# *Improving the Economic Viability of Biological $CO_2$ Utilization by Improved Algae Productivity & Integration with Wastewater Treatment*

Cooperative Agreement No: DE-FE0030822

CO2 Capture Technology
Project Review Meeting
August 2019

NATIONAL ENERGY TECHNOLOGY LABORATORY

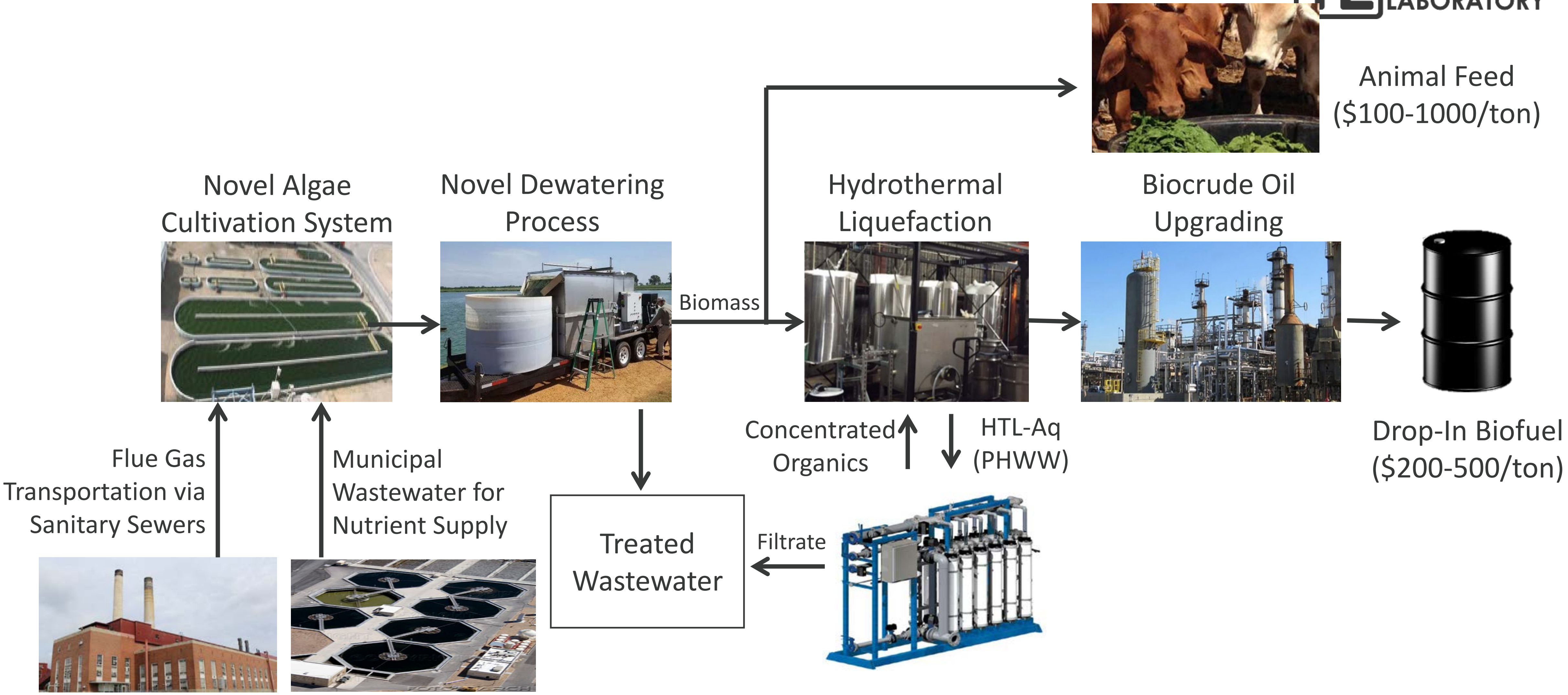
Illinois Sustainable Technology Center | ILLINOIS

Helios-NRG, LLC

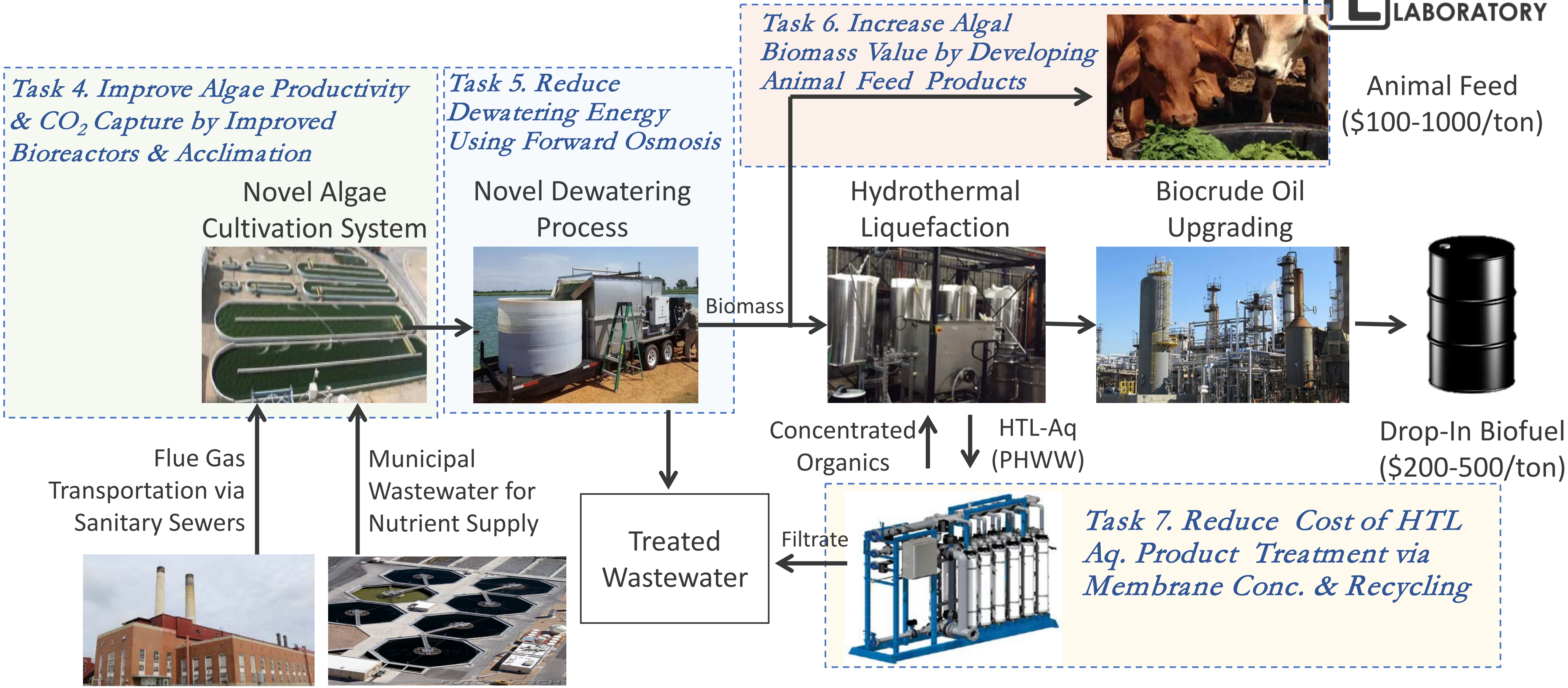
# Basic Project Information for DE-FE0030822

- **Title:** *Improving the Economic Viability of Biological Utilization of Coal Power Plant $CO_2$ by Improved Algae Productivity & Integration w/ Wastewater Treatment*
  - DOE Program Manager: Andy Aurelio
  - Lead Organization: University of Illinois- Illinois Sustainable Technology Center
  - Primary Collaborating Organization: Helios-NRG
    - CO-Pi: Ravi Prasad, Fred Harrington
- **DOE Funding Program DE-FOA-0001622:** *Applications for Technologies Directed at Utilizing Carbon Dioxide from Coal Fired Power Plants*
  - Total Project Value: $ 1,249,873 Government : $999,536 Cost Share: $250,337
  - Currently in Budget Period 2 (BP2)- October 1, 2018 – September 30, 2019
- *Major Project Objectives & Goals*
  - End of project performance goals
    - 35 $g/m^2$day biomass productivity (vs 8.5 $g/m^2$ day DOE Baseline- 2015 State of Technology)
    - 70% $CO_2$ capture efficiency
    - $470/ton algal biomass projected $n^{th}$ plant (vs $1,641/ton current DOE Baseline)

