CO₂ to Bioplastics: Beneficial Re-use of Carbon Emissions from Coal-Fired Power Plants Using Microalgae

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Project Overview
(DE-FE0029623)

- **Funding:**
  DOE: $999,742
  Cost share: $258,720
  Total project: $1,258,462

- **Performance dates:**
  6/1/2017 – 5/31/2020

- **Project Participants:**
  - University of Kentucky
  - Colorado State U.
  - Algix LLC
  - Duke Energy

**Project Objectives:**

- A dual PBR/pond cultivation system will be evaluated with respect to capital and operational costs, productivity, and culture health, and compared to pond-only cultivation systems.

- A high-value biomass utilization strategy will be developed to simultaneously produce a lipid feedstock for the production of fuels, a carbohydrate feedstock for conversion to chemicals and/or bio-ethanol, and a protein-rich meal for the production of algal-based bioplastics.

- Techno-economic analyses will be performed to calculate the cost of CO₂ capture and recycle using this approach, and a life cycle assessment will evaluate the potential for reducing greenhouse gas emissions.
Advantages and Challenges

- Ability to generate a valuable product, thereby off-setting costs of CO$_2$ capture (potential for new industry)
- No need to concentrate CO$_2$ stream
- Potential to polish NO$_x$ and SO$_x$ emissions
  - Areal productivity such that very large algae farms required for significant CO$_2$ capture
  - CO$_2$ capture efficiency modest for conventional systems (<50%)
  - Challenging economics: cost of algae cultivation is high (currently >$1,000/MT), hence improved productivity is required, along with medium/high value applications for produced algal biomass
  - Market size generally inversely related to application value (hence risk of market saturation)
Technical Approach

Key issues to be resolved:

1) Can algal biomass production costs be lowered by the use of a combined PBR + pond cultivation system?
   → Combine the low capex of ponds with the high productivity of PBRs

2) In the case of algae-based bioplastic production, which processing scheme offers the greatest potential for revenue generation and large-scale application?
   → Whole biomass vs. wet lipid extraction vs. combined algal processing (CAP)

3) From a TEA and LCA perspective, which cultivation system and processing scheme(s) offer the greatest potential?
Project Scope/Milestones (BP 2)

• **LCA and TEA**
  - initial TEA
  - initial LCA
→ Demonstrate bioplastic production using this process is <0 g CO\textsubscript{2}-eq/kg

• **Algae Cultivation: Demonstration**
  - site preparation
  - PBR and pond operation
  - monitor culture health and identify potential contaminant
→ PBR + ponds installed and operating at East Bend Station

• **Biomass Processing: Valorization and Scale-up**
  - market analysis – sugars and lipids
  - bioplastic material characterization and film/fiber demonstration
→ Algae meal from biomass fractionation has increased protein content (>45 wt%) and lower ash content (<11 wt%) compared to whole biomass
## Success Criteria

<table>
<thead>
<tr>
<th>Decision Point</th>
<th>Date</th>
<th>Success Criteria</th>
<th>Status</th>
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<tbody>
<tr>
<td>Algae productivity</td>
<td>5/31/2018</td>
<td>PBR/pond cultivation system demonstrated to show superior productivity to pond-only system</td>
<td>Completed (Continuation Application, April 2018)</td>
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| Fractionation of algal biomass          | 5/31/2018| (i) 10 lb of algae produced for utilization studies  
(ii) >80% lipids and >50% fermentable sugars recovered from algae                                                                                                                                           | Completed (Continuation Application, April 2018)                       |
| Validation of bioplastic properties     | 5/31/2019| Algae meal meets Algix’s QC standards, including total odor compound count <200                                                                                                                               | Completed (BP2 review meeting, May 2019)                               |
| Algae productivity                      | 5/31/2019| >15 g/m² algae production demonstrated for hybrid cultivation system using coal-derived flue gas                                                                                                             | Target not met (Continuation Application, April 2019)                  |
| Life cycle assessment                   | 5/31/2019| Demonstrate bioplastic production using this process is <0 g CO₂-eq / kg bioplastic                                                                                                                         | Completed (Continuation Application, April 2019)                       |
| Techno-economic analysis                | 5/31/2020| Demonstrate a pathway to produce algae bioplastic feedstock for <$1,000 / ton biomass                                                                                                                          | Pending                                                               |
Algae Cultivation: PBR-ORP versus ORP Systems

**Operating Conditions**

- Open Raceway Pond (ORP) system operated traditionally in semi-batch mode, with harvesting and dilution from 0.6 g/l to 0.2 g/l
- PBR + ORP system harvested at 0.6 g/l to 0.1 g/l with an additional ‘over seed’ of 0.1 g/l from PBR
- PBR system harvested to match the other systems at 0.2 g/l
Results: PBR-ORP vs. ORP Productivity

