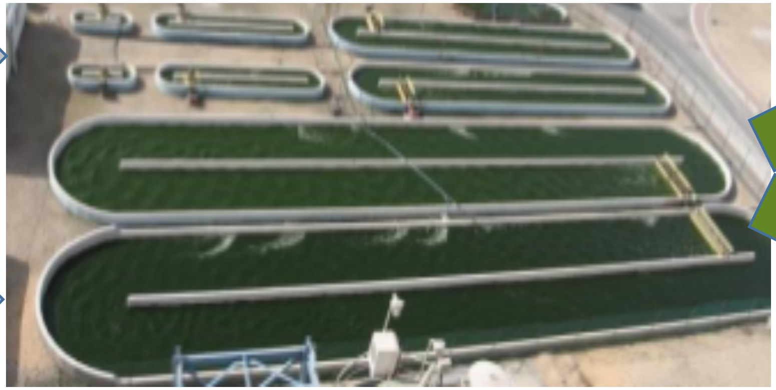
Improving the Economic Viability of Biological CO_2 Utilization by Improved Algae Productivity & Integration with Wastewater Treatment

Cooperative Agreement No: DE-FE0030822

BP2 Annual Review
September 26, 2019



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Helios-NRG, LLC

Basic Project Information for DE-FE0030822

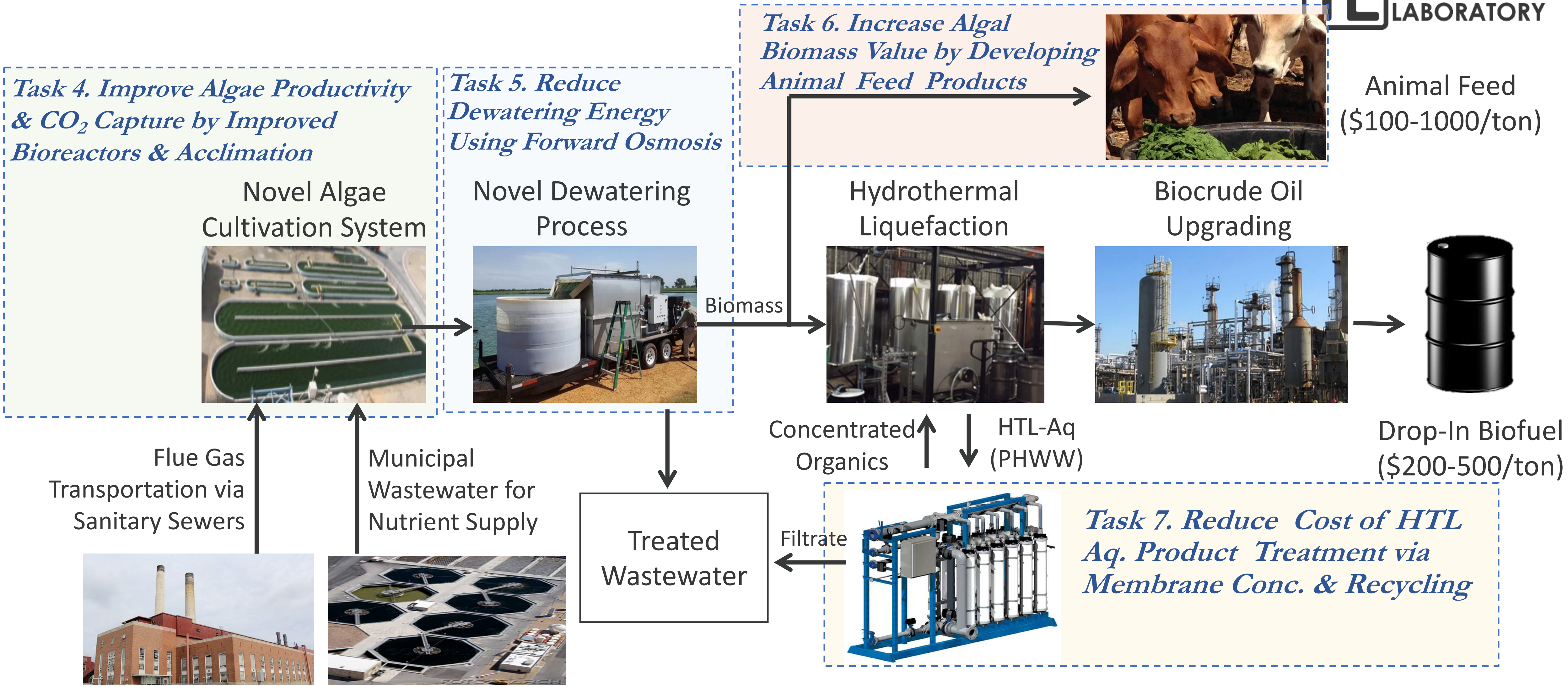
- Title: ***Improving the Economic Viability of Biological Utilization of Coal Power Plant CO_2 by Improved Algae Productivity & Integration w/ Wastewater Treatment***
  - DOE Program Manager: Andy Aurelio
  - Lead Organization: University of Illinois- Illinois Sustainable Technology Center
    - PI: Lance Schideman, Josh McCann
  - 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^2day biomass productivity (vs 8.5 g/m^2 day DOE Baseline- 2015 State of Technology)
    - >70% CO_2 capture efficiency (during lighted hours)
    - $470/ton algal biomass projected n^{th} plant (vs $1,641/ton current DOE Baseline)

