2017 Project Peer Review

1.3.3.100:
Algal Feedstock Logistics and Handling
Goal Statement

The goal of this project is to manage seasonal variation in algal biomass production through stabilization to reduce conversion costs and to reduce ash to increase conversion yield

Project Outcomes

• A process that preserves harvested microalgal biomass over a six-month period and enables a biorefinery to run year round with a consistent feedstock supply
• A process for simultaneous ash reduction and stabilization of biomass derived from an algal turf scrubber that could be applicable to multiple high-ash algae species

Relevance

• Supports long-term goals of emerging algae industry
  – Seasonal variation in microalgae necessitates long-term storage
  – Wet storage eliminates natural-gas-based drying, reducing costs and GHGs
• Supports near-term goals of emerging algae industry
  – Stabilization methods allow for transportation to conversion facility
  – Blending can bridge the gap for utilizing algae biomass before dedicated algae conversion facilities are constructed
Quad Chart Overview

Timeline

• Task 1: 4/22/15-9/30/18
  – Percent complete: 50%
• Task 2, 3: 10/01/17-9/30/19
  – Percent complete: 15%
• Ongoing Project

Barriers

• Aft-F. Algae Storage Systems
• Aft-G. Algal Feedstock Material Properties
• Aft-H. Overall Integration and Scale-up

Budget

<table>
<thead>
<tr>
<th>DOE Funded</th>
<th>FY 15 Costs</th>
<th>FY 16 Costs</th>
<th>Total Planned Funding (FY 17-Project End Date)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$150K</td>
<td>$340K</td>
<td>$2,000K</td>
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</tbody>
</table>

Partners

DOE partners
• NREL, PNNL, SNL
Collaborations
• ASU/AzCATi/ATP³
• Univ. of Arizona
• Cal Poly-San Luis Obispo
Project Overview

Feedstock logistics studies are essential to ensure that the maximum amount of biomass harvested is convertible to valuable energy and co-products.

Scale-up lessons learned in cellulosic industry
Lack of integration of unit operations = slow start-up
- Batch to continuous-feed operations lead to unforeseen problems
- Feed handling issues underestimated
- Soil contamination leads to abrasion of equipment and issues in conversion
- “Dry” biomass still contains 10-20% moisture, which migrates during long-term storage and causes degradation

Microalgae studies @ INL
- Gas formation occurs in many types of harvested algae biomass
- Short-term dry matter loss is high; 2-3% loss per day measured
- Material properties vary widely for harvested microalgae at 20% solids
Productivity swings due to seasonal variation necessitates long-term stabilization to maximize conversion efficiency

- DOE BETO Design Cases utilize drying to stabilize a portion of algae grown in summer for use in winter
- Drying is expensive: $136-158 per AFDW ton
- Dry storage stability is unknown in hot, humid environments

Historical average from Beaumont, TX

Adapted from Davis et al. 2014
Technical Approach

Wet storage is an alternative to drying and dry storage of harvested algae

Commonly used for livestock feed
• Currently available infrastructure
• Field deployable and scalable
• <5% dry matter loss possible

Creates anaerobic, acidic conditions
• Mechanical exclusion of air
• Lactic acid fermentation lowers pH and stabilizes biomass

Goal: Determine if microalgae is preserved in wet storage
1. Determine if the properties of herbaceous biomass can be extended to microalgae through blending to stabilize biomass
2. Determine if algae can be stored by itself in wet storage systems
3. Determine if chemical treatment can upgrade biomass by reducing ash and provide stabilization
Technical Approach

Three tasks explore optimization of harvested algae from multiple angles

1. Stabilization through blending

2. Stabilization of algae alone

3. Ash reduction and subsequent stabilization
Management Approach

Task Overview

- **Year 1:** Optimization at bench scale
  - Laboratory-based screening at INL

- **Year 2:** Scale-up on performance metrics achieved, assess conversion potential
  - Leverage INL Biochemical and Thermochemical Conversion Interface Projects as well as partner national labs

- **Year 3:** Collaborate with conversion labs for full validation
  - NREL, PNNL, SNL

