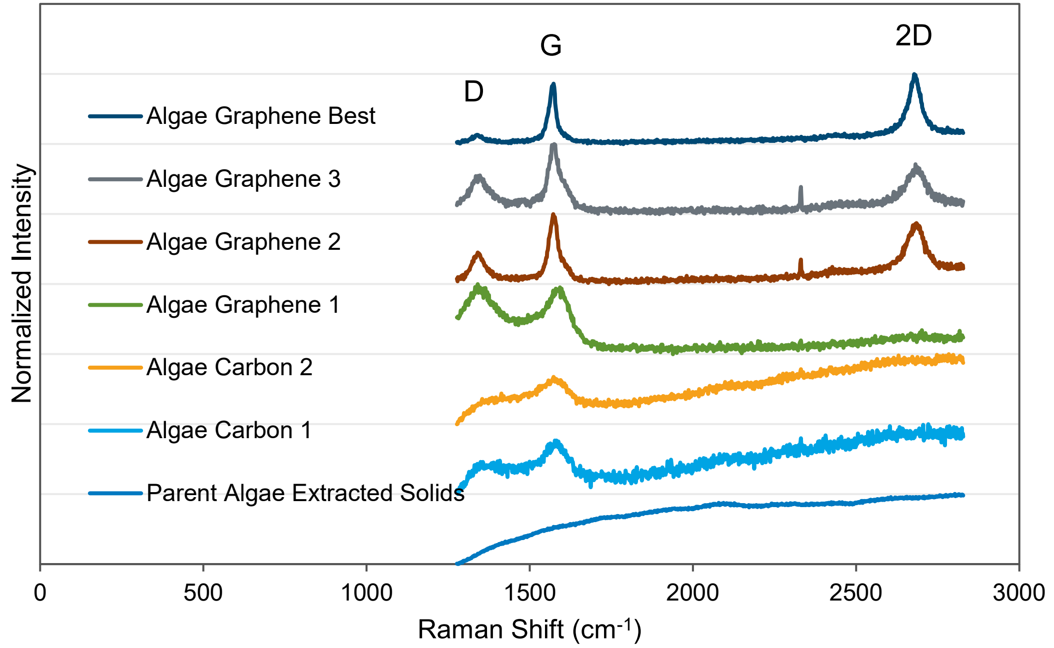
- Demonstrated one-step hydroprocessing using Pt/SAPO-11 catalyst
- Potential to save $0.14/GGE

