Hydrothermal Processing for Algal Based Biofuels and Co-Products

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Principal Investigator
Pacific Northwest National Laboratory (PNNL)

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Advanced Algal Systems Program

This presentation does not contain any proprietary, confidential, or otherwise restricted information.
• New Start Annual Operating Plan (AOP) in Fiscal Year (FY) 2020:
  - Builds on algae hydrothermal liquefaction (HTL) pathway to fuels (Peer Reviewed FY 2019)
  - Focused on sequential hydrothermal liquefaction (SEQHTL) processing to enable the production of fuels and co-products
• Developed SEQHTL processing and provided data for FY 2020 state of technology (SOT).
  - Reduced fuel costs by $0.50 to $4.48/gasoline gallon equivalent (GGE).
  - Algae feedstocks account for 82% of production cost.
• Project has pivoted in FY 2021-2022.
  - Adapted SEQHTL process to low-cost waste algal feedstocks as recommended by the FY 2019 Peer Review Panel.
1 – Management Risk Mitigation

Technical risks and challenges used to define R&D approach.

No Upgrading R&D; leveraging other projects

Feedstock Availability

Algae + Cellulosic

10% Solids Slurry

Carbohydrates

Stage 1 HTL

Preprocessing Carbohydrate Stream

Concentration Enzymatic Hydrolysis

Bioprocessing

Residual Solids Composition

25% Residual Solids

Process for Carbohydrate Extraction

Stage 2 HTL

Separations

Biocrude Yield and Quality

Biocrude

Phosphate Recovery

Solids (Ash)

Naphtha Jet Diesel

Crude Pre-Treatment

Catalytic Hydrotreating

H₂

Distillation

Nutrient Recycle to Algae Ponds

Stain Testing Adaptation, Media Formulation, Inhibitor Mitigation

Co-Products

Strain/Bioprocess Development

Stage 3 HTL

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No Upgrading R&D; leveraging other projects

Technical risks and challenges used to define R&D approach.
Project structured to address technical risks and challenges.
Project is integrated with modeling and other related projects to promote communication and collaboration.
Management Approach and Communication

- Detailed work breakdown structure (WBS) with experienced task leaders.
  - Well-defined scope/deliverables structured to address risk/challenges
  - Funding authorizations
- Defined AOP Milestones (1/Quarter) and Deliverables
  - Quarterly Reports
- Formal monthly project team/modeling team meetings
  - Review progress, schedule, and budget
  - Discuss issues, risks, mitigation plans, and task integration
- Informal weekly discussions at task level
- Regular Meetings with BETO (technical and progress updates)
- Management and integration of supporting projects and partners

► Integrated Project Team
► Strong Project Management
► Experienced Task Leaders
► Structured Plan and Communications
## Approach

### FY 2020 Technical Objectives

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Risk/Challenges</th>
<th>Technical Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sequential HTL Processing</strong></td>
<td>Developing HTL Stage 1 Carbohydrate Extraction</td>
<td>Optimize process conditions for carbohydrate extraction (ML)</td>
</tr>
<tr>
<td></td>
<td>Verifying HTL Stage 2 Biocrude Production</td>
<td>Evaluate effect of processing blended feedstocks (algae + stover)</td>
</tr>
<tr>
<td></td>
<td>Pre-processing of Carbohydrate Extract to Enable Bioconversion</td>
<td>Maximize residul solids and composition from Stage 1</td>
</tr>
<tr>
<td></td>
<td>Developing a Bioprocess to Produce Co-products</td>
<td>Optimize process conditions for biocrude yield (ML)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Determine biocrude composition for upgrading and fuel quality</td>
</tr>
<tr>
<td><strong>Co-product Production</strong></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Nutrient Recycle</strong></td>
<td>Recycle and Reuse HTL Waste Streams for Algae Cultivation</td>
<td>Validate HTL aqueous recycle to support DISCOVR strains</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HTL filter solids reuse (P and other minerals)</td>
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<tr>
<td></td>
<td></td>
<td>Confirm sustainable cultivation of DISCOVR strains (ML)</td>
</tr>
<tr>
<td><strong>Provide Process Data</strong></td>
<td>Developing Targeted Comprehensive Data Sets</td>
<td>Provide mass balance data for each segment to modeling team (ML)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SOT Updates/Pathway Options Analysis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Adjust R&amp;D Focus</td>
</tr>
</tbody>
</table>

Approach is focused on addressing key challenges with defined objectives and milestones (ML).
### 2 – Approach
Assumptions and Technical Targets