Project Tasks

- *Task 1- Project Management*
- *Task 2- Demonstrate Stable Algae Cultivation w/ Simulated Flue Gas*
- *Task 3- Demonstrate Stable Algae Cultivation w/ Wastewater Nutrients*
- *Task 4- Optimize CO_2 Capture Efficiency in the Algae Cultivation Process*
- *Task 5- Evaluate Novel Algae Dewatering Processes (forward osmosis)*
- *Task 6- Characterize algal biomass for HTL and animal feed applications*
- *Task 7- Demonstrate ability to concentrate & recycle HTL aqueous phase*
- *Task 8- Evaluate the potential of sewer network flue gas distribution*
- *Tasks 9- Techno-Economic Analysis*
- *Tasks 10- Life-Cycle Analysis*

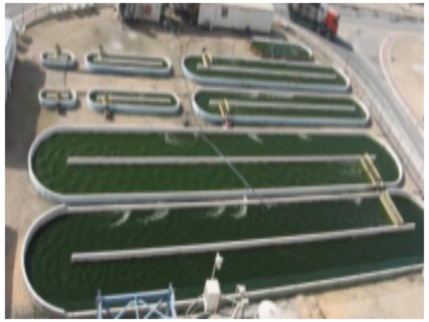
BP2

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

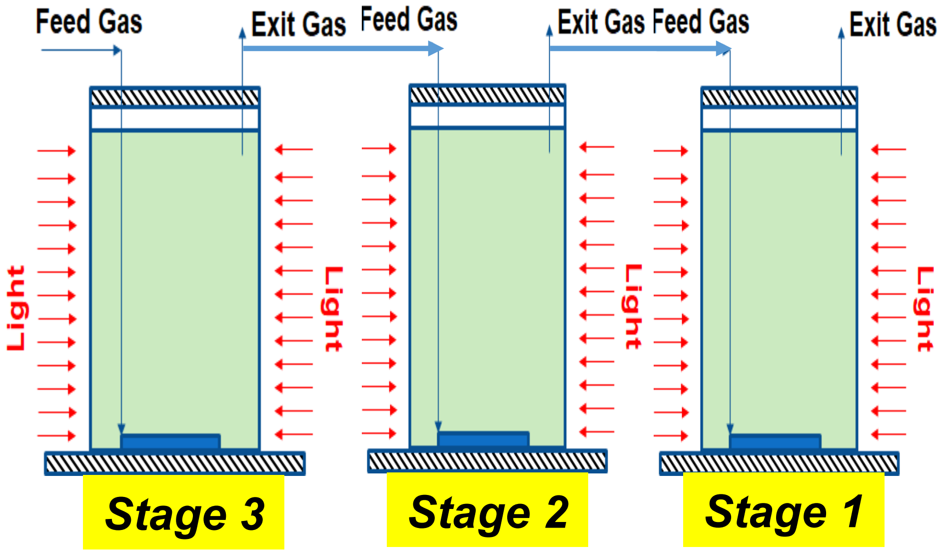
$ 480 - $1,040 /DT

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

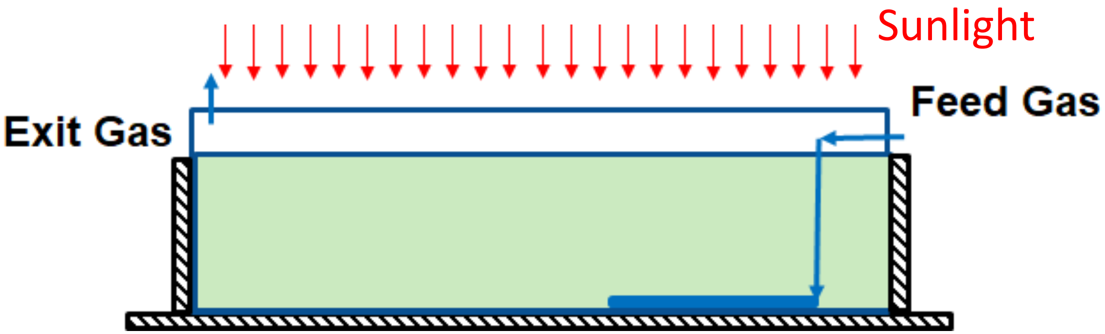
Task 4- BP2 Algae Testing Plan Overview

- 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

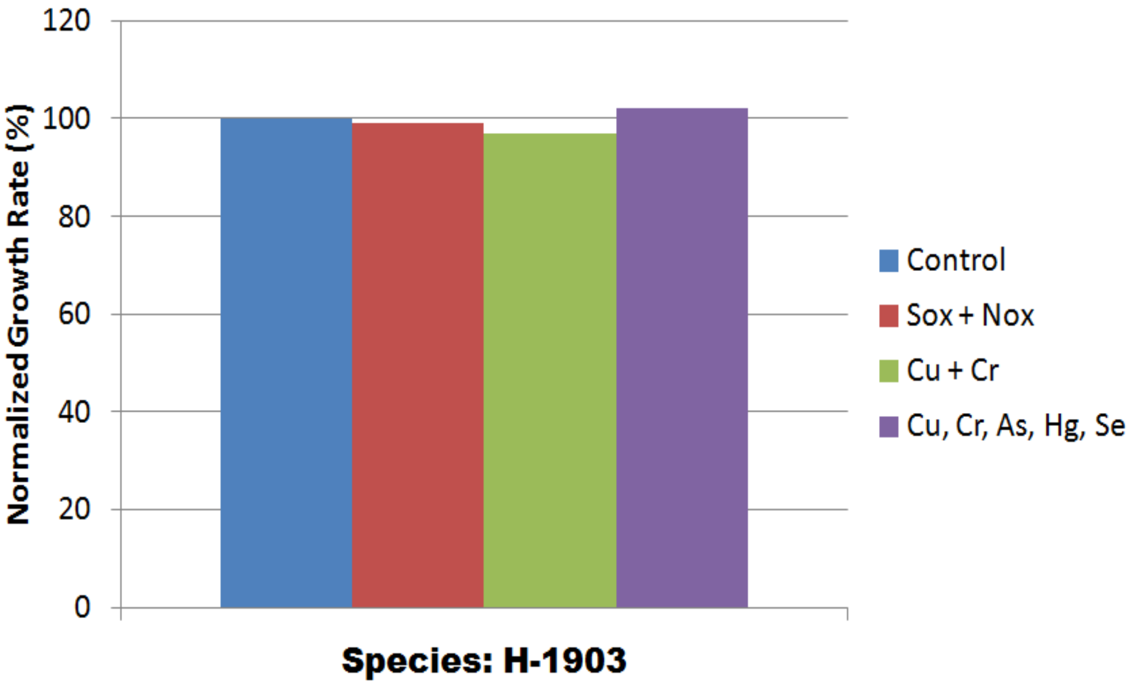
Lab Side-Lit & Multi-Stage Continuous System