# BP2 Project Tasks in Context of Process Flow Diagram



# BP2 Project Tasks in Context of Process Flow Diagram



# Techno-Economic Rationale: Integrating wastewater (WW) treatment can make algal animal feed cost-effective

| | Ponds/Inoculum: | Harvest & Dewater | Total Biomass Cost |
|---|---|---|---|
| 2015 DOE Case | $1,359/DT | $82/DT | $1641 /DT |
| Proposed Case | $331/DT | $50/DT | $ 537 /DT |

$CO_2$ $ 99/DT

Nutrient $ 25/DT

$CO_2$ credits

Nutrient removal credits

| Cost Categories | 2015 SOT DOE Baseline 8.5 g/m²/day | Proposed Case for BP2 25 g/m²/day |
|---|---|---|
| Ponds & Inoculum | $ 1,359 | $ 331 |
| $CO_2$ Supply | $ 99 | $ 99 |
| Dewatering Operations | $ 82 | $ 50 |
| Nutrient Supply | $ 25 | $ 25 |
| Other Costs | $ 76 | $ 32 |
| TOTAL Algae Biomass Prod | $ 1,641 /DT | $ 537 /DT |

**Revenue for Algal Biomass**

$CO_2$ Removal: $ 0 - $ 60 /DT
Nutrient Removal: $ 380 - $ 680 /DT
Wet Animal Feed: $ 100 - $ 300 / DT

**$ 480 - $1,040 /DT**

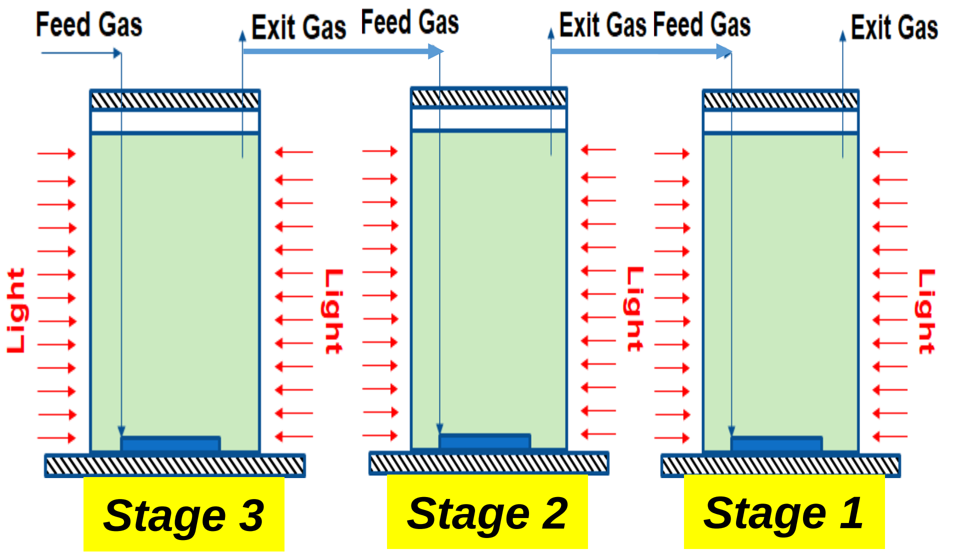
*Animal feed revenue potential of >$ 1000 / DT, but will likely require extra drying cost ($330/DT)*

# Task 4- BP2 Algae Testing Plan Overview

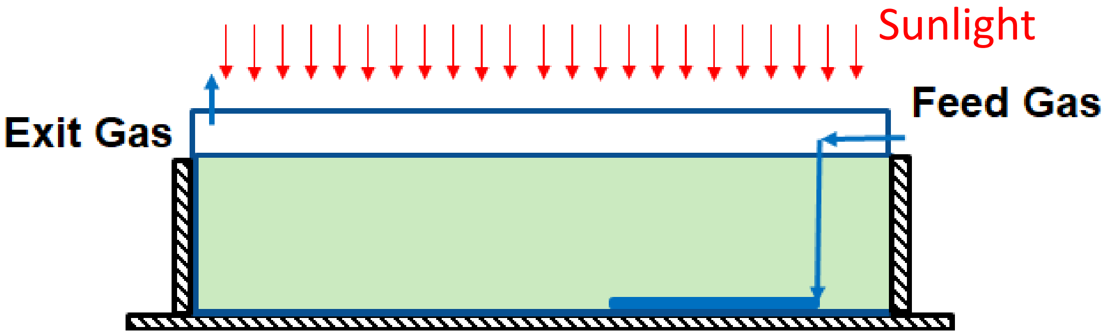
NATIONAL ENERGY TECHNOLOGY LABORATORY

- Transition from lab batch to continuous (w/liquid transfer)
- Transition from artificial lighting to sunlight (Greenhouse)
  - Quantify sunlight variations and impact on performance
- Greenhouse tests w/ simulated flue gas
  - 12% $CO_2$ + $SO_X$, $NO_X$ & 5 heavy metals (Cu, Cr, Hg, As, Se)
- Investigate and optimize greenhouse cultivation operations
  - Algae concentration effects on productivity
  - Gas/liquid flow rates effect on $CO_2$ capture & productivity
  - Long term stability & performance in greenhouse
- Demonstrate weekly average productivity of 25 $g/m^2/day$ with 70% $CO_2$ capture simultaneously for a simulated Multi-Stage Continuous (MSC) reactor system