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Achieved</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algae/Corn Stover Blend Stocks</td>
<td>50:50 Blend</td>
<td>50:50 Blend</td>
</tr>
<tr>
<td>Stage 1 HTL Plug Flow Reactor (PFR) Carbohydrate Extraction</td>
<td>65%</td>
<td>60%</td>
</tr>
<tr>
<td>Stage 2 HTL Biocrude Yield</td>
<td>50%</td>
<td>57%</td>
</tr>
<tr>
<td>Carbohydrate Conversion to Co-products</td>
<td>LA yield: 0.37 g/g total carbohydrates</td>
<td>LA yield: 0.55 g/g total carbohydrates</td>
</tr>
<tr>
<td>HTL Nutrient Recycle</td>
<td>3 DISCOVR Strains Same productivity as defined media</td>
<td>3 DISCOVR Strains Same productivity as defined media</td>
</tr>
</tbody>
</table>

Project is retiring assumptions and technological uncertainty for scale-up and commercialization.
3 – Impact
Enabling DOE Biofuel Cost Target

- Fuel conversion cost reduced from $0.88/GGE in FY 2019 to -$0.33/GGE in FY 2020.
- Projected improvements in key cost factors still do not meet the BETO’s $2.5/GGE 2030 goal.
- Shifting to lower cost algae feedstocks provides major impact (e.g., eutrophic algae <$100/ton vs. $478/ton).

Even with 29% reduction, algae feedstock cost projected for 2030 cost is still $478/ton.

Higher algae blend ratios offset algae price decrease.

Minimum Fuel Selling Price, $/GGE

2020 SOT:
- Algae drying (summer & spring only): $1.39
- HTL biocrude production: $1.22
- HTL biocrude upgrading to finished fuels: $0.88
- Bioprocessing for co-product generation: $-0.33
- Balance of plant: $0.0

Projected:
- Algae price: $591/ton, blend ratio algae:CS 58:42
- Projected algae price changes to 71:29
- Projected blend ratio algae:CS changes to 71:29
- Co-product fermentation productivity increase to 1 g/L-hr
- Co-product yield increase 50%
- 2030 projected: $5.0

Even with 29% reduction, algae feedstock cost projected for 2030 cost is still $478/ton.
3 – Impact Technology Transfer

• Project has developed HTL technology that is being leveraged for other wet waste feedstocks, providing environmental solutions in addition to biofuel and co-products.

• Project has led the way in demonstration of full nutrient recycle.

• Project has led to several collaborative competitive projects with U.S Department of Energy (DOE).

• Project has led to several industrial collaborations and projects.

• Project has resulted more than 20 publications and 20 presentations.

• Project has supported the development of several patents.

• Technology was awarded the 2015 FLC technology transfer excellence award and the 2015 R&D 100 Award “Hydrothermal Processing to Convert Wet Biomass into Biofuels.”

Project is providing impact for DOE, research community, and technology commercialization.
SEQHTL, Bioprocessing and, Nutrient Recycle Process Data Developed

FY 2020 Milestone
Complete and deliver data packages on hydrothermal processing of corn stover: DISCOVR algae feedstock blend to fuel blend stocks.

- Processing experiments were completed and data packages were delivered to modeling team.
  - Stage 1 HTL process conditions/mass balances
  - Stage 2 HTL process conditions/mass balances
  - Co-product bioprocessing conditions/mass balances
  - HTL nutrient recycle

- Low temperature 1st stage combined with acid addition produces a carbohydrate-rich aqueous phase with high concentrations of simple sugars that can be used to produce co-products.
- High temperature 2nd stage processes 1st stage solids into biocrude that is upgraded to fuel.
- HTL waste streams used for nutrient recycle.
4 – Progress and Outcomes

Sequential HTL Stage 1 Testing

FY 2020 Milestone

Complete the integrated sequential HTL test (Stage 1 and Stage 2), processing greater than 80-L of corn stover/algae blend in Stage 1 at best stage 1 conditions and processing the residual in Stage 2.

- Processed greater than 80-L of corn stover/algae blend in Stage 1 at best stage 1 conditions and processing the residual in Stage 2.

- Continuous flow Stage 1 HTL was successfully transitioned from a continuous stirred tank reactor to a PFR.

- Algal biomass was DISCOVR algae strain (Acutodesmus obliquus UTEX393).

- Carbohydrate extract from the Stage 1 testing was provided for co-product fermentation to produce a product (lactic acid).