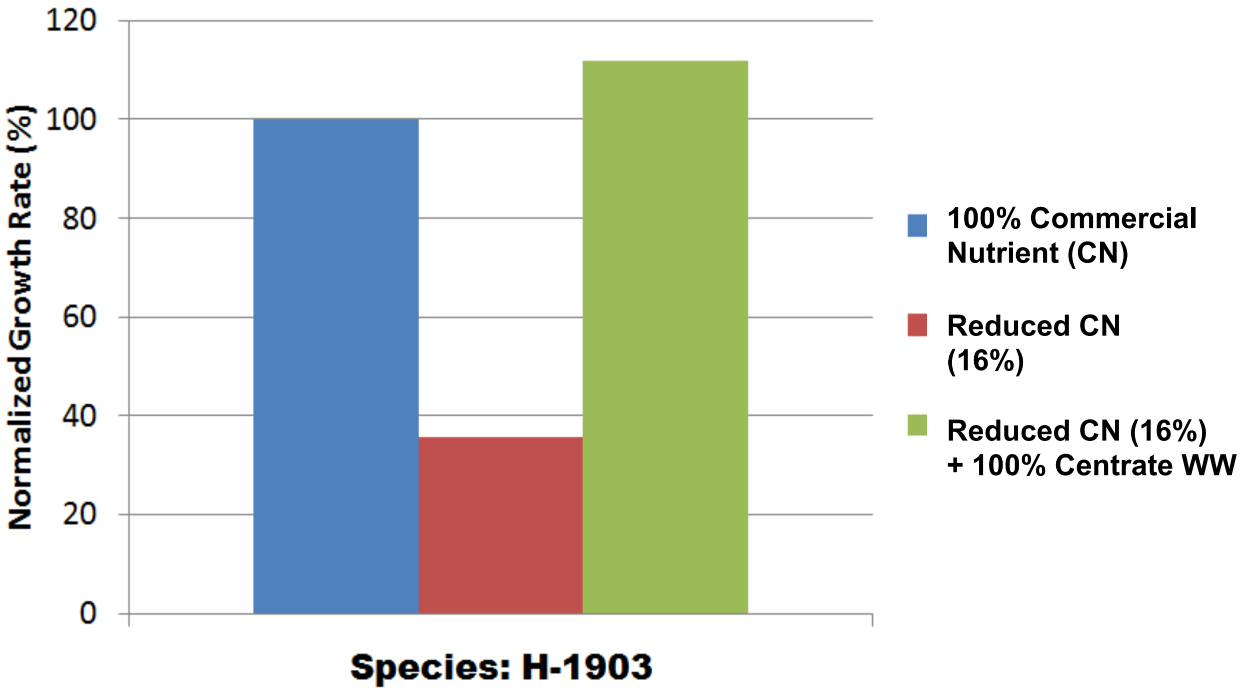


Greenhouse Top-Lit (Sun) System



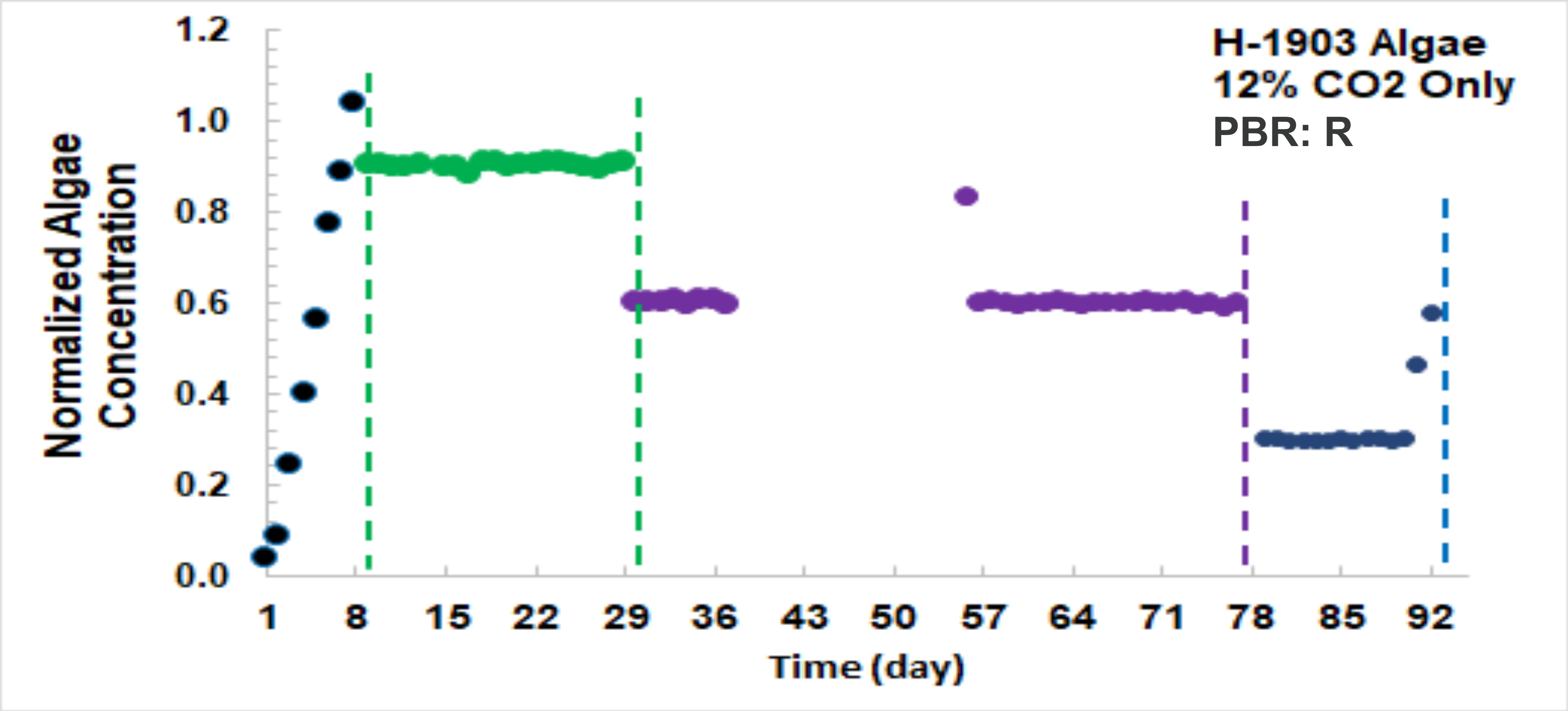
Lab- Algae cultivation w/ simulated flue gas & WW nutrients