- Annual and Go/No-Go Milestones
- TEAs assist in comparing solutions to SOT
- Collaborations with industry and academia provide access to a wide range of biomass types and growth conditions
Technical Approach

Challenges
• Herbaceous biomass is inactive once harvested, algae is metabolically active
• Wet anaerobic storage must preserve dry matter and composition

Critical Success Factors
• Wet storage can compete with drying/dry storage in TEA and LCA
• Wet storage methods compatible with existing conversion approaches

How do we determine success in storage?
• Go/No-Go Milestone (3/30/17): Determine if wet storage of blends can reduce dry matter loss to less than 30% over 6 months
• 6-17% loss observed
• Goal: 10% loss or as indicated by TEAs
Technical Approach

Three tasks explore optimization of harvested algae from multiple angles

1. Stabilization through blending

2. Stabilization of algae alone

3. Ash reduction and subsequent stabilization
Technical Approach - Task 1

- Low-cost logistics systems exist for herbaceous biomass
- Blending extends rheological properties of herbaceous biomass to algae
  - Up to 40% algae can be blended and maintain herbaceous properties
- Approach: Use low cost blending and storage to solve seasonal variation problem
- Herbaceous biomass used for blending must be
  - Compatible with algae conversion
    o Hydrothermal Liquefaction (HTL)
    o Combined Algal Processing: Fermentation, Lipid upgrading
  - Sufficiently available where algae industry is likely to emerge
    o Gulf coast, arid southwestern states

MSW yard waste in Southwest and Southeast US, estimated 5 million tons currently available annually
Accomplishments - Task 1

TEA comparing costs of dried algae to blended algae shows opportunities for wet storage

High Winter Productivity Scenario
• 3:1 Summer-to-Winter Variation
• Blending and wet storage reduces cost of diesel by 25 to 42% compared to drying

Low Winter Productivity Scenario
• 5:1 Summer-to-Winter Variation
• Blending and wet storage reduces cost of diesel by 0 to 18% compared to drying
• Algae production can be shut down during winter without impacting conversion throughput
• Expands algae production and conversion to northern latitudes

Blending and wet storage systems eliminate natural gas-based drying
• 90% reduction in energy consumption
• 75% reduction in greenhouse gas release
Blends of algae and herbaceous biomass are able to undergo ensiling in storage and are preserved.

Storage Parameters
- Moisture content
- Blend ratios
- Sugar content
- 35 days of storage
Accomplishments - Task 1

Long-term storage study showed stability over 6 months

Go/No-Go Milestone (due 3/30/17)

Determine if wet storage can reduce dry matter loss to less than 30% over 6 months, which is a 50% improvement over wet algae stored aerobically

Result: *Scenedesmus obliquus/corn stover* blends were preserved over 6 months

Observed changes in composition
- Higher Heating Value (HHV) and Carbon increase
- Structural sugars are preserved over 6 months or decline proportionally with loss depending on blend ratio
- Protein preserved
- Lipid analysis underway

![Graph showing % Dry Matter Loss over Wet Anaerobic Storage Time (Months) for different blend ratios.](chart.png)
Future Work - Task 1

Investigate storage and conversion performance of additional blends
- *Scenedesmus acutus*, MSW yard waste: 4.8% ± 0.8% dry matter loss (DML)
- *Scenedesmus acutus*, sweet sorghum: 6.3% ± 3.1% DML
- Biomass from Algal Turf Scrubber, biomass sorghum:
  - Pioneer turf, primarily benthic diatoms: 4.6% ± 0.8% DML
  - Established turf, filamentous green algae: 6.2% ± 1.5% DML

Assess conversion potential for blends through INL interface projects
- HTL screening
- Dilute acid pretreatment, enzymatic hydrolysis, lipid extraction

Incorporate algae strains of industrial relevance
- *Chlorella zofingiensis*
- *Chlorella vulgaris*
- *Porphyridium purpureum*
- *Nannochloropsis gaditana*

FY18: Assess conversion of blends with partner labs, finalize TEA and LCA
Technical Approach