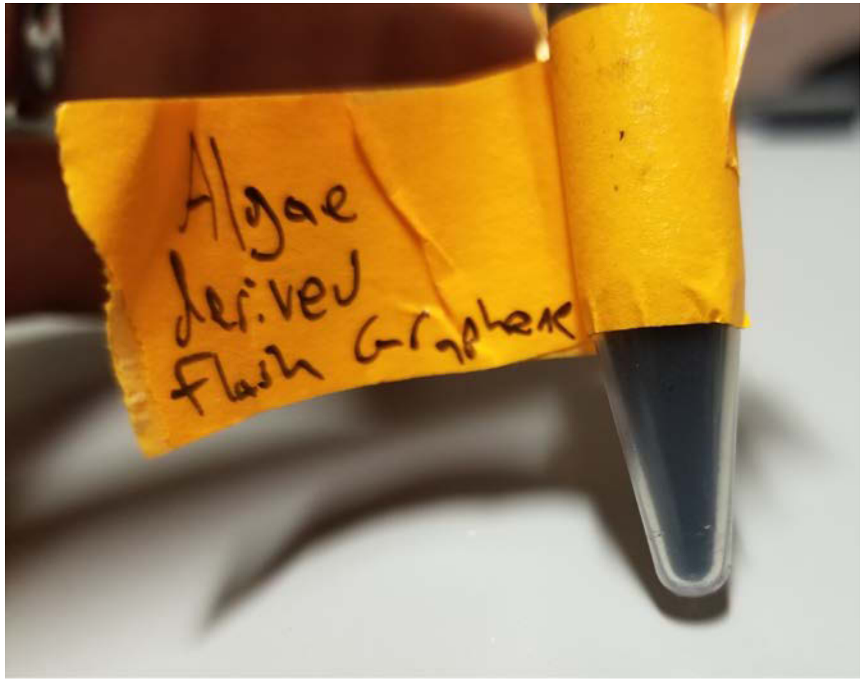


Kruger et al., *Johnson Matthey Tech Rev*, **2021**, 65:227-246

# Progress and Outcomes



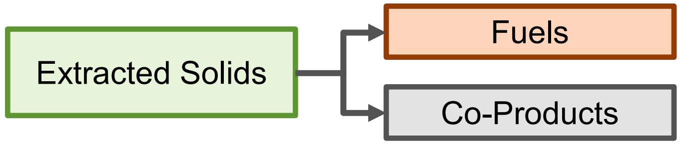




## Insoluble Solids to High-Value Conductive Carbons

- Graphene and graphite represent new market for insoluble solids
- "Battery-grade" graphite market price is $25-30/kg
- Pre-carbonization and flash Joule heating produce graphene (Rice U), ~80% carbon purity