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

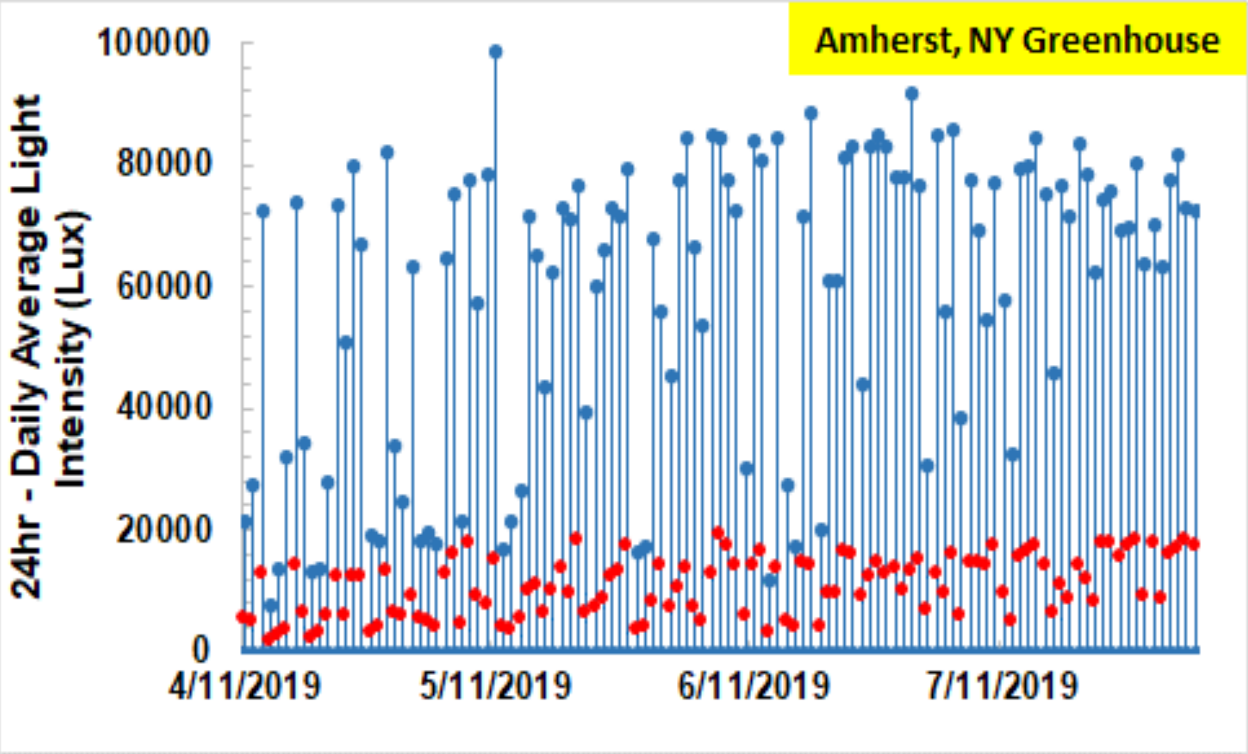
Transition from batch to continuous liquid transfer in the Lab