Lab Side-Lit & Multi-Stage Continuous System

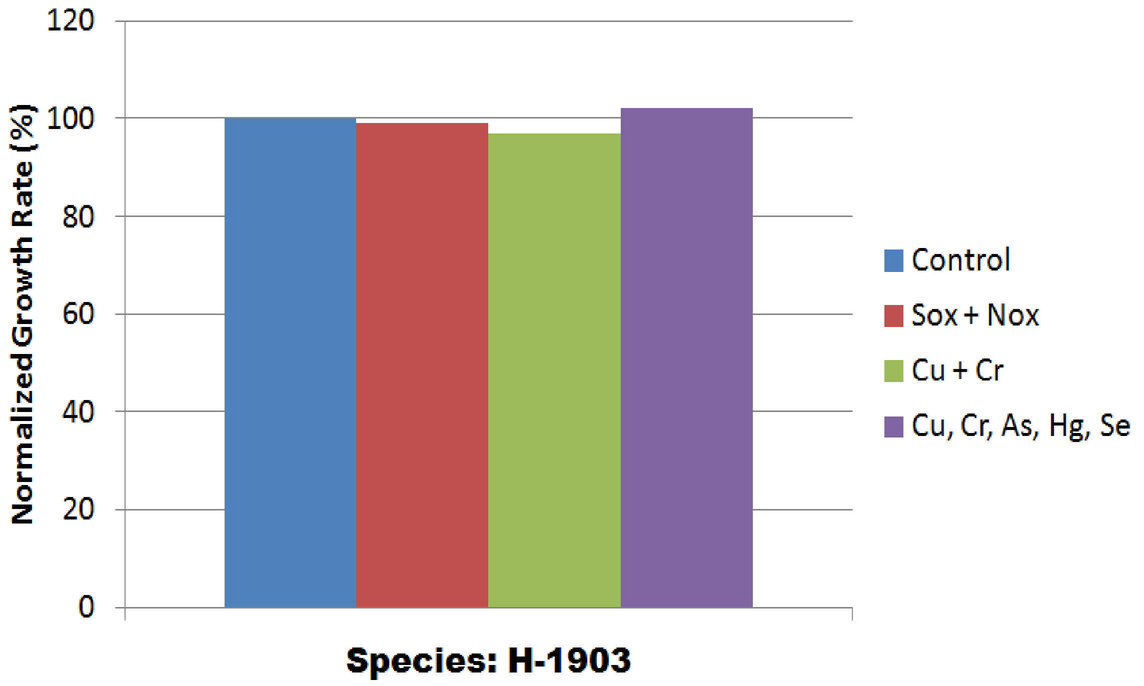


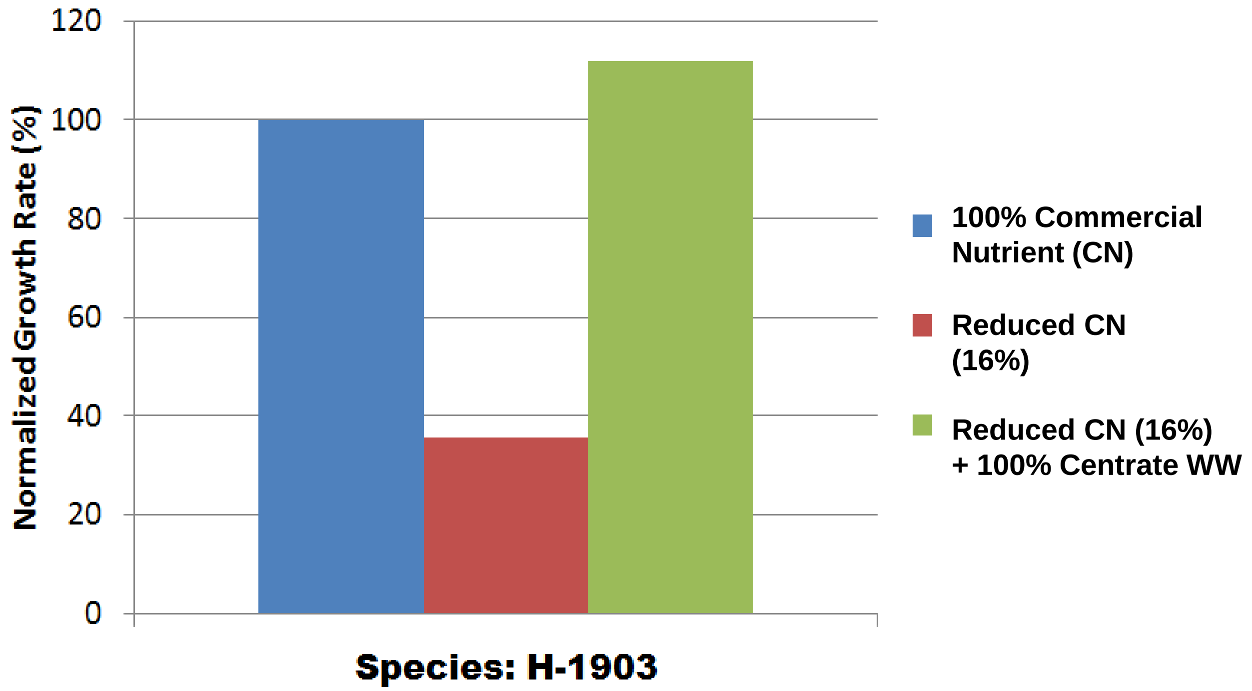

Greenhouse Top-Lit (Sun) System



# Lab- Algae cultivation w/ simulated flue gas & WW nutrients

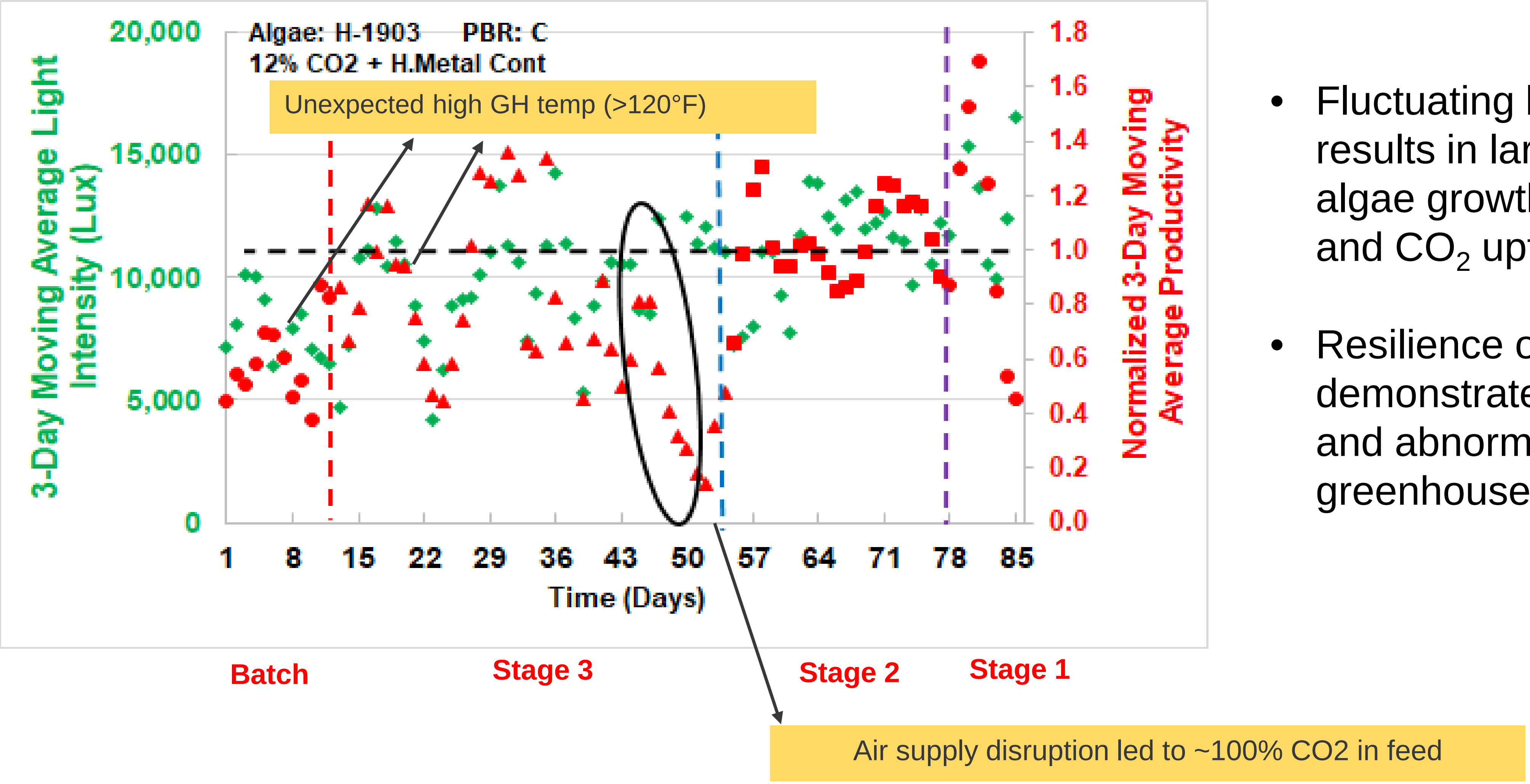





- ***Algae tolerance to key post-FGD flue gas contaminants demonstrated***
- ***Wastewater can beneficially replace purchased nutrients to reduce costs***