Three tasks explore optimization of harvested algae from multiple angles

1. Stabilization through blending

2. Stabilization of algae alone

3. Ash reduction and subsequent stabilization
Technical Approach - Task 2

Algae are stable during simulated ensiling
• Losses limited to 6-12% over 30 days
Ensiling doesn’t occur as easily on its own as when blended with herbaceous biomass (preliminary results)
• Anaerobic storage, no treatment: 30% DML
• Anaerobic storage with lactic acid bacteria: 20% DML

Approach for stabilization
• Manipulate storage conditions to enable ensiling
• Explore value-added benefit of storage
  – Produce stabilizing co-products

Storage treatments under consideration
• Enzyme addition to release algal sugars for subsequent microbial fermentation
• Enzyme addition to produce preservatives
• Sulfuric acid treatment; compatible with dilute acid pretreatment
• Production of value-added organic acids for stability

Initial results promising
Scenedesmus acutus: 11% DML
Chlorella zofingiensis: 6.5% DML
Validation of storage approaches in multiple freshwater, saline, and filamentous strains over 1 and 6 months

- *Scenedesmus acutus*
- *Chlorella zofingiensis*
- *Chlorella vulgaris*
- *Porphyridium purpureum*
- *Nannochloropsis gaditana*
- Biomass from Algal Turf Scrubber-Corpus Christie, TX
- *Oedogonium* sp., filamentous algae grown on wastewater-Cal Poly-San Luis Obispo

- Assess storage performance and resulting composition-FY17
- TEA: Provide results to NREL to assess wet storage costs compared to the SOT of drying-FY17, Q2-Q3
- Down-select treatments, assess performance through collaboration with conversion labs as in Task 1, FY18-FY19
Technical Approach

Three tasks explore optimization of harvested algae from multiple angles

1. Stabilization through blending

2. Stabilization of algae alone

3. Ash reduction and subsequent stabilization
Ash reduction and subsequent stabilization solves seasonality aspect while upgrading biomass qualities

• Biogenic Ash: Diatoms in ATS biomass contain silica in the cell wall and intracellular silica
• Non-Biogenic Ash: Contamination from soil, silt, dissolved inorganics

• Approach
  – Reduce ash content in ATS biomass, which can be as high as 50 wt%
    o Alkaline extraction to solubilize silica
  – Determine short- and long-term stability of treated blend
    o Short-term stability addresses need for transportation to conversion facility
    o Long-term stability addresses seasonal variation in production
Goal: Develop a robust process to reduce ash content while preserving organic material

- Alkaline extraction targets
  - 70% ash reduction with 90% organic recovery
  - Methods developed for corn stover could be more efficient for algae

- One-step method
  - Biogenic and non-biogenic removal combined

- Two-step method
  - Sequential biogenic and non-biogenic removal

- Investigate stability of alkaline-treated solids
  - Storage stability
  - Possibility of reduced pretreatment requirements

- Results will assist SNL in defining a logistics system for biofuel production from ATS biomass

- Results may be applicable to multiple high-ash algae species
Relevance

• Feedstock logistics bridges the gap between production and conversion
• Lack of integration across all operations led to issues for current cellulosic industry suffered during startup, costly repairs/replacement, low fuel yield
• Integrating feedstock logistics and conversion now will save in the future

• Wet storage offers opportunities to lower conversion costs and energy requirements through the elimination of drying in order to manage seasonal variation in production
• Ash reduction in ATS biomass can reduce conversion costs by increasing yield while stabilizing biomass

Relevance for the emerging algal biofuels industry

• Short-term storage can enable stable transport to a central conversion facility, mobilizing rural economic resources
• Blending offers an opportunity for utilization of algae biomass before a dedicated algae conversion facility is built
Summary

Overview
• Manage seasonal variation of produced algal biomass through high-moisture stabilization to reduce the risk of feedstock loss prior to conversion
• Reduce ash to increase conversion yield while stabilizing biomass

Relevance
• Optimization in feedstock logistics can assist in meeting or lowering conversion cost targets, integrates production and conversion

Approach
• Stability research addresses seasonal variation in production and optimization of properties prior to conversion