Demonstrated >65% carbohydrate extraction in Stage 1 PFR process.
FY 2020 Milestone

Quantify the production of a co-product from 1st stage HTL carbohydrate extract from a feedstock blend of algae and corn stover.

- An initial bioprocessing study was completed.
- Stage 1 carbohydrate extract was concentrated by evaporation.
- Concentrated extract was treated by enzymatic hydrolysis to release sugar monomers.

- *Lactobacillus pentosus* and *Lactobacillus rhamnosus* were tested for direct conversion of carbohydrate extract to lactic acid in bioreactors.
- Glucose was rapidly converted to lactic acid. Conversion of xylose, galactose, and mannose was incomplete and produced acetic acid as a side product.
- Additional bioprocess development will be required for optimization.

**Demonstrated lactic acid co-product production from SEQHTL.**
FY 2020 Milestone

Complete the integrated SEQHTL test (Stage 1 and Stage 2) processing. Meet SEQHT technical target of 50% biocrude yield from Stage 2 HTL processing of residual solids.

- Continuous Stage 2 HTL processing was conducted using Stage 1 residual solids.
- Process conditions were 3000 psia, 350°C, LHSV 4/
- Target biocrude yield of 50% (around 2nd Stage) was demonstrated.
- HTL aqueous phase and ash solids provided for nutrient recycle evaluation.

**Demonstrated 50% biocrude mass yield for Stage 2 SEQHTL processing of residual solids.**
FY 2020 Milestone

Demonstrate that 3 DISCOVR algal strains can be grown in recycled media derived from HTL wastewaters without reduced productivity.

- Completed screening DISCOVR strains in photobioreactors. Eight strains showed strong growth in HTL derived media.

- Recycle of HTL aqueous phase from a wood: algae blend stock had an inhibitory effect. Inhibitory impacts were mitigated by simple filtration of char particles and micronutrient addition.

Demonstrated nutrient recycle using SEQHTL derived media with DISCOVR strains.
**Objective:** Adapt SEQHTL to low-cost algae feedstocks

**Management:** Same Team, New Risks, and New WBS

- New Risks and Challenges
  - High ash, dirt, and moisture content
  - Slurry prep and separations challenging
  - High carbohydrate/low lipid
  - Harvesting and transport costs may be significant

**Approach:** Revised R&D Plan

- Task 1 - Selection and Sourcing of Target Algae Feedstocks for Characterization and Testing
  - (coastal kelp farms, turf-scrubber remediation projects, tertiary wastewater treatment, etc.)
- Task 2 - Develop Processing Scenarios and Experimental Plan for Macroalgae and Scrubber Algae Feedstocks
  - (thermal hydrolysis below 200 °C to hydrothermal carbonization, HTL, SEQHTL, and co-product production)
- Task 3 - Hydrothermal Process Development for Targeted Algae Feedstocks
- Task 4 - Provide Process Data for Modeling/Techno-Economic Analysis (TEA) to Focus R&D on the Most Promising Pathways

**Impacts:** Process economics, environmental benefits, and technology adoption

**Progress:** Task 1 and 2 underway (Q2 MLs); Task 3 beginning in Q3

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**Objectives**

- Demonstrate hydrothermal processing methods for low-cost, high ash algae feedstocks.
- Evaluate co-product product options and biocrude production.
- Provide process data to modeling team for conducting TEA.
- Go/No-Go 9/30/22
Acknowledgements

• Daniel Fishman – BETO Technology Manager

• Project Team
  • Dan Anderson
  • Andy Schmidt
  • Justin Billing
  • Sam Fox
  • Todd Hart
  • Rich Hallen
  • Scott Edmundson
  • Heather Job
  • Lesley Snowden-Swan
  • Yunhua Zhu
  • Kyle Pomraning
  • Jim Collett
Summary

1 - Management
- Project WBS structured to address technical risks and challenges
- Integrated project team with strong project management, experienced task leaders, and structured communications

2 - Approach
- Based on key risks and technical challenges
- Clear R&D objectives and milestones

3 - Impact
- Developed fully-integrated SEQHTL process to produce fuel and co-products
  - Potential to meet BETO FY 2030 goal of $2.50/GGE
  - Potential to be adapted to low-cost algae feedstocks and other wet wastes
- Publications, presentations, awards, and collaborations
Summary