# Optimizing Long-term Greenhouse Operations

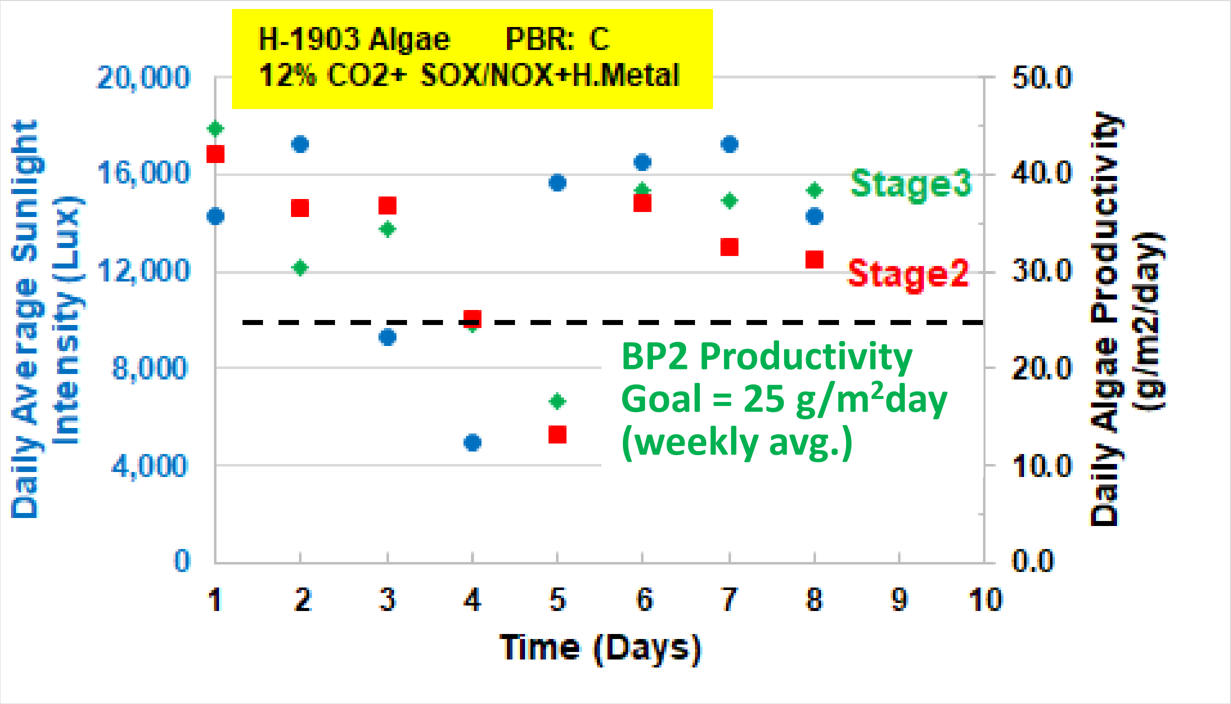


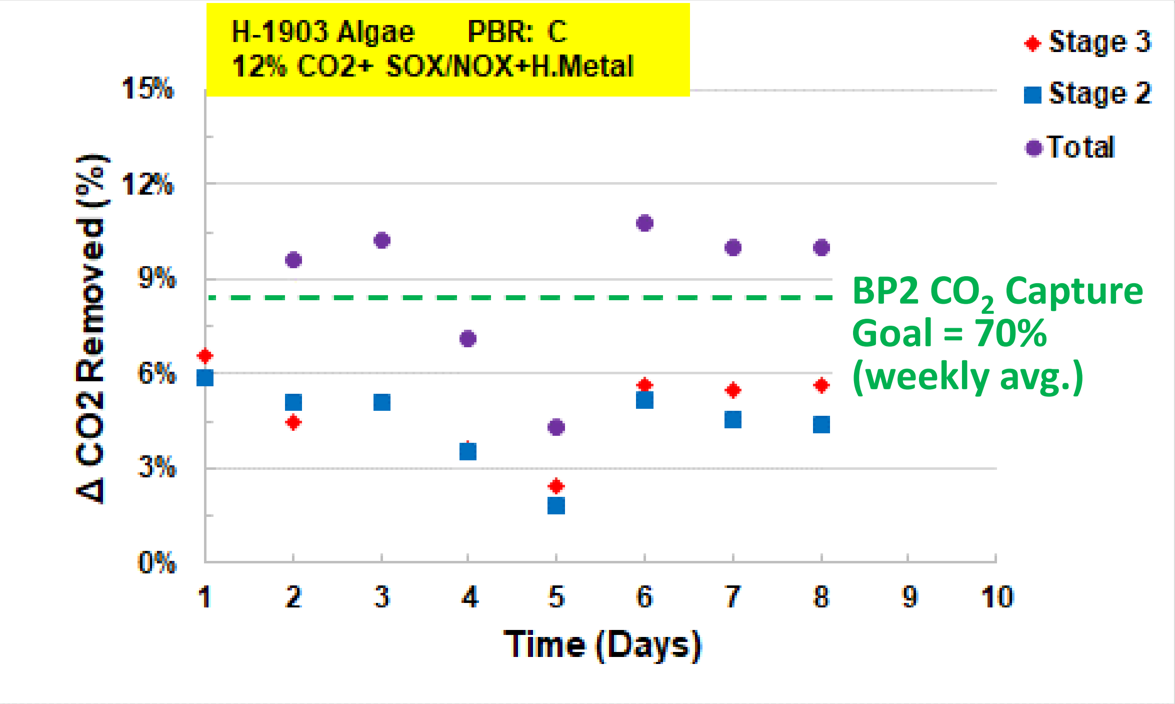

- Fluctuating light intensity results in large variations in algae growth (productivity) and $CO_2$ uptake
- Resilience of system demonstrated despite natural and abnormal fluctuations in greenhouse conditions

# Demonstration of CO2 Capture and Productivity Goals



## Greenhouse Operation

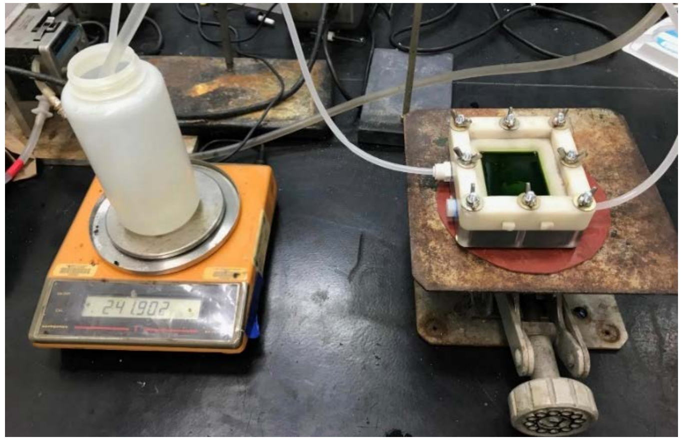



**BP2 algae cultivation targets met→ Weekly average of 30 $g/m^2/day$ productivity achieved simultaneous with 74% $CO_2$ capture demonstrated for a 2-stage MSC system**

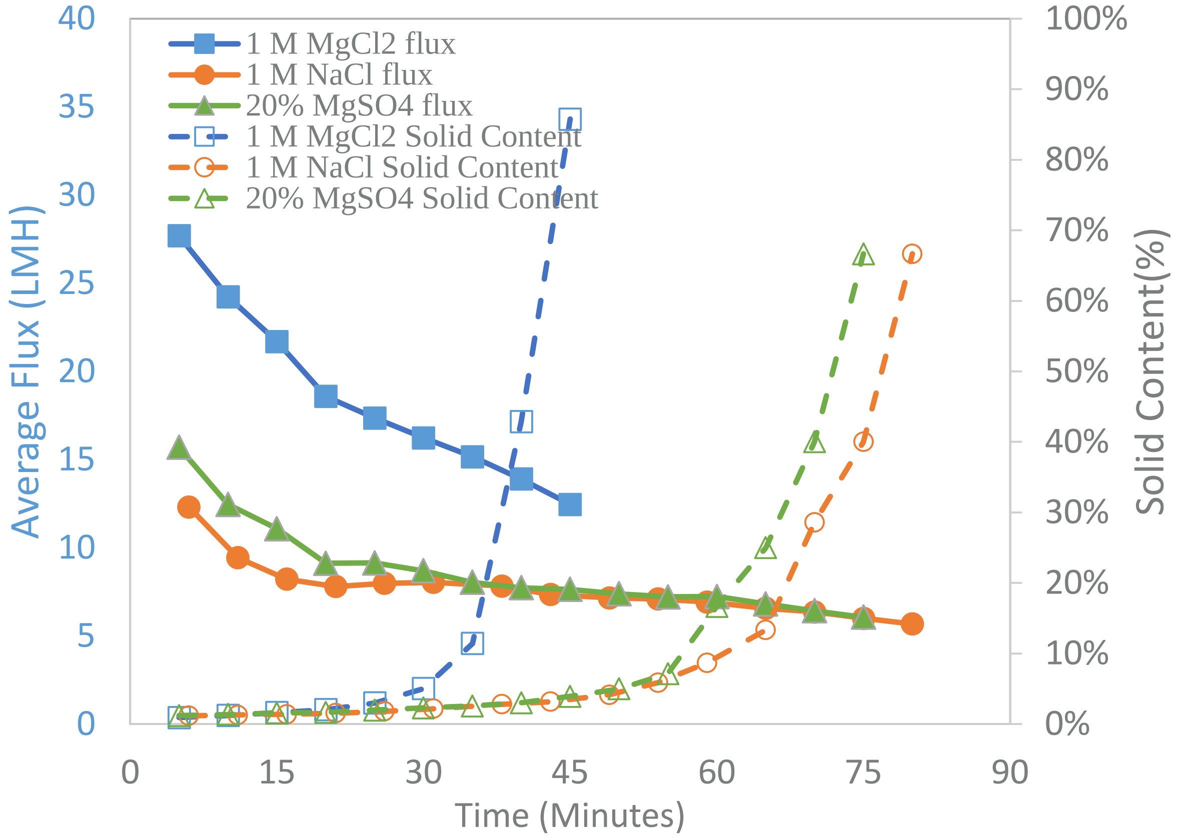
# Task 5. Evaluate novel forward osmosis algae dewatering process