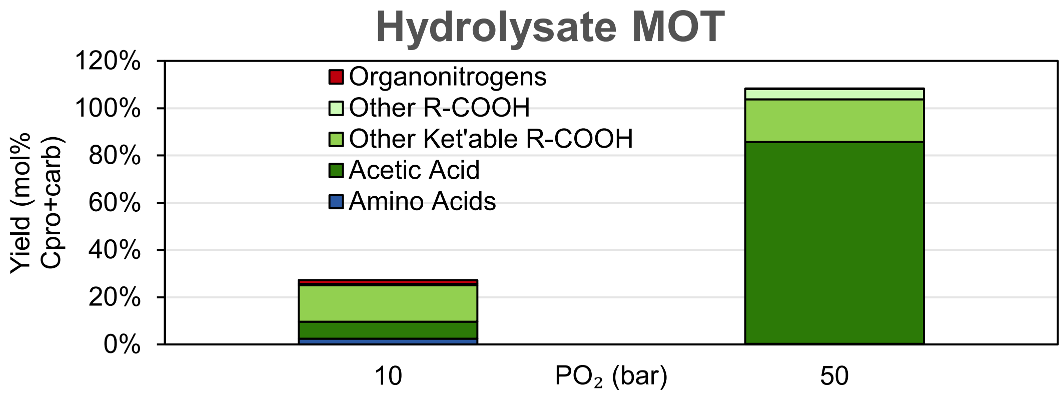
# Progress and Outcomes

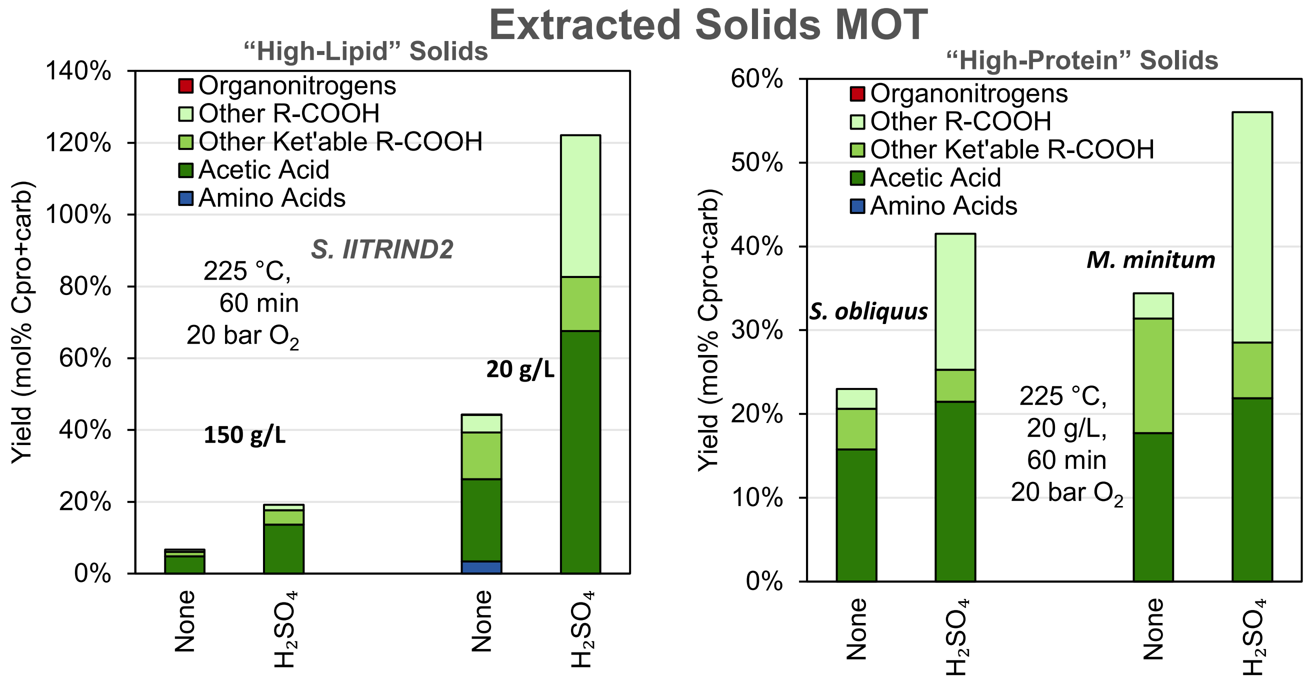



## Mild Oxidative Treatment

- Theorized to generate carboxylic acids from soluble and insoluble proteins, carbohydrates, and "unidentified" organics
- Determined pre-solubilization is critical for high carboxylic acid yields
- Main carboxylic acid products are acetic and succinic – not ideal for upgrading to fuel
- Pivot upgrading technology to fermentation-produced acids
- Developed technology to sequentially recover $NH_3$ and $PO_4$ by ion exchange in presence of carboxylic acids
- **Still holds promise as nutrient recovery approach**

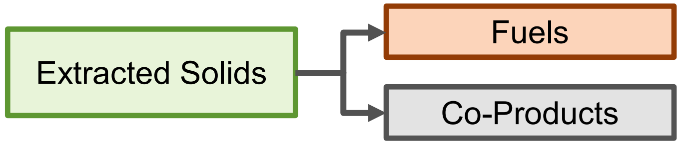
| Scenedesmus extracted liquor | Carboxylic Acid Recovery | N recovery | P recovery |
|---|---|---|---|
| After MOT | 100% | | |
| After cation exchange | 97.7% | 78.5% | |
| After anion exchange | 91.1% | | 72.5% |