Progress
• Demonstrated losses 6-17% in algae/corn stover blends stored for 6 months and as low as 6.5% in algae stored alone over 1 month
• TEA shows that stabilization through blending and wet storage is competitive with drying, can eliminate winter production in low-yield scenarios

Future Work
• Optimize storage performance while preserving composition
• Assess conversion performance, TEA, and LCA
Acknowledgments

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Hank Gehrkin

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Nick Nagle

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John Lucas
Publications


Presentations


Two invention disclosures submitted in 2016
Accomplishments - Task 1

Resource assessment completed to identify herbaceous biomass available for blending during summer months in Southwest and Southeast US

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Annual Inventory, Southeastern U.S. (US ton)</th>
<th>Annual Inventory, Southwestern U.S. (US ton)</th>
<th>Total Annual Inventory (US ton)</th>
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</thead>
<tbody>
<tr>
<td>Corn stover</td>
<td>27,958,773</td>
<td>11,187,082</td>
<td>39,145,855</td>
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<tr>
<td>Cotton stalks</td>
<td>4,174,541</td>
<td>4,064,226</td>
<td>8,238,767</td>
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<tr>
<td>Peanut hay</td>
<td>4,383,210</td>
<td>462,923</td>
<td>4,846,133</td>
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<tr>
<td>Rice straw</td>
<td>7,157,144</td>
<td>2,756,610</td>
<td>9,913,754</td>
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<td>Sorghum</td>
<td>776,201</td>
<td>1,256,652</td>
<td>2,032,853</td>
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<td>Haylage</td>
<td>934,803</td>
<td>2,866,954</td>
<td>3,801,757</td>
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<td>Distillers grains</td>
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<td>2,496,000</td>
<td>4,560,000</td>
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<td>Sugar cane/energy cane</td>
<td>27,380,199</td>
<td>1,401,926</td>
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<td>MSW Yard waste</td>
<td>2,439,955</td>
<td>2,588,903</td>
<td>5,028,858</td>
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</table>
Techno-economic analysis compares blending and wet storage to drying

Defined unit operations for wet storage of algae/terrestrial biomass blends at a reactor throat

- HTL is assumed conversion method
- Cost comparison includes
  - Feedstock cost
  - Drying or wet storage cost
- Total cost compared by estimating fuel yield and resulting cost/gallon
Accomplishments - Task 1, TEA

<table>
<thead>
<tr>
<th>Feedstock Cost&lt;sup&gt;b&lt;/sup&gt;</th>
<th>3:1 Drying</th>
<th>3:1 Wet Storage</th>
<th>5:1 Drying</th>
<th>5:1 Wet A&lt;sup&gt;a&lt;/sup&gt;</th>
<th>5:1 Wet B&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
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<tbody>
<tr>
<td>Algae Produced</td>
<td>$5,995,808</td>
<td>$5,995,808</td>
<td>$3,446,820</td>
<td>$3,446,820</td>
<td>$3,446,820</td>
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<tr>
<td>Corn Stover Purchased</td>
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<td>$1,790,719</td>
<td>-</td>
<td>$715,009</td>
<td>$715,009</td>
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<tr>
<td>Upgraded Blend</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>($907,651)</td>
<td>($466,982)</td>
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<td>Stabilization Cost ($/ton)</td>
<td>$140.80</td>
<td>$81.84</td>
<td>$140.80</td>
<td>$112.13</td>
<td>$113.75</td>
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<td>Stabilization Cost ($)</td>
<td>$1,719,368</td>
<td>$3,287,384</td>
<td>$988,416</td>
<td>$2,020,398</td>
<td>$2,049,587</td>
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<td>Total Costs ($)</td>
<td>$7,715,177</td>
<td>$11,073,911</td>
<td>$4,435,236</td>
<td>$5,274,575</td>
<td>$5,744,434</td>
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</tbody>
</table>