## Forward osmosis open cell experiments with different draw solutions



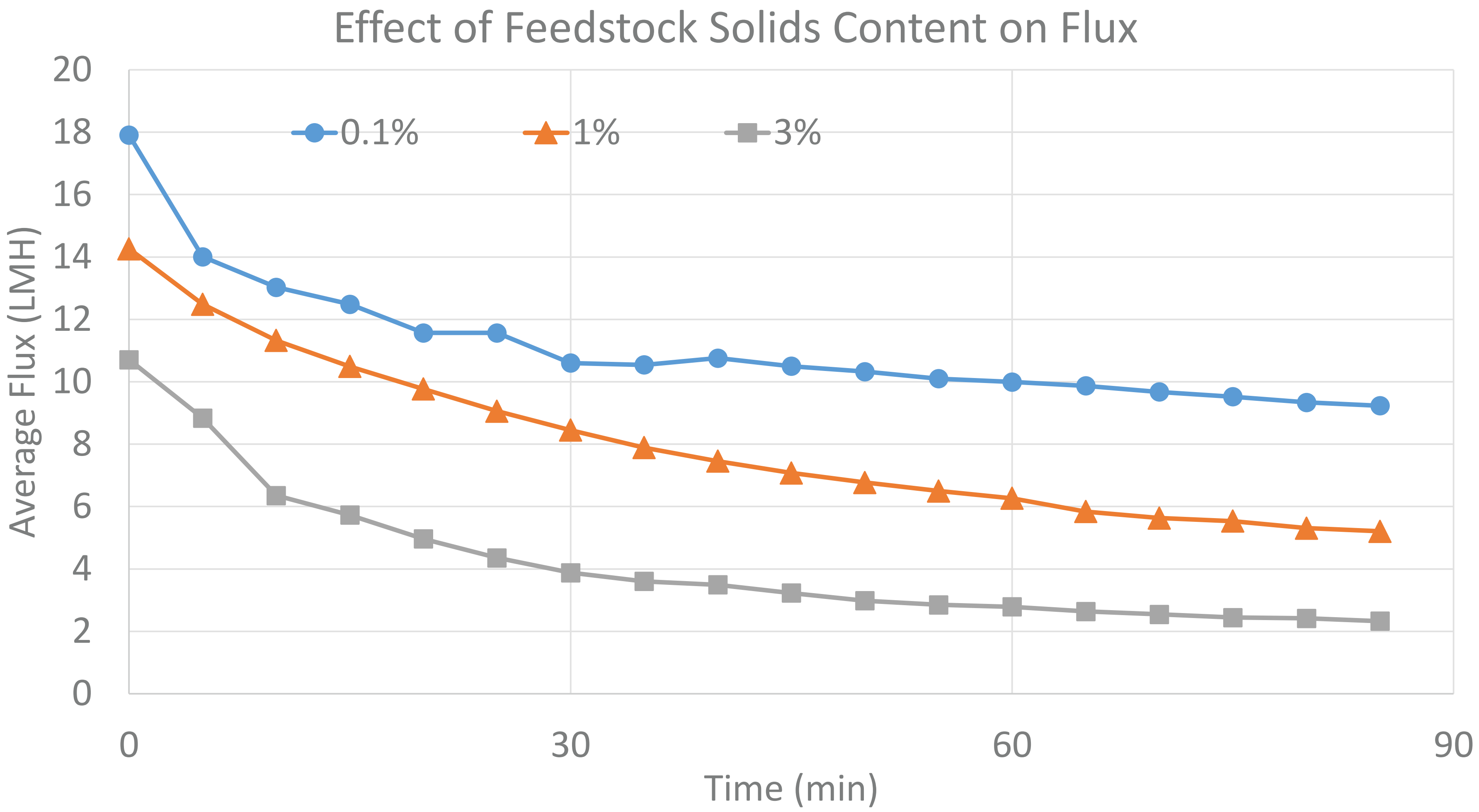
Open Cell FO System

Dewatered Biomass (40% Solid Content)



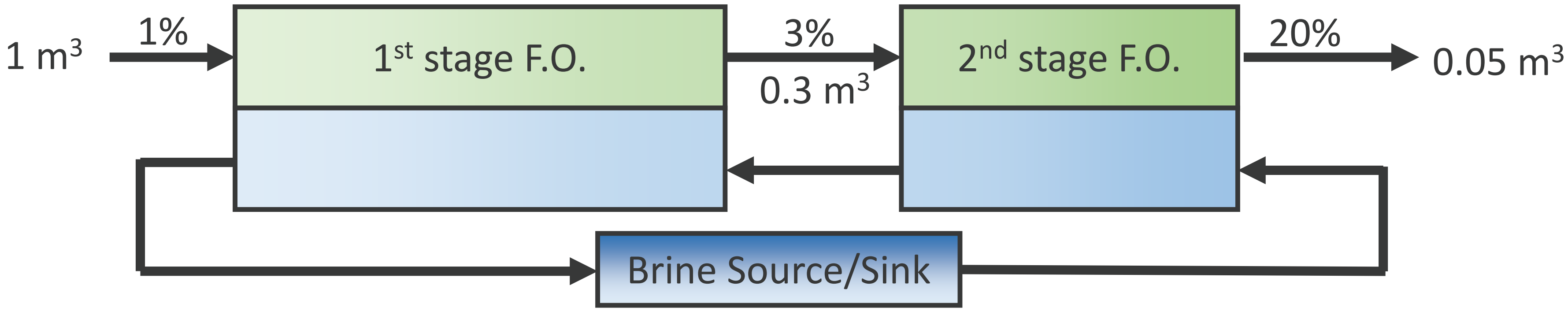

- Bench-scale open cell forward osmosis system was developed to test algae dewatering
- Biomass dewatered to above 20% solid content without pre-treatment in reasonable time
- Dewatering efficiency: 1 M $MgCl_2$ > 20% $MgSO_4$ ~1 M NaCl