- PBR showed higher productivity than ponds
- PBR-fed ponds showed 14% improvement in productivity over conventionally operated ponds
- Areal productivity target not met (15 g m\(^{-2}\) day\(^{-1}\)) due to poor weather

East Bend Station power plant, fall 2018
(ponds 1 & 2 PBR-fed)
Algal Biomass Processing

<table>
<thead>
<tr>
<th>Sample</th>
<th>Protein (%, db)</th>
<th>Nitrogen, sulfur and furans at 140 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proteinaceous solid from fractionation</td>
<td>52.3</td>
<td>7</td>
</tr>
<tr>
<td>Defatted biomass</td>
<td>50.7</td>
<td>12</td>
</tr>
<tr>
<td>Whole biomass</td>
<td>44.2</td>
<td>16</td>
</tr>
</tbody>
</table>

- Biomass fractionation according to CAP protocol*
- Increased protein content after processing (52%) and decreased ash (2%)
- GCMS volatile compound test found only 7 problematic odor compounds, well below threshold count
- Biomass passed every qualification test according to Algix’s metrics

Bioplastic Material Characterization

Fractionated algae ("UK-T-PBAT") + PBAT versus neat PBAT

- Raw (dried-only), lipid-extracted and fractionated algal biomass used to prepare bioplastics
- PLA (polylactic acid)-PBS (polybutylene succinate), PBAT (polybutylene adipate terephthalate) and Nylon resins used
- Raw and lipid-extracted biomass gave similar results
- Nylon fiber and PLA-PBS products showed suitable properties for commercial use, but did not show significant improvements compared to the neat polymer
- Significant increase in extension found for fractionated biomass-PBAT tensile bars of >21% before breaking over neat PBAT. Promising for film applications with higher toughness and better suitability film applications
Sustainability Modeling

Process Overview

System Boundary

ORP
PBR
PBR/ORP Combined

Dewater

Biomass
Biomass 25% Dry
Fractionsation

Lipid Extraction

High Protein Biomass

BPFS Preparation

Bioplastic Feedstock 100% Dry

Fuels

Flue Gas
Fertilizer
Fresh Water
Recycle Water

Heat
Fuels
Sustainability Modeling

Methods Overview

Life Cycle Assessment

Life cycle inventory
TRACI Assessment

Energy costs
Maintenance costs
Purchase price
Loan structure

Techno-economic analysis

Process Model
**TEA Results**

- **Cost of biomass production:**
  - PBR > PBR-ORP > ORP
  - Fractionation > Lipid extraction > Drying only
- **Capital costs dominate**
- **Co-production credits minimal (if fuel)**
Current range for algal biomass feedstock
LCA Results

Net CO₂ emission reduction: PBR > PBR-ORP > ORP
LCA Results Summary

![Graph showing LCA results summary with categories: Drying Only, Lipid Extraction, Fractionation, ORP Only, Combined Growth, PBR Only. The graph plots kg CO$_2$eq/kg BioPlastic FS. The unit of measurement is kg CO$_2$eq/kg BioPlastic FS. The x-axis represents the process categories, and the y-axis represents the kg CO$_2$eq/kg BioPlastic FS. The graph shows a dashed line indicating Plastic resin.](image-url)
Sensitivity Analysis: Drying only vs. Fractionation

ORP, Drying t-ratio

-40 -30 -20 -10 0 10 20

Water Recycling Efficiency
OPR Productivity
Microwave Dryer
Evaporation Rate
Paddle Wheel Power Demand
Fresh Water Pumping Power Demand
Membrane Dewater

ORP, Fractionation t-ratio

-80 -60 -40 -20 0 20

Hexane Recycle Efficiency
Water Recycling Efficiency
OPR Productivity
Microwave Dryer
Evaporation Rate
Yield, Lipids
Fermentable Sugars
Lipids
Vent Carbon Balance
Algal biomass Carbon wt...
Fuel Range Hydro...
Yield, Ethanol
Proteins
Carbohydrates
Future

- Develop PBR and ORP growth models such that TEA and LCA analyses can be tailored to different geographic regions
- Investigate the effect of the PBR to ORP ratio on the TEA and LCA of the system. Identify strategies to optimize the ratio
- Update TEA with projected value for proteinaceous biomass from fractionation – does the added value justify the extra cost of fractionation?
- Reporting
Summary

Based on these results, algae bioplastics could be made economically in an NOAK plant today.

All scenarios are more environmentally favorable than petroleum plastic resins.

A fuels co-product is not the best choice for this system

Proteinaceous algal biomass from fractionation shows promise as a feedstock for bioplastic film applications
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