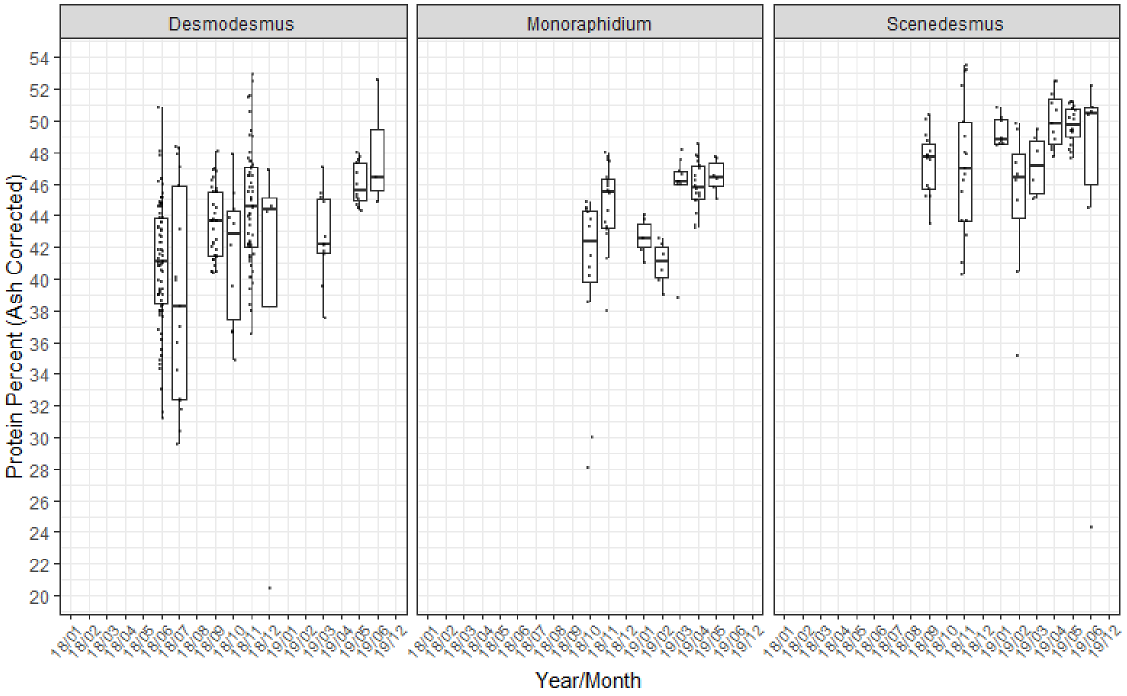


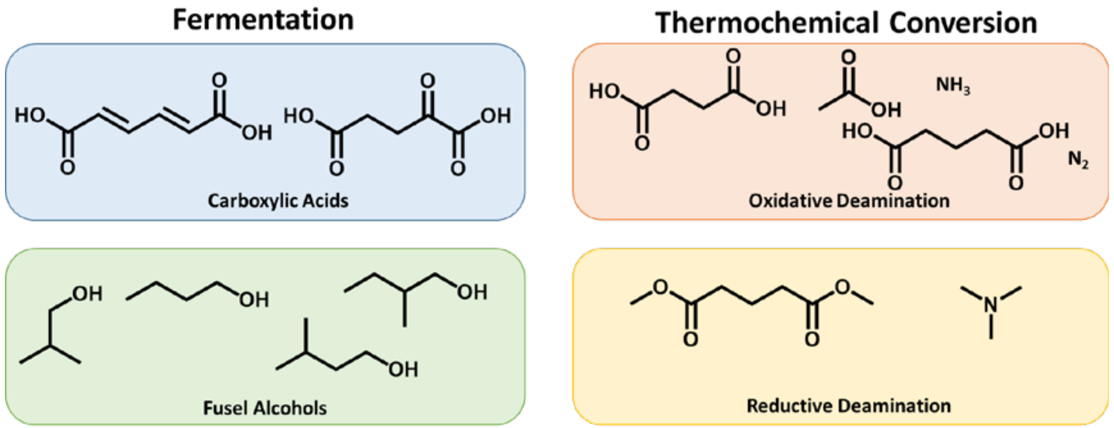




Kruger et al., **2021**, *in preparation*

# Progress and Outcomes



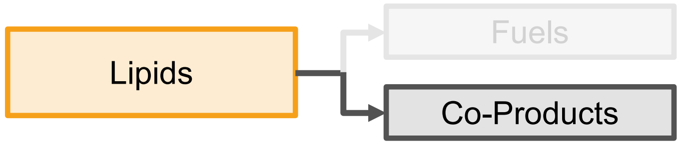



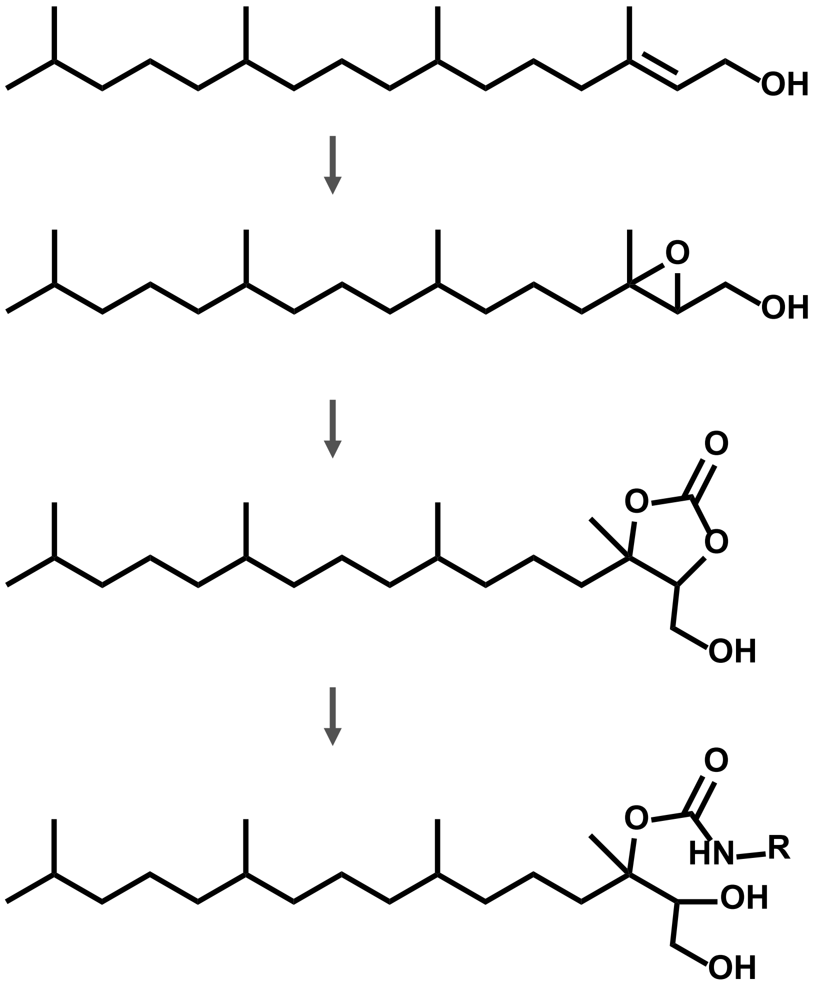

## Many possible protein processing options

- Co-authoring literature review with Sandia National Lab
- High-protein algae composition, pretreatment fractionation options, 11 possible pathways and products identified
- Detailed analysis on animal feed and biopolymers by SNL