# Improving F.O. dewatering process for cost and energy inputs




- Forward osmosis dewatering efficiency drops as culture concentration increases

# Improving F.O. dewatering process energy inputs

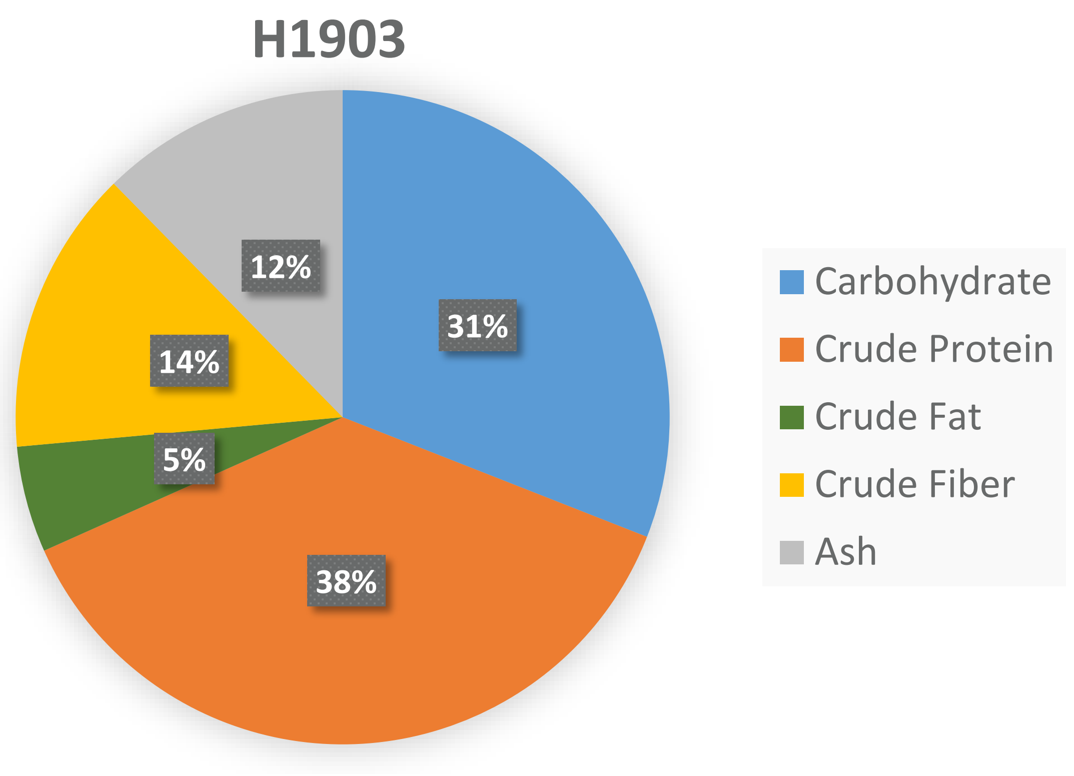


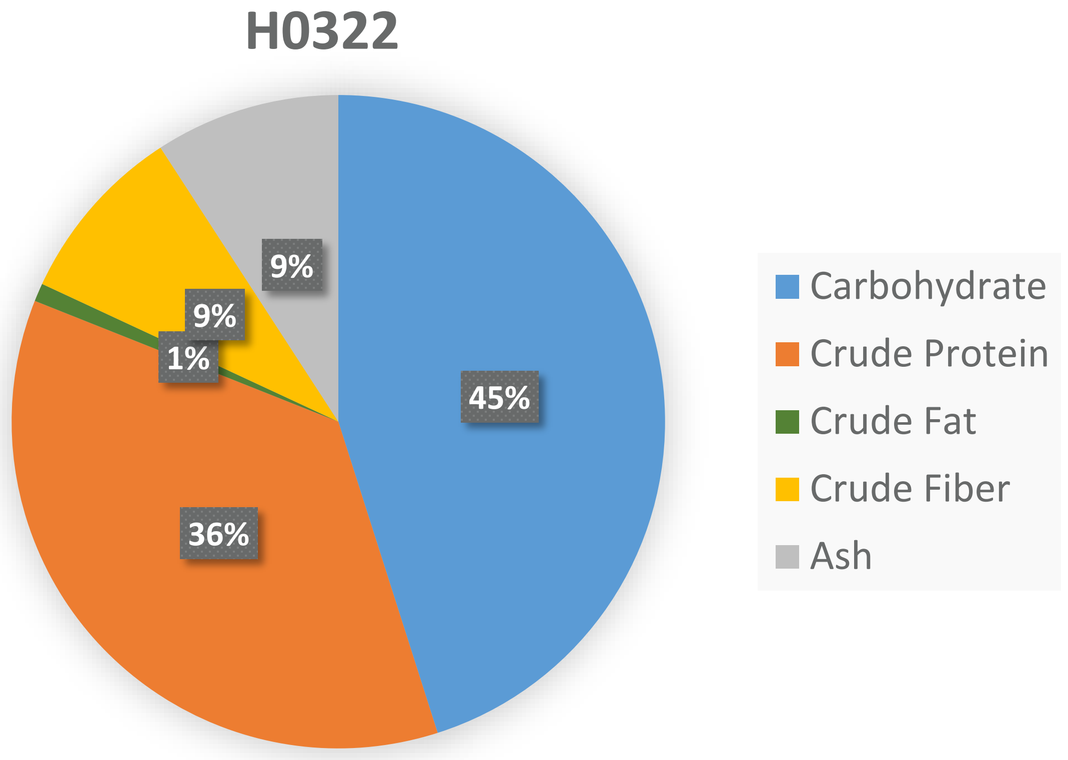

| | Starting Solid (%) | Ending Solid (%) | Energy consumption (kWh/m3) |
|---|---|---|---|
| Settling Pond | 0.1 | 1 | - |
| Membrane | 1 | 13 | 0.04 |
| Centrifuge | 13 | 20 | 1.35 |
| Forward Osmosis 1st Stage | 1 | 3 | 0.26 |
| Forward Osmosis 2nd Stage | 3 | 20 | 0.57 |

* 2-stage F.O. process using natural brines or sea water can greatly reduce dewatering energy inputs

# Task 6. *Characterize algal biomass for HTL & animal feed*

Proximate analysis of flue gas fed algal biomass




- **Both species are rich in protein and carbohydrates, low in fat, which is suitable for animal feeds**

# Heavy metals in algae grown w/ flue gas contaminants

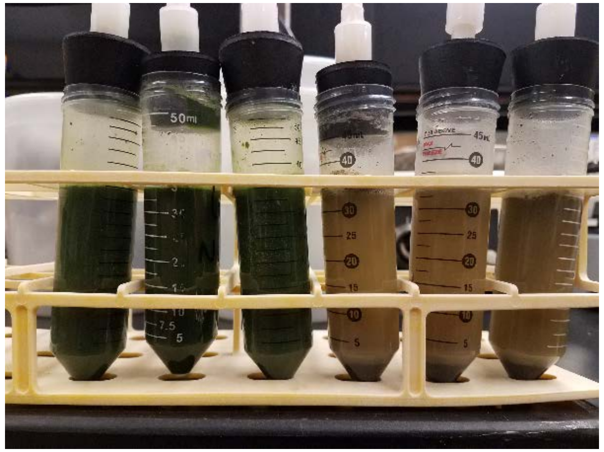
Compare with animal feed maximum tolerable level (MTL)

| Minerals | H-1903 Cu, Cr, As, Hg, Se (ppm) | Poultry Feed MTL (ppm) | Swine Feed MTL (ppm) | Cattle Feed MTL (ppm) | Fish Feed MTL (ppm) |
|---|---|---|---|---|---|
| As | 2.18 | 30 | 30 | 30 | 5 |
| Cd | <1 | 10 | 10 | 10 | 10 |
| Cr | 1.16 | 100 | 100 | 100 | 3,000* as CrO |
| Co | <2 | 25 | 100 | 25 | |
| Cu | 46.6 | 250 | 250 | 40 | 100 |
| Hg | 0.5 | 1 | 2 | 2 | 1 |
| Pb | <5 | 10 | 10 | 100 | 10 |
| Ni | <5 | 250 | 250 | 100 | 50 |
| Se | 0.54 | 3 | 4 | 5 | 2 |
| Zn | 11.3 | 500 | 1000 | 500 | 250 |

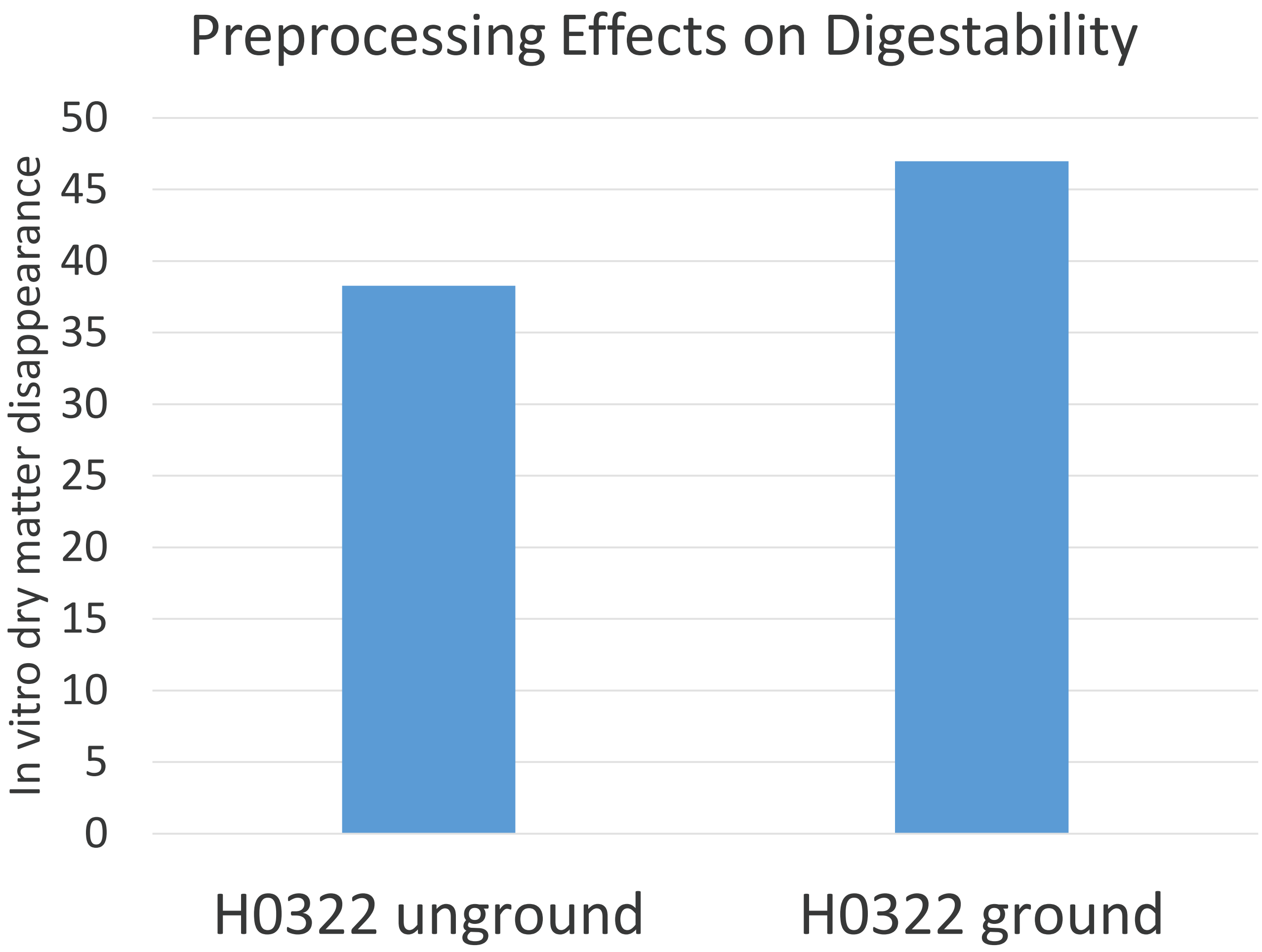
- **Algal biomass grown with flue gas contaminant meets most animal feed limits for metals and it can be blended with other feeds to mitigate any heavy metal concerns**