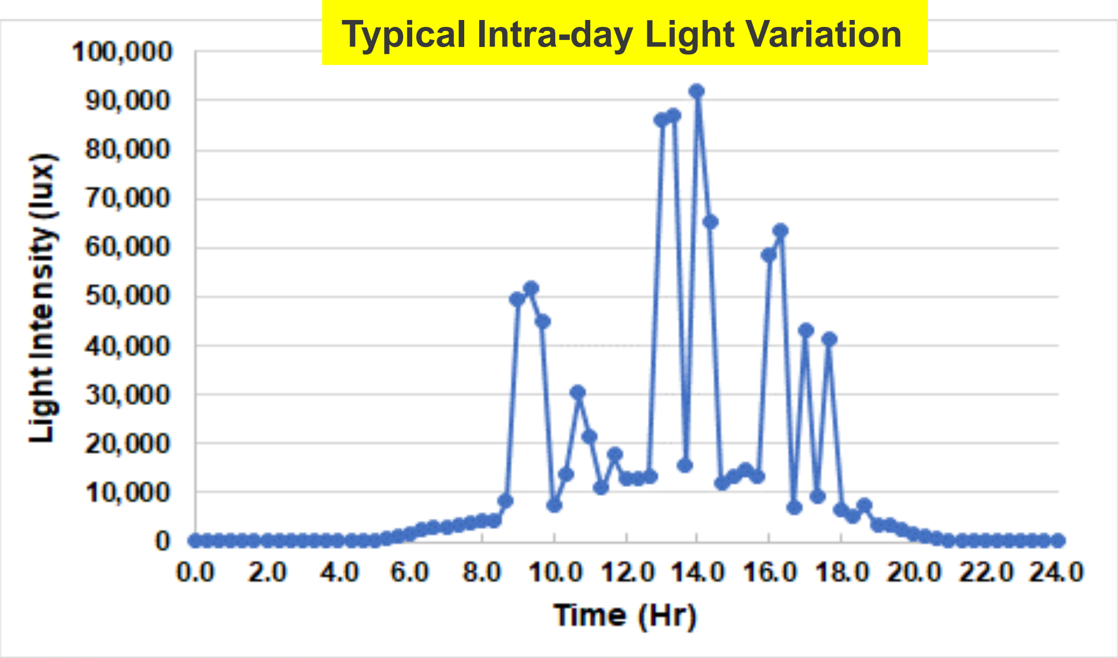


Batch Growth | Stage 3 | Stage 2 | Stage 1

Stability of MSC stage algae concentration with liquid transfer demonstrated

Greenhouse Operations in Natural Sunlight





- Substantial inter & intra-day variation
- Improving sunlight from spring to summer
- ~2x light loss from outside to GH

Month	Month Average Light Intensity (Lux)	
	Internal GH	External GH
Apr-19	6893	
May-19	9423	
Jun-19	11306	
Jul-19	12877	23243