Total Diesel Produced (Gallons)<sup>c</sup>

<table>
<thead>
<tr>
<th></th>
<th>From Algae</th>
<th>From Corn Stover</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>3:1 Summer:Winter</td>
<td>1,489,794</td>
<td>-</td>
<td>1,489,794</td>
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<tr>
<td>Variation</td>
<td>1,415,304</td>
<td>1,859,141</td>
<td>3,274,444</td>
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<tr>
<td>5,000 acre pond</td>
<td>856,440</td>
<td>-</td>
<td>856,440</td>
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<tr>
<td>5:1 Summer:Winter</td>
<td>490,367</td>
<td>422,037</td>
<td>912,404</td>
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<tr>
<td>Variation</td>
<td>657,848</td>
<td>566,181</td>
<td>1,224,029</td>
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<tr>
<td>1,000 acre pond</td>
<td>90.6%</td>
<td>111.6%</td>
<td>142.9%</td>
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</table>

<table>
<thead>
<tr>
<th>Cost ($/gallon diesel)</th>
<th>From Algae</th>
<th>From Corn Stover</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>3:1 Drying</td>
<td>$5.18</td>
<td>$3.38</td>
<td>$5.18</td>
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<tr>
<td>5:1 Wet A&lt;sup&gt;a&lt;/sup&gt;</td>
<td>$5.18</td>
<td>$5.78</td>
<td>$5.78</td>
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<tr>
<td>5:1 Wet B&lt;sup&gt;a&lt;/sup&gt;</td>
<td>$4.69</td>
<td></td>
<td>$4.69</td>
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</table>

*All costs reported in 2011 dollars on an ash-free dry weight basis

<sup>a</sup>5:1 Wet A case assumes winter operation of algae ponds, while the 5:1 Wet B case assumes no algae is produced during winter

<sup>b</sup>Algae: $491/ton [Davis, 2016]; Corn stover 3:1: $64.05/ton; Corn stover 5:1: $65.01/ton; Upgraded Blend: ($128.40)/ton

<sup>c</sup>Algae: 122 gallons/ton [Jones, 2014]; Corn Stover: 70 gallons/ton
Accomplishments - Task 1, TEA

TEA comparing blending and wet storage to drying for the fraction of biomass needing preservation

- Fuel yield from algae was assumed at 122 gallons/ton biomass
- Fuel yield from corn stover was estimated at 53.2-87.5 gallons/ton biomass

![Graph showing cost of diesel vs. yield from corn stover for different storage methods.](image)
Accomplishments - Task 1

Energy consumption and greenhouse gas release associated with blending and wet storage is reduced significantly compared to drying

<table>
<thead>
<tr>
<th></th>
<th>3:1 Summer:Winter Variation</th>
<th>5:1 Summer:Winter Variation</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>5,000 acre pond</td>
<td>1,000 acre pond</td>
</tr>
<tr>
<td>3:1 Drying</td>
<td>49,420,000</td>
<td>28,410,000</td>
</tr>
<tr>
<td>3:1 Wet Storage</td>
<td>4,956,000</td>
<td>2,292,000</td>
</tr>
<tr>
<td>5:1 Drying</td>
<td>28,410,000</td>
<td>2,292,000</td>
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<tr>
<td>5:1 Wet A(^a)</td>
<td>2,328,000</td>
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</tr>
<tr>
<td>5:1 Wet B(^a)</td>
<td>2,328,000</td>
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<tr>
<td><strong>Total Energy (kWh)</strong></td>
<td><strong>49,420,000</strong></td>
<td><strong>28,410,000</strong></td>
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<tr>
<td>% of Drying Case</td>
<td>—</td>
<td>10.0%</td>
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<tr>
<td>GHG (kg CO(_2) equiv/tonne)</td>
<td>993.25</td>
<td>993.25</td>
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<td>Total GHG release (kg CO(_2) equiv)</td>
<td>11,003,280</td>
<td>6,325,473</td>
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<tr>
<td>% of Drying Case</td>
<td>—</td>
<td>25.1%</td>
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</tbody>
</table>

*All tonnages reported on an ash-free dry weight basis

\(^a\)5:1 Wet A case assumes winter operation of algae ponds, while the 5:1 Wet B case assumes no algae is produced during winter

\(^b\)Data from Drying cases from Davis, 2016.