# Cattle digestibility test with algal biomass

- **In vitro fermentation assay**
  - Rumen fluid from cannulated steer
  - Incubate samples for 24 hours



- **Results**
  - Grinding with mortar and pestle increased In-vitro dry matter digestability (IVDMD)
  - Looking into other biomass treatments to increase digestability
  - Working to reduce run to run variations

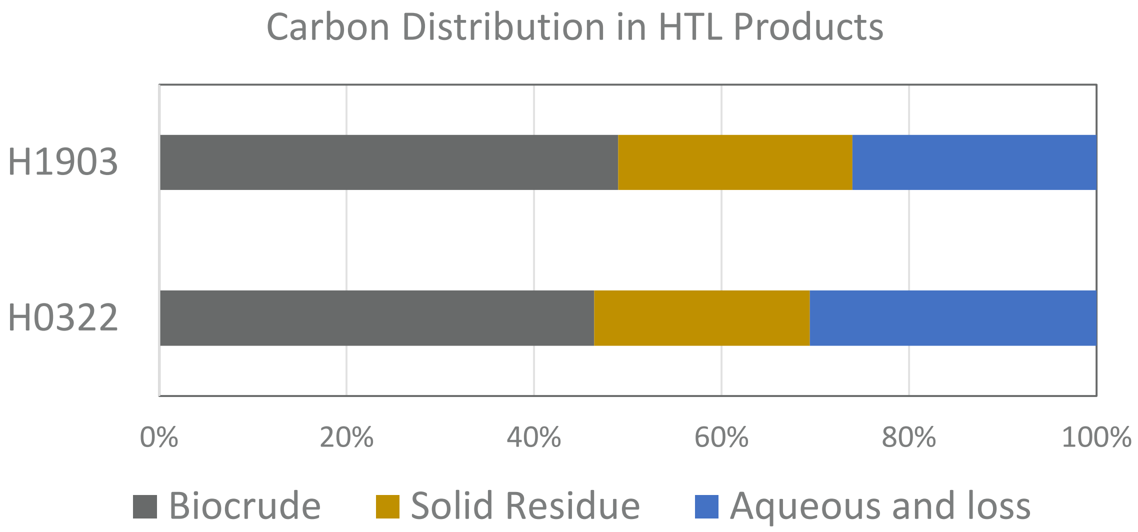


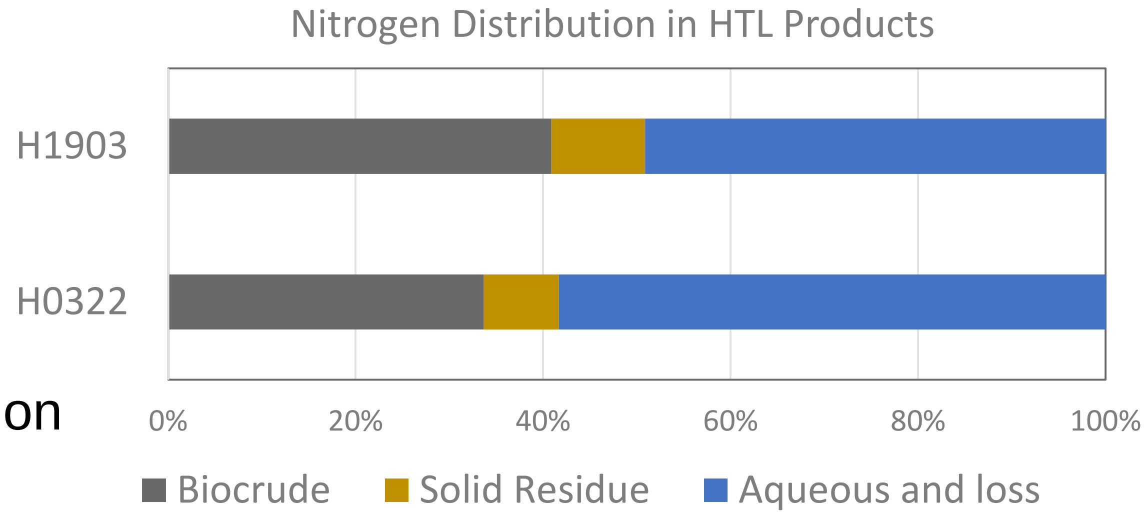
# Biomass elemental analysis and HTL Performance

NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

| | H1903 | H0322 |
|---|---|---|
| C (% dw) | 52.44 | 46.83 |
| H (% dw) | 7.54 | 7.11 |
| O (% dw) | 35.52 | 40.98 |
| N (% dw) | 4.50 | 5.10 |
| Biomass Heating Value (MJ/kg) | 22.15 | 18.66 |
| HTL Biocrude oil Fraction | 0.347 | 0.312 |
| HTL Biocrude oil HHV (MJ/kg) | 35.1 | 34.8 |

- H1903 biomass was preferable for biocrude production
- Most of N is distributed to HTL aqueous product

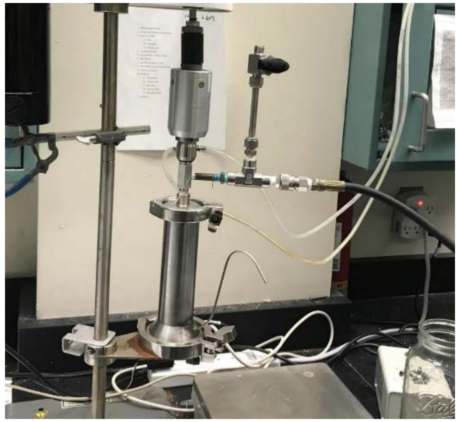


# Task 7. *Demonstrate ability to concentrate & recycle HTL aqueous phase (PHWW)*

Integration of HTL with nanofiltration for carbon recycle

Nanofiltration system



Algae Slurry

NF Retentate (Organics)

HTL

PHWW

Nano-Filtration

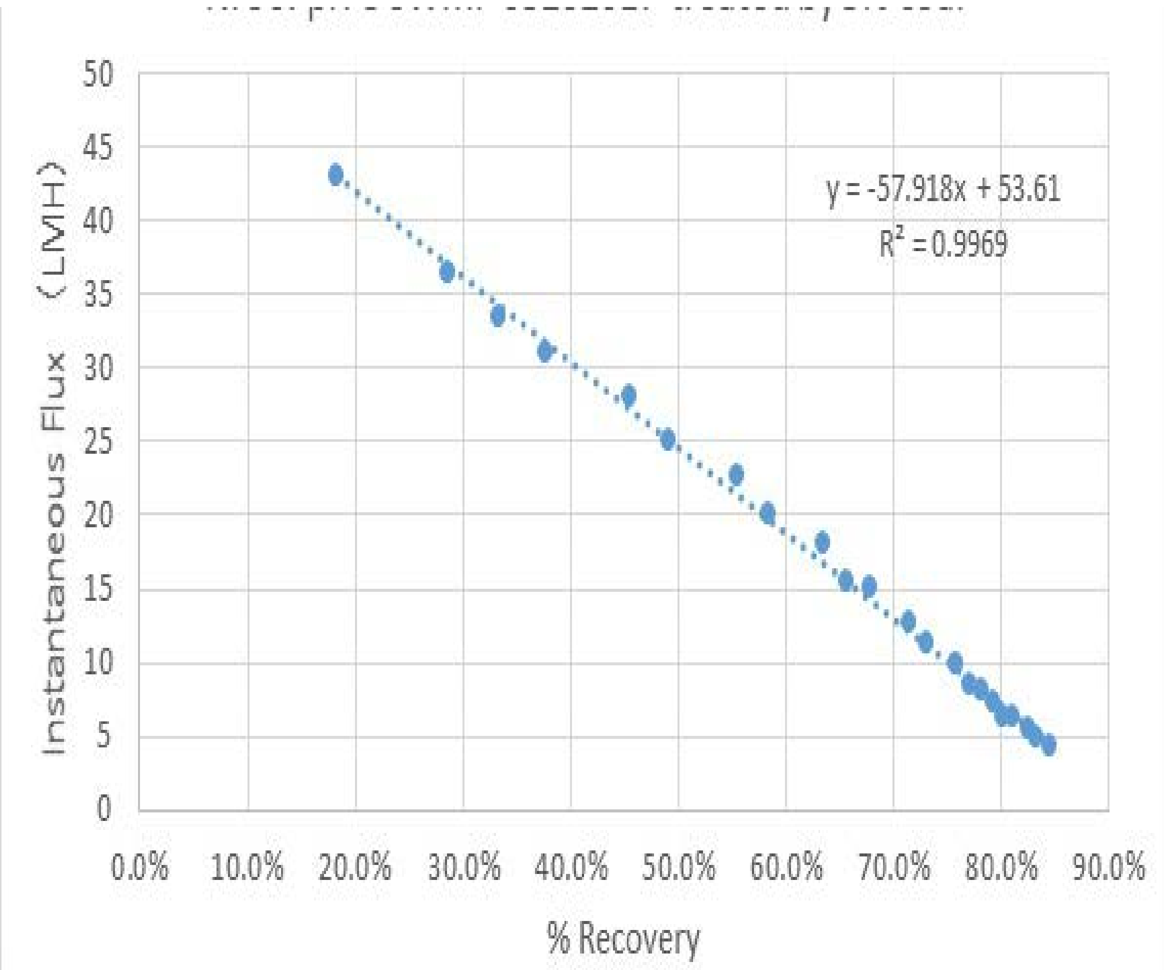
NF Permeate (Nutrients)