4 - Progress and Outcomes

- SEQHTL, bioprocessing, and nutrient recycle process data developed
- Demonstrated >65% carbohydrate extraction in Stage 1 PFR process
- Demonstrated lactic acid co-product production from SEQHTL
- Demonstrated 50% biocrude mass yield for Stage 2 SEQHTL processing of residual solids
- Demonstrated nutrient recycle using SEQHTL derived media with DISCOVR strains
- Provided process data for modeling/TEA and SOT
- Pivoted direction in FY 2021 – 2022 to focus on SEQHTL processing of low-cost algae
# Quad Chart Overview

## Hydrothermal Processing for Algal Based Biofuels and Co-Products 1.3.4.101

### Timeline
- 10/1/2019
- 9/30/2022

<table>
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<tr>
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<td>DOE Funding</td>
<td>(10/01/2019 – 9/30/2020) $525,000</td>
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<td>(negotiated total federal share over active project) $1,575,000</td>
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### Project Goal
Develop/adapt hydrothermal process technology to enable the commercialization of algal-based biofuels and co-products from lower-cost algae feedstocks derived from nutrient remediation in wastewater treatment and marine macroalgal farms.

### End of Project ML
Provide conversion pathways and associated data for processing two low-cost algae feedstocks to the PNNL HTL Model Development project (WBS 1.3.1.202) for completion of a new design case or the FY 2022 SOT for HTL of a down-selected, low-cost algae feedstock.

### Related/Leveraged Projects
- 1.3.5.202 HTL Model Development
- 1.3.2.501 Algae DISCOVR Project
- 2.2.2.301 PNNL Hydrothermal Process Development Units

### Barriers Addressed
**Aft-H. Overall Integration and Scale-Up**
Process integration (HTL, Upgrading, Recycle), TEA; Engr. Scale HTP system being tested

**Aft-J. Resource Recapture and Recycle**
Aggressively demonstrating reuse of HTL byproduct stream

### Funding Mechanism
Lab Call 2019
Additional Slides
Responses to Previous Reviewers’ Comments
2019 Peer Review Report

This project demonstrates further progress in optimizing hydrothermal liquefaction (HTL) process technology with the goal of meeting the BETO liquid biofuel cost target. Results achieved over this review period have shown how increases in feed solids loading for biocrude production and pre-treatment and an improved catalyst for upgrading are helping to drive down the overall cost towards the BETO goal. PNNL staff have continued to investigate methods of improvement to the HTL process from many angles, as shown by the results of blending tests and nutrient recycle tests. While it is understood that the HTL algae work has laid the groundwork for subsequent tests with real wet wastes (e.g., sludge), the algae used in these tests are not waste and therefore this project may not really belong in this group (though this is a BETO decision). However, eutrophic algae would qualify as a waste and its negative feedstock cost would further help meet the BETO biofuel cost target, so it should be considered as a future feedstock. The only major concern with the work shown is the apparent disconnect in the modeling cost results between that shown in this project and in the formal TEA modeling project (2.1.0.301), also performed by PNNL staff. Future modeling work in any of the PNNL HTL projects should all be performed on the same basis with the same cost categories to avoid confusion.

We thank the reviewers for their thoughtful comments. This project is part of the Algae Program at BETO specifically focused to develop an HTL conversion pathway for algal biomass to produce biofuels. BETO decided to conduct the peer review of this Algae Program project as part of the Waste to Energy Program and this resulted in some confusion for Waste to Energy reviewers. On the positive side we were able to show the reviewers how this algae HTL project had laid the technical groundwork for establishing the HTL conversion and Modeling projects focused on wet wastes. However, there was disconnect with algae project and its relationship to the wet waste process/TEA since the associated Algae HTL Process Model project was reviewed in the Algae program session. This project has a direct connection with HTL Algae Model/TEA project from the very beginning, but it was not presented to the reviewers. So, there is direct connection between the Algae HTL Conversion project and the Algae HTL Modeling effort as the reviewers suggest. We do agree that focusing on eutrophic algae as a potential negative cost feedstock makes sense and we are pursuing project opportunities in that area.
Recent Publications


Past Publications


Past Publications (cont.)


Past Publications (cont.)


Past Presentations

- An oral presentation entitled “Complete NPK Recycle following Algal Bio-crude Production via Hydrothermal Liquefaction” was presented by Scott Edmundson at the 7th International Conference on Algal Biomass, Biofuels, and Bioproducts in Miami, FL on June 21st, 2017.