Quiroz Arita et al., *in preparation*

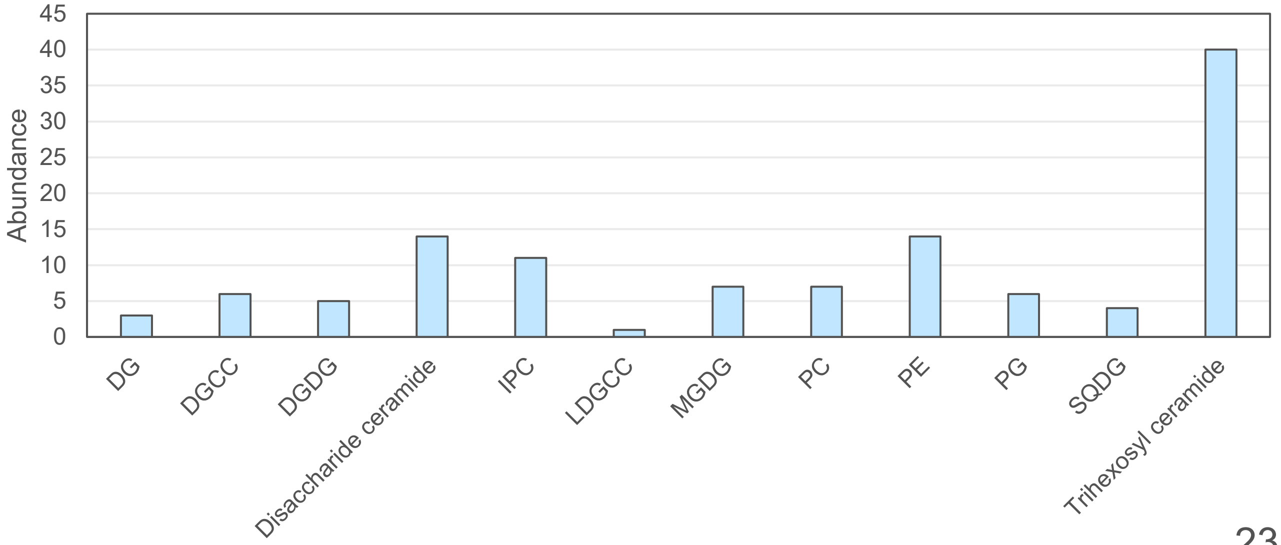
# Progress and Outcomes




## Co-products based on lipid "impurities" can significantly reduce MFSP

- Leverage ABC lipidomics database
- Identified 120 unique algae lipid head groups with surfactant potential
- Apply NIPU technology to phytol as novel class of nonionic surfactants
- For phytol content of 1.6 wt%, phytol-based surfactant can reduce MFSP by $0.91/GGE



# FY2019 Milestones

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| **FY19 Q1:** Identification of volatile compounds as potential coproducts. Test minimum of four biomass samples for release of volatile compounds during pretreatment process. Identify at least one compound or class of compounds making up more than 1% of total biomass. (QPM) | **Goal:** Identify new co-product opportunities that may be easily separable. |
| **FY19 Q2:** Large scale pretreatment of high lipid biomass from halotolerant strain as well as with algal biomass blended with brown grease. Achieve 85% monomeric sugar release and 90% lipid extraction efficiency. (QPM) | **Goal:** Demonstrate effective pretreatment and extraction for halotolerant biomass and blends with low-cost biomass supplement as a way to mitigate seasonal variability. |
| **FY19 Q3:** Evaluate process options for conversion of high protein biomass to establish modified CAP process focusing on high carbon conversion efficiency of proteins to biofuels. (QPM) | **Goal:** Identify potentially-necessary process modifications for transitioning from high-carbohydrate to high-protein biomass. |
| **FY19 Q4:** Integrated CAP processing of biomass and biomass/brown grease blend pretreated in Q2 to provide data for FY19 SOT. Convert bulk lipids to RDB and naphtha at 80% yield. Convert algae sugars to butyric acid and acetic acid at >50%. Convert proteins to carboxylates with mild oxidative depolymerization yield at 50% and yield to hydrocarbons at 25% (Annual) | **Goal:** Demonstrate integrated process with halotolerant biomass and blends with low-cost biomass supplement as a way to mitigate seasonal variability. |
| **FY19 Q4**: Joint Milestone with INL: Demonstrate that CAP process with wet-stored biomass can be carried out with no significant loss in yields. Conduct pretreatment, flocculation, fermentation of carbs to carboxylates and extractions of lipids. (QPM) | **Goal:** Demonstrate effective pretreatment, extraction, and fermentation of stored biomass as a way to mitigate seasonal variability. |