Optimizing Long-term Greenhouse Operations

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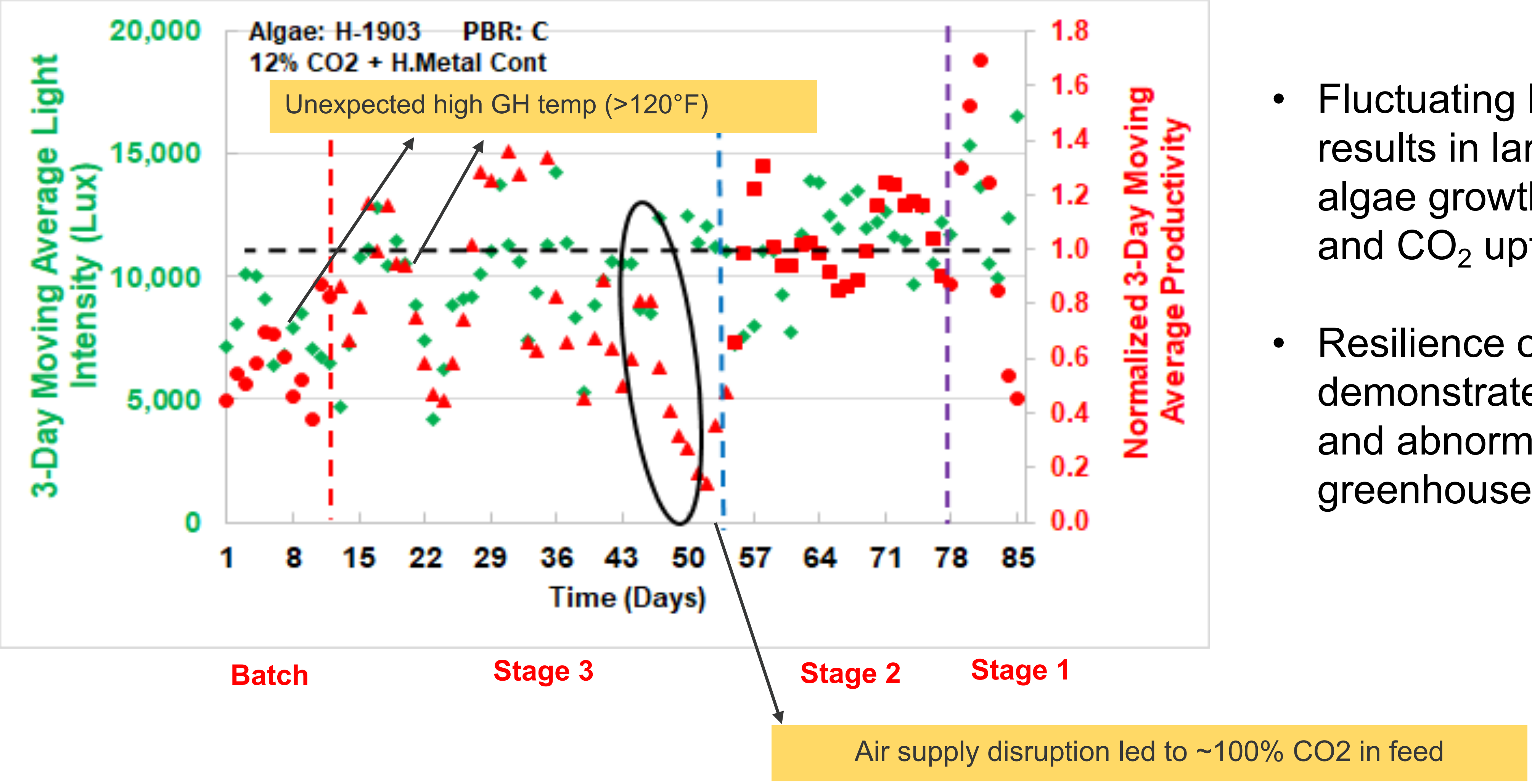
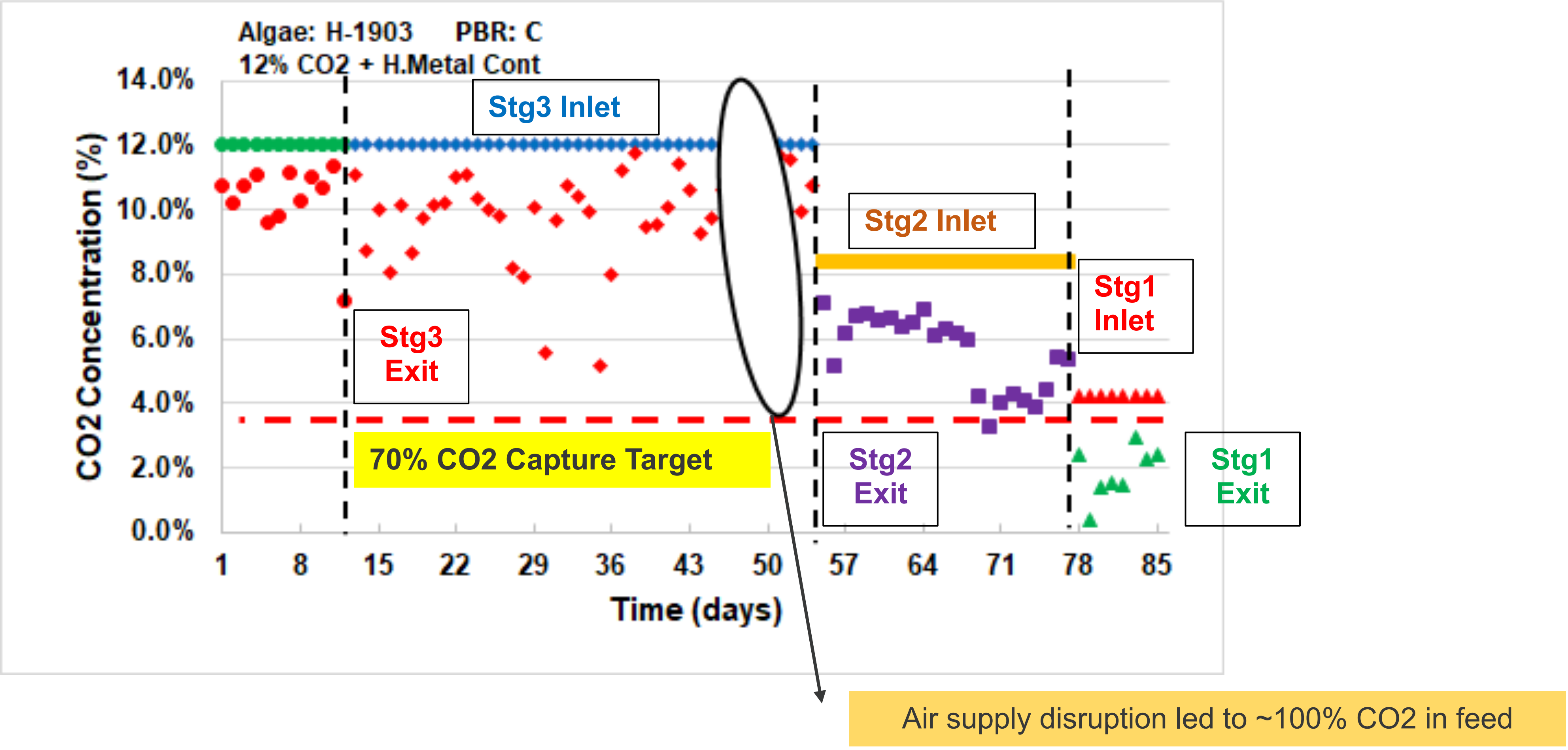


- Fluctuating light intensity results in large variations in algae growth (productivity) and CO_2 uptake
- Resilience of system demonstrated despite natural and abnormal fluctuations in greenhouse conditions

CO_2 Capture in Greenhouse Operations



Fluctuating light intensity results in varying exit CO_2 concentration in the respective stages