- A poster entitled “Climate simulated biomass productivities of Chlorella sorokiniana DOE 1412 using recycled nutrients derived from hydrothermal liquefaction processing” was presented by Robert Kruk at the 7th International Conference on Algal Biomass, Biofuels, and Bioproducts in Miami, FL on June 19th, 2017.


Past Presentations (cont.)


Patents, Awards, and Commercialization

Awards

- 2015 FLC technology transfer excellence award
- 2015 R&D 100 Award “Hydrothermal Processing to Convert Wet Biomass into Biofuels”

Patents

Project History

- **FY 2013:** Algal HTL potential demonstrated as part of the National Alliance of Advanced Biofuels and Bioproducts.

- **FY 2014 - 2019:** Thermochemical Interface project focused on developing algae HTL pathway for fuel production.
  - Project conducted process R&D and developed HTL design case and SOT outlining cost reduction targets for the 2022 timeframe.
  - Conversion cost were driven down from $3.02/GGE in FY 2015 to $.88/GGE in FY 2019.
  - Demonstrated fuel production costs of $4.98/GGE for FY 2019 SOT. (Modeled algae feedstock cost at $670/US ton dry ash free basis accounts for 82% fuel production cost).

- **FY 2020:** Began the current project to further drive down minimum fuel selling price $/GGE.
  - Focused on microalgae with terrestrial feedstocks supplement in non-summer seasons and sequential HTL to produce both fuels and co-products.
  - FY 2020 SOT demonstrated potential to drop fuel production costs to $4.48/GGE.
  - Conversion cost were driven down from $0.88/GGE in FY 2019 to $-0.33/GGE in FY 2020.

- **FY 2021 - 2022:** BETO requested a change in project approach focusing on hydrothermal processing of low-cost algae feedstocks.
1- Management: FY 2021 Milestones

**Q1**
- Provide all remaining process data from FY 2020 to the modeling team for completing a final SOT for publication. (QPM)

**Q2**
- Prepare and present the scenario analysis with experimental plan for both a marine macroalgae and another wastewater algae used for nutrient remediation to BETO. (AMR)

**Q3**
- Compile resource availability report on low-cost algae feedstock from wastewater treatment and marine macro algae farming. Obtain materials needed for characterization and bench-scale processing work. (QPM)
- From batch testing results, select a processing strategy for one of the low-cost algae feedstocks and develop an approach for implementing the strategy in a continuous process. (QPM)

**Q4**
- From batch testing results, select a processing strategy for the second low-cost algae feedstock and develop an approach for implementing the strategy in a continuous process. (QPM)

**FY 2022**
- Provide performance data from continuous processing experiments to modeling/TEA team. (QPM)
- Provide all remaining process data from FY 2020 to the modeling team for completing a final SOT for publication. (QPM)
Adapting SEQHTL for Low-Cost Algae Feedstocks

- SEQHTL has potential to enable processing low-cost feedstocks (<$100 vs. $670 per DMT).
- Micro- and macroalgae wastes could be processed into fuel and products.
- SEQHTL could provide mitigation of environmental problems.
  - Nutrient recovery, metals recovery, etc.
- Nearer term commercial application of the SEQHTL possible with existing waste/low-cost algae feedstocks.
4 – Progress and Outcomes: FY 2019 Lessons Learned

- Synergistic biocrude yields achieved using algae/wood blends.
- Algae/wood silage storage blends feasible for long-term storage of a blended feedstock.
- Sequential HTL conditions identified to produce:
  - carbohydrate stream for co-product production in Stage 1, and
  - residual stream that is 25 wt% solids increasing Stage 2 throughput and higher biocrude yields of 50%.
- Initial testing of blended feedstocks for sequential HTL showed likely blended feedstocks will yield more carbohydrates.
- Methods identified enabling hydrotreating algal biocrudes at industrial relevant conditions.
- HTL aqueous recycle and HTL derived nutrients work with multiple DISCOVR algal strains.
FY 2020 Milestone

Determine conditions for recovery of up to 60% of total carbohydrates from algae/corn stover blended feedstocks.

- Stage 1 extraction studies were completed in high throughput center.