Raw Oil Product Separation

Ash/Char

Biocrude oil

Permeate PHWW Retentate

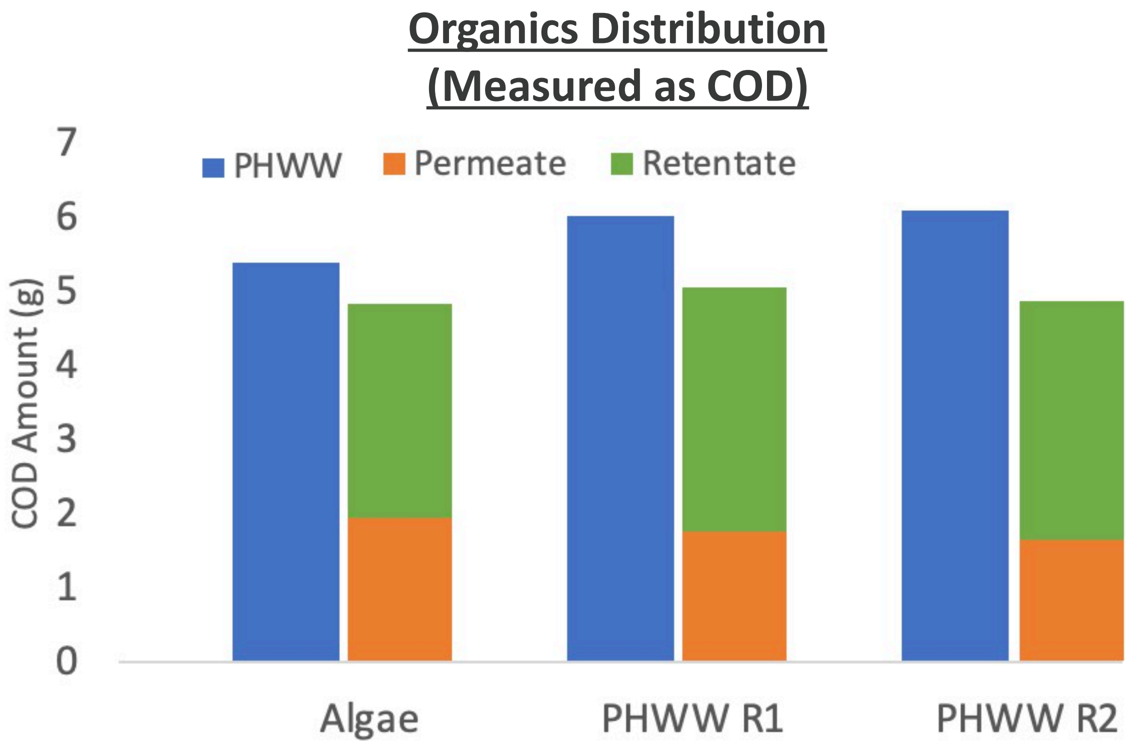


# Effect of recycling PHWW on biocrude yield & quality

NATIONAL ENERGY TECHNOLOGY LABORATORY

| | Algae Only | Algae + Run 1 Retentate (20%) | Algae + Run 2 Retentate (20%) |
|---|---|---|---|
| Biocrude Oil Yield Fraction | 0.349 | 0.368 | 0.371 |
| C (%) | 70.64 | 73.74 | 73.42 |
| H (%) | 8.78 | 9.38 | 9.12 |
| N (%) | 5.63 | 5.59 | 5.72 |
| O (%) | 14.95 | 11.29 | 11.74 |
| HHV (MJ/kg oil) | 33.7 | 36.3 | 35.7 |

- 6% increase in biocrude yield w/ PHWW recycle
- Small N increase in the biocrude oil




- ~60% of PHWW organics captured in NF retentate
- Significant N also captured in NF retentate (~50%)
  - May not be desirable→ Zeolite treatment can mitigate

# TEA: Integrating WW treatment can make algal biofuels cost-effective

NATIONAL ENERGY TECHNOLOGY LABORATORY

## Algal biomass for fuel

Algal Biomass Supply Cost:
$15.15/gge ($1,641/DT)

Algal Biomass Supply Cost:
$5.25/gge ($537/DT)

Hydrothermal Liquefaction
$1.18/gge

Bio-oil Upgrade
$0.44/gge

Aqueous Product Treatment
**Catalytic Hydrothermal Gasification**
$1.54/gge

**Nanofiltration**
$0.28/gge

| Biofuel Production Cost | DOE Baseline (2015 case) | Proposed case for BP2 |
|---|---|---|
| Algal Biomass | $15.15 /gge | $ 5.25/gge |
| Hydrothermal Liquefaction | $ 1.18/gge | $ 1.18/gge |
| Bio-oil Upgrade | $ 0.44/gge | $ 0.44/gge |
| Aqueous post treatment | $ 1.54/gge | $ 0.28/gge |
| Balance of plant | $ 0.29/gge | $ 0.29/gge |
| TOTAL Biofuel Cost | **$ 18.60/gge** | **$ 7.44/gge** |

**Revenue for Algal Biofuels**

| | |
|---|---|
| $CO_2$ Removal: | $ 0 - $ 0.6 /gge |
| Nutrient Removal: | $ 3.7 - $ 7.2 /gge |
| Fuel Selling Price: | $ 2.0 - $ 3.5 /gge |
| | **$ 5.7 - $ 11.3/gge** |

# Project Milestones for Budget Period 2

NATIONAL ENERGY TECHNOLOGY LABORATORY

| Budget Period | Task # | Mile-stone # | Milestone Description | Planned Completion Date | Actual Completion Date | | Comments |
|---|---|---|---|---|---|---|---|
| 2 | 4 | T4.1 | Single stage test of MSC representation with >70% $CO_2$capture and >25 $g/m^2/d$ | 9/30/2019 | 7/30/2019 | | Simulated Multi-stage $CO_2$ capture demonstrated >70% w/ single-stage tests |
| 2 | 5 | T5.1 | Dewater algal biomass >15% solid content through forward osmosis using <1.35 $kwh/m^3$ | 9/30/2019 | | | In-Progress- >20% solids content shown w/ min. energy input of 0.83 $kWh/m^3$ when seawater available |
| 2 | 6 | T6.1 | Characterize algal species that biomass heating value > 18MJ/kg and protein content > 30% | 3/31/2019 | 3/20/2019 | | Completed- 2 species sample analyzed |
| 2 | 6 | T6.2 | Demonstrate a minimum in vitro dry matter disappearance of 40% for algal strains digested in rumen fluid | 9/30/2019 | | | In-Progress- H0322 ground sample had >45% dry matter disappearance, but the result was not yet repeated |
| 2 | 7 | T7.1 | Recycle >50% of carbon from HTL aqueous and increase biocrude oil yield by > 5% | 9/30/2019 | 6/30/2019 | | Completed- ~60% of carbon from HTL-aq recycled to enhance oil by 5% |

# Project Success Criteria for Each Budget Period

| Decision Point | Date | Success Criteria |
|---|---|---|
| G/N-1<br>Go/No-Go Budget Period 1 | 9/30/2018 | Algal Productivity > 25 $g/m^2/d$ (weekly average) with Simulated Flue gas containing 12% CO2, SOX, NOX and representative levels of heavy metals Hg, Se, As, Cu and Cr |
| G/N-2<br>Go/No-Go Budget Period 2 | 9/30/2019 | Algal Productivity > 25 $g/m^2/d$ (weekly average) and >70% CO2 capture with Simulated Flue gas containing 12% CO2, SOX, NOX and representative levels of heavy metals Hg, Se, As, Cu and Cr |
| G/N-3<br>Go/No-Go Budget Period 3 | 9/30/2020 | Integrated Application of Project Technologies w/ Projected Cost of Algal Biomass < $470 /dry ton |

# Questions and Comments…

Lance Schideman
schidema@Illinois.edu
217-390-7070



***istc.illinois.edu***