# FY2020 Milestones

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| **FY20 Q1:** Downselect between dilute acid pretreatment and ozonolysis based on process potential for distribution of total carbon including sugars and soluble amino acids and peptides between solid and liquid phases. Criteria: Minimum of 20% of feedstock carbon to be recovered in the liquor fraction. (QPM) | **Goal:** Evaluate alternative to dilute acid pretreatment. |
| **FY20 Q1:** Demonstrate nutrient recovery from FY19 MOT mixture. Criteria: Achieve >75% N and > 75% P recovery, with < 10% loss of upgradable carboxylates. (QPM) | **Goal:** Demonstrate ability of MOT to facilitate nutrient recycle. |
| **FY20 Q2:** Demonstrate production of NIPU resins using unsaturated fatty acids recovered from linseed oil in Q1; Demonstrate production of NIPU resins from phototrophic algal oil (Qualitas waste stream). (QPM) | **Goal:** Produce NIPU from algae oil product available now. |
| **FY20 Q2:** Joint with SNL: Evaluate at least 3 process options for accommodating high-protein algal biomass including CAP process with MOT, muconate to fuels and chemicals and SNL process. Results to be incorporated into outline for publication co-authored by NREL and SNL. (QPM) | **Goal:** Compare opportunities for CAP in high-protein algae space relative to existing protein fermentation to fusel alcohols. |
| **FY20 Q3:** Joint with Algal Biomass Composition: Identify at least one new coproduct for high protein CAP process. Regular goal: Review potential for hydroxylipid-based surfactants produced from high protein biomass to reduce MFSP by at least 10% based on composition as well as low cost purification and conversion processes. Stretch goal: Identify new coproduct opportunity for high protein biomass capable of reducing MFSP by at least 10% if significant novel components are identified in ABC Q3 mass balance closure milestone. (Stretch) | **Goal:** Identify new co-product opportunities based on new discoveries of algal lipid components, that leverage NIPU technology. |

# FY2020 Milestones

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| **FY20 Q3:** Perform conversion of high protein algal liquor to muconic acid using bench scale fermentor. Establish performance parameters and substrate range (monomeric and oligomeric sugars, amino acids and peptides). (QPM) | **Goal:** Evaluate feasibility of fermenting high-protein hydrolysates. |
| **FY20 Q3:** Compare a minimum of two deconstruction processes for halotolerant high-protein microalgae to previous CAP pretreated strains (FY19Q4). Determine, yields and distribution into solids and liquor fractions for TOC, carbohydrates and amino acids and peptides. 20% of algal feedstock organic carbon to liquor. Operate in scalable fashion at 15% solids using validated aspirational MBSP (for open ponds, $490/ton AFDW) with >50% of algal carbon slated for biofuel production. (G/NG) | **Goal:** Evaluate alternatives to dilute acid pretreatment. |
| **FY20 Q4:** Produce and characterize NIPU from enriched unsaturated fatty acids stream separated from high protein algal lipid. Achieve polymer properties comparable to those produced by soybean oil and linseed oil. (QPM) | **Goal:** Compare NIPU produced from high-protein algae oil to previous baselines. |
| **FY20 Q4:** Joint Milestone with LANL: Demonstrate sugar hydrolysis and lipid extraction with algal biomass grown in presence of cellulosic material. Achieve higher sugar recovery from algae cultivated with plant than algae or plant alone with small-scale dilute acid pretreatment under a variety of conditions. (QPM) | **Goal:** Evaluate applicability of CAP to algae cultivated in promising new configurations. |
| **FY20 Q4:** Demonstrate conversion of extracted high protein solids via MOT using deamination catalyst and ketonization catalyst. 40% increase in carbon yield to C12-C20 range ketone intermediates compared to FY19 benchmark. (Annual) | **Goal:** Improve MOT, ketonization, and condensation performance compared to previous baseline. |