- A range of process conditions were evaluated, including:
  - temperature, acid concentration, residence time, and temperatures
  - 60% recovery achieved

- Residual solids recovery for Stage 2 conversion were determined:
  - 50-60% yield dry wt. basis
  - 20% solids
# FY 2020 Risk Matrix

<table>
<thead>
<tr>
<th>Name</th>
<th>Status</th>
<th>Target Completion Date</th>
<th>Severity</th>
<th>Response/Progress</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Access to Algal Biomass</td>
<td></td>
<td>9/30/2022</td>
<td>High</td>
<td>Mitigate</td>
<td>Lack of algae feedstock availability for integrated sequential HTL testing (need about 10 kg dry per test)</td>
</tr>
<tr>
<td>Access to formatted Forest Product Residual</td>
<td>Known</td>
<td>9/30/2022</td>
<td>High</td>
<td>Mitigate</td>
<td>Lack of forest product residual feedstock availability for integrated sequential HTL testing (need about 15 kg dry per test)</td>
</tr>
<tr>
<td>Stage 1 Plug Flow Processing</td>
<td>Closed</td>
<td>6/30/2021</td>
<td>Medium</td>
<td>Mitigate</td>
<td>Failure to successfully conduct Stage 1 HTL in pure PFR mode (e.g., persistent plugging)</td>
</tr>
<tr>
<td>Stage 1 Additives to Boost Carbohydrate Extraction</td>
<td>Response Selected</td>
<td>6/30/2021</td>
<td>Medium</td>
<td>Mitigate</td>
<td>Failure to identify Stage 1 additive that boosts carbohydrate recovery.</td>
</tr>
<tr>
<td>Recycle Toxicity from Blended Feeds</td>
<td>Known</td>
<td>9/30/2022</td>
<td>Medium</td>
<td>Mitigate</td>
<td>Toxicity of combined feedstocks is increased and inhibits algal growth.</td>
</tr>
<tr>
<td>Bacterial/Fungal Contamination of Algal Cultures</td>
<td>Analyzed</td>
<td>9/30/2022</td>
<td>Medium</td>
<td>Mitigate</td>
<td>Bacterial/fungal contamination of algal cultures.</td>
</tr>
<tr>
<td>Bioconversion Metabolic Inhibitors</td>
<td>Partially understood. Established mitigation measures.</td>
<td>9/30/2022</td>
<td>Medium</td>
<td>Mitigate. Evolve strains to tolerate higher concentration of inhibitors. Search of alternative strains with higher tolerance.</td>
<td>Varying metabolic inhibitors in carbohydrate extract from feedstock blends</td>
</tr>
</tbody>
</table>
## Risk Matrix FY 2021 - 2022

<table>
<thead>
<tr>
<th>Name</th>
<th>Status</th>
<th>Target Completion Date</th>
<th>Severity</th>
<th>Response</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Access to Algal Biomass</td>
<td>Known</td>
<td>9/30/2022</td>
<td>High</td>
<td>Mitigate</td>
<td>Lack of algae feedstock availability for integrated sequential HTL testing (need about 10 kg dry per test).</td>
</tr>
<tr>
<td>Hydrothermal Processing High Ash Feedstocks</td>
<td>Known</td>
<td>9/30/2022</td>
<td>High</td>
<td>Mitigate</td>
<td>High ash feedstocks require new sequential HTL processing methods to enable separations and processing.</td>
</tr>
<tr>
<td>Adapt Batch Processing to Plug Flow Processing</td>
<td>Known</td>
<td>9/30/2022</td>
<td>Medium</td>
<td>Mitigate</td>
<td>Processing in pure PFR mode may lead to plugging and co-product degradation.</td>
</tr>
<tr>
<td>Additives to Enable Extraction Co-Product Biopolymers</td>
<td>Known</td>
<td>9/30/2022</td>
<td>High</td>
<td>Develop</td>
<td>Failure to identify additive that boosts co-product recovery in plug flow processing.</td>
</tr>
<tr>
<td>Direct Conversion High Ash Algae Biomass to Fertilizer</td>
<td>Known</td>
<td>9/30/2022</td>
<td>Medium</td>
<td>Develop</td>
<td>Carbonization requires new plug flow process.</td>
</tr>
</tbody>
</table>
Abbreviations and Acronyms

- AMR: Annual Milestone Regular
- AOP: annual operating plan
- BETO: Bioenergy Technologies Office
- DOE: U.S. Department of Energy
- FY: fiscal year
- GGE: gasoline gallon equivalent
- HTL: hydrothermal liquefaction
- PDU: Process Development Unit
- PFR: plug flow reactor
- PNNL: Pacific Northwest National Laboratory
- QPM: Quarterly Progress Measure
- SEQHTL: sequential hydrothermal liquefaction
- SOT: state of technology
- TEA: techno-economic analysis
- WBS: Work Breakdown Structure