Demonstration of CO2 Capture and Productivity Goals

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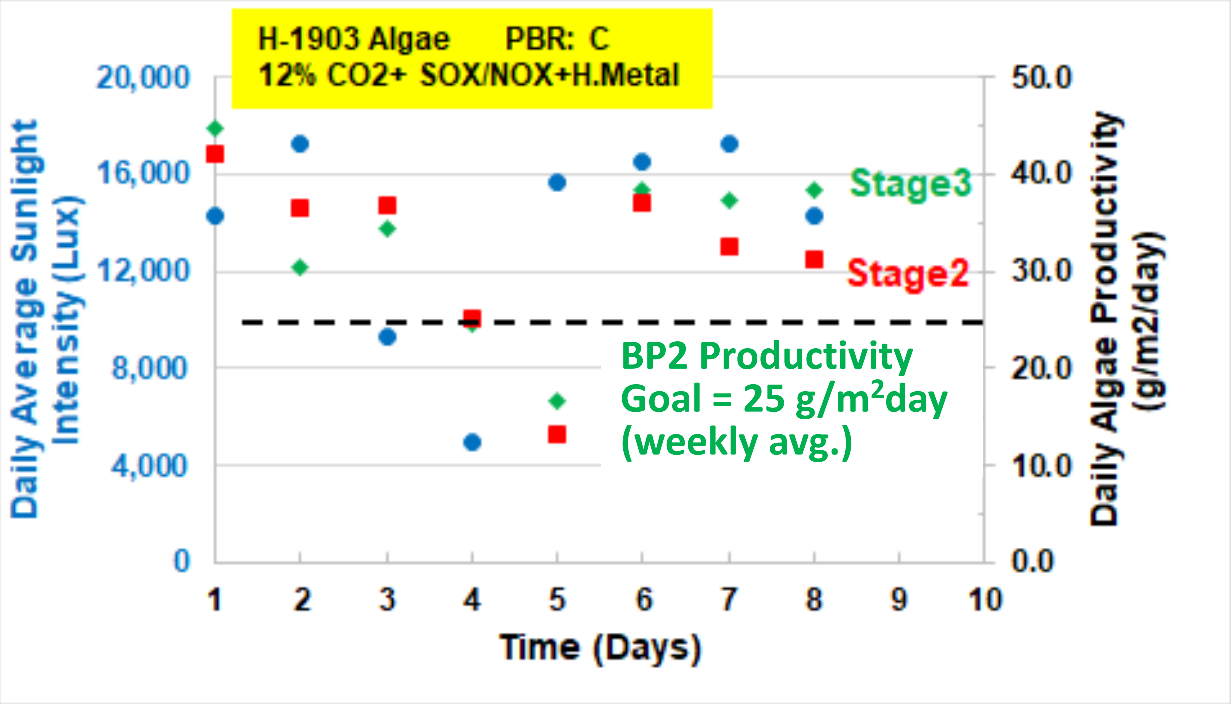
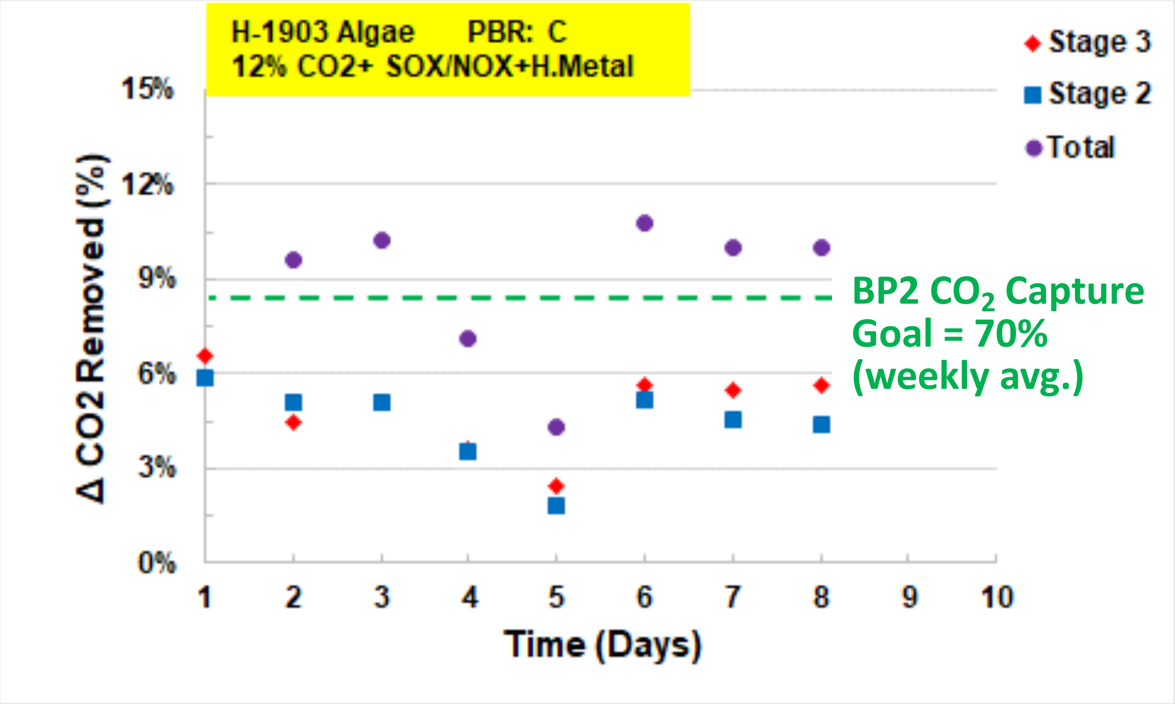
Greenhouse Operation





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

Demonstration of BP2 Milestones for Algae Bioreactors

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Simulated MSC process performance using single-stage experimental results