# FY2021 Milestones

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| **FY21 Q1:** Evaluate feasibility of producing algae-based conductive carbons. Target 25% carbon yield from extracted solids with qualitative indication of graphitic carbon formation by XRD, Raman spectroscopy, and/or SEM. (QPM) | **Goal:** Valorize solids to high-value product that is nominally agnostic to solids composition. |
| **FY21 Q2:** Evaluate conversion of algal carbohydrates and proteins to unsaturated lipids using at least one strain of heterotrophic algae. (QPM) | **Goal:** Convert soluble proteins to lipids with high degree of unsaturation to increase NIPU production. |
| **FY21 Q3:** Demonstrate production of at least two new coproducts based on NIPU technology, including one photopolymer sample from acrylated algae oil and one surfactant based on phytol. (QPM) | **Goal:** Expand polymer portfolio to high-value products that can utilize lipids with lower degree of unsaturation and impurities that are co-extracted with lipids. |
| **FY21 Q4:** Comprehensively evaluate pretreatment options by screening biomass types and growth stages, comparing pretreatment conditions (dilute acid vs. EH vs. FH vs. dilute alkali), and performing in-depth characterization of incoming and pretreated solids for a minimum of eight biomass samples. Characterization to include (at least) enhanced compositional analysis (standard suite, plus distinguish between soluble and insoluble ash, and lipid speciation via SPE), spectroscopic/microscopic techniques, and slurry pH (before and after pretreatment) (Annual) | **Goal:** Maximize solubilization of biomass into hydrolysate across wide range of composition; evaluate possibility to combine downstream steps (saponification, fermentation) into pretreatment step, thereby reducing capital costs. |

# Response to Reviewer Comments

| Comment | Response |
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| Collaborative efforts within project and with other projects not clearly defined. Scale-up and commercialization challenges not fully appreciated. Future work should also include explicit efforts to architect solutions that have downstream users/customers for all products. | CPR coordinates project planning and material processing and handoffs at biweekly meetings that all contributors attend (including leads of other NREL algae projects). CPR works with DISCOVR consortium to process fastest-growing strains, with ABC project (and biochem platform) to identify new coproducts, and TEA team to vet new process concepts. CPR also works with industry partners (including TCF projects) and TEA team to understand scale-up and commercialization issues. |
| Project lacks clarity and quantitative measures in milestones, timelines, and project goals. Without quantitative milestones, it is difficult to evaluate progress. | The ultimate quantitative metric is a reduction in modeled MFSP for algal biofuels. TEA models incorporate quantitative experimental data (rates, titers, yields, process conditions) provided by this project. Milestones include quantitative metrics where appropriate, and comparative metrics for proof-of-concept milestones. We have historically prioritized our research based on the primary influencing parameters on the baseline costs, e.g. lipid extraction yield, sugar hydrolysis and solubilization yields, and most recently protein conversion and associated nutrient recycling. As stated above, for the last 3 years, this project has contributed to a reduction in minimum fuel selling price through annual TEA calculations, and thus is positioned at the forefront of making significant cost impacts moving forward. With the dynamic process concepts incorporating new algae compositions, new products and new process configurations, it is inherently difficult to evaluate progress via, e.g., improved titers for a specific fermentation product. |
| Need to narrow focus to one or two algae species with most promise. Freshwater for growth is considered cost and resource prohibitive. | CPR works with DISCOVR to process highest-performing algal strains, and with industrial partners to source algae available from their processes. The highest-performing strains vary depending on time of year, geographic location, and cultivation configuration. Thus, it is important to validate the robustness of CAP concepts across a range of compositions. The transition to halotolerant and high-protein algae reflects developments in DISCOVR, but algae available from, e.g., WWT may not be saltwater-grown. |
| Unclear if high CAPEX and complexity of CAP biorefinery justified, or if product yields are industrially relevant. | TEA modeling takes CAPEX and OPEX, reflected through product rates, titers, yields, and processing conditions, into consideration. All decisions based on carbon allocation to various product options are based on consideration of both TEA and LCA impacts. For each of the products chosen, a preliminary market analysis is carried out in the context of the total project farm output of >190,000 tons biomass. |