Test Series	Light		Feed Gas		# of Stages	Overall Performance	
	Source	Intensity Avg (Lux)	CO2	Post FGD Cont		Max Weekly Avg Prod (g/m2/day)	Total CO2 Cap Eff (%)
1	Artificial	~9,000	12.0%	N/A	3	14.1	54%
2	Artificial	~9,000	12.0%	N/A	3	19.9	80%
3	Sunlight	~11,000	12.0%	SOX/NOX + HM	3	21.2	73%
4	Sunlight	~14,500	12.0%	SOX/NOX + HM	2	30.8	74%

Performance was dependent lighting intensity and reactor operating conditions

Summary of BP2 Work

- Transitioned tests to natural sunlight in greenhouse
- Demonstrated long term stability
- Assessed impact of gas and liquid flows on MSC performance
- Refined MSC process via successive single stage PBR tests
- Exceeded BP2 goal with just 2 stage MSC
- Investigating use of waste water (Centrate & HTL recycle) in CO2 capture tests

Task 4- Algae Cultivation Workplan Overview (Helios)

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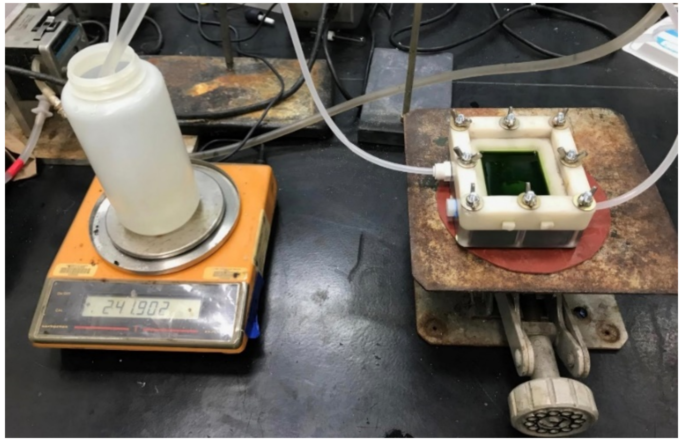
- Validate in Top-lit PBR's
- Transition from batch to liquid transfer operation
- Transition tests from artificial light to sunlight
- Quantify sunlight intensity variations and impact on performance
- Study impact of gas/liquid flow rates on capture efficiency and productivity
- Demonstrate long term stability & performance in GH operation
- Conduct GH tests with acid gases & 5 HM contaminants
- Demonstrate average productivity and capture efficiency targets

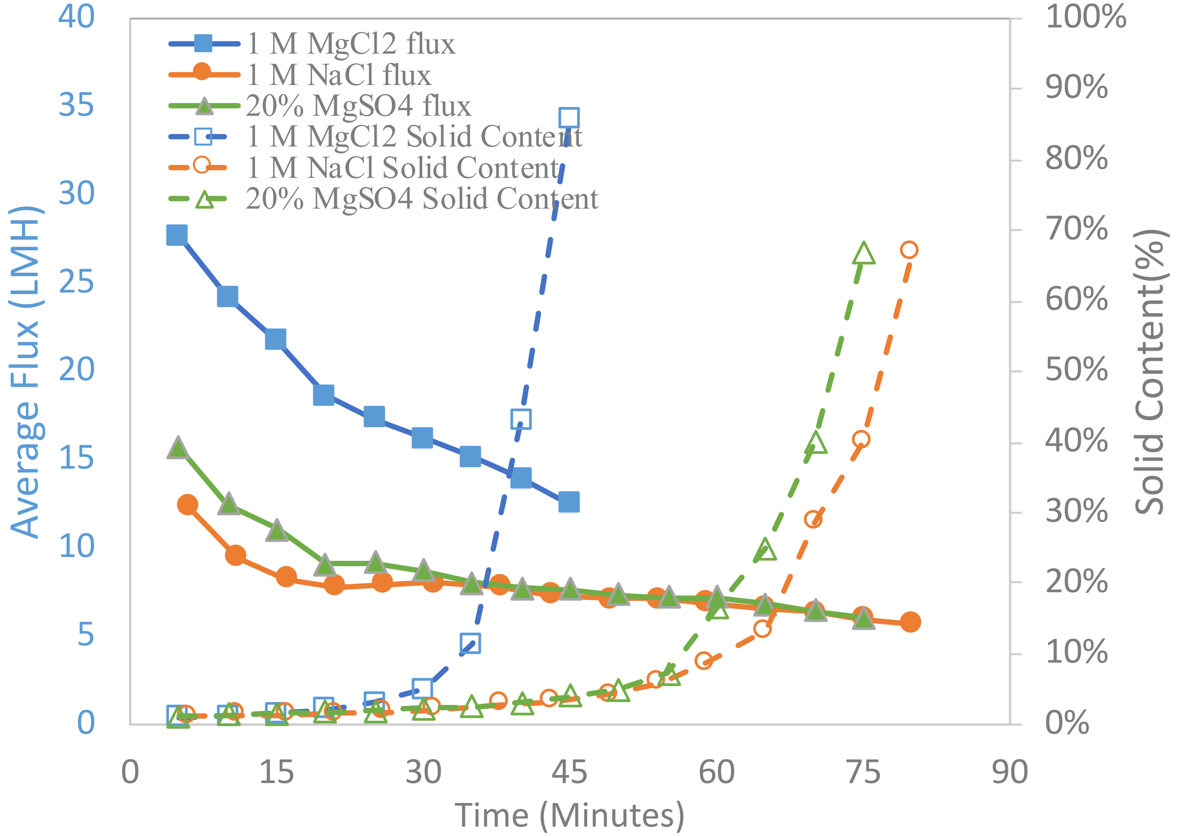
Task 5. Evaluate novel forward osmosis algae dewatering process

Forward osmosis open cell experiments with different draw solutions