# Publications


1. Y. Li, S Leow, T. Dong, N. J. Nagle, E. P. Knoshaug, L. M. L. Laurens, P. T. Pienkos, J. S. Guest, and T. J. Strathmann. Demonstration and Evaluation of Hybrid Microalgae Aqueous Conversion Systems for Biofuel Production. *ACS SusChemEng*, **2019**, 7:5835-5844
2. L. M. Wendt, B. D. Whalen, E. P. Knoshaug, R. Spiller, N. Nagle, T. Dong, P. Pienkos. Anaerobic Storage and Conversion of Microalgal Biomass to Manage Seasonal Variation in Cultivation, *ACS SusChemEng*, **2020**, 8:13310-13317.
3. R. Spiller, E. P. Knoshaug, N. J. Nagle, T. Dong, A. Milbrandt, J. Clippinger, and P. T. Pienkos. Upgrading brown grease for the production of biofuel intermediates, *Biores Technol Reports*, **2020**, 9:100344
4. A. Pereira, R. Spiller, E. P. Knoshaug, N. Nagle, T. Dong, and P. T. Pienkos. An alternative biorefinery approach to address microalgal seasonality: blending with spent coffee grounds. *Sus Energy Fuels*, **2020**, 4:3400-3408.
5. J. S. Kruger, E. P. Knoshaug, T. Dong, T. C. Hull, P. T. Pienkos. Catalytic Hydroprocessing of Single-Cell Oils to Hydrocarbon Fuels, Johnson Matthey Tech Rev, **2021**, 65:227-246.
6. C. Quiroz-Arita, S. Shinde, S. Kim, E. Monroe, J. Quinn, N. J. Nagle, E. P. Knoshaug, J. S. Kruger, T. Dong, P. T. Pienkos, L. M L. Laurens, R. W. Davis. Bioproducts from high-protein algal biomass: An economic and environmental sustainability review and risk analysis. In preparation.
7. T. Dong, E. Dheressa, M. Wiatrowski, A. Prates-Pereira, A. Zeller, L. M.L Laurens, P.T. Pienkos. Assessment of Plant and Microalgal Oil Derived Non-isocyanate Polyurethane Products for Potential Commercialization. In preparation.
8. 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.
9. 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.
10. J. S. Kruger, T. C. Hull, K. J. Adams, E. D. Christensen, N. J. Nagle, T. Dong, and P. T. Pienkos. Mild Oxidative Treatment of Algae Residues. In preparation.

# Presentations

1. A. Pereira, C. Chuck, P. T. Pienkos. Biorefinery to produce value chemicals and fuels from spent coffee grounds blended with microalgae. 257th ACS Annual Meeting, **2019**.
2. Samaratung, A, A. Teymouri, M. Martin, T. Dong, N. Nagle, P. T. Pienkos, and S. Kumar. Acid-assisted flash hydrolysis of Scenedesmus acutus for recovery of sugars and lipids. ODU Graduate Research Achievement Day, College of Engineering & Technology (Batten) Posters, **2019**. (Poster).
3. T. Dong, E. Dheressa, A. Prates-Pereira, L. M. L. Laurens, P. T. Pienkos. Fully renewable non-isocyanate polyurethane polymers produced from bio-based LIpids and amines. 41st Symposium on Biotechnology for Fuels and Chemicals, **2019**.
4. J. S. Kruger, E. Christensen, T. Dong, G. Fioroni, N. J. Nagle, P. T. Pienkos. Effects of Impurities in Two-Step Vs. One-Step Hydroprocessing of Algae Oils. 41st Symposium on Biotechnology for Fuels and Chemicals, **2019**.
5. J. S. Kruger, E. Christensen, T. Dong, G. Fioroni, N. J. Nagle, P. T. Pienkos. Effects of Impurities in Two-Step Vs. One-Step Hydroprocessing of Algae Oils. AIChE Annual Meeting, **2019**.
6. P. T. Pienkos. Non-Isocyanate Polyurethanes for Carbon Capture Reuse and Sequestration, ABLC NEXT, **2019**.
7. T. Dong and P. T. Pienkos. Non-isocyanate Polyurethane Produced from Microalgal Oil via a Carbon Sequestration Pathway. Algae Biomass Summit, **2020**.

# Patents and Records of Invention

1. T. Dong, L. M. L. Laurens, P. T. Pienkos, P. F. Spinelli. Renewable polymers and resins and methods of making the same. **2020**. US Patent App. 16/483,844.
2. T. Dong, P. T. Pienkos. 2020. Method to make foam material. US Patent App. 63/063,666.
3. J. S. Kruger, T. Dong. Process for Upcycling Mixed Plastic Waste. Record of Invention NREL/20-87.
4. T. Dong. Phytol-based surfactant. Record of Invention NREL/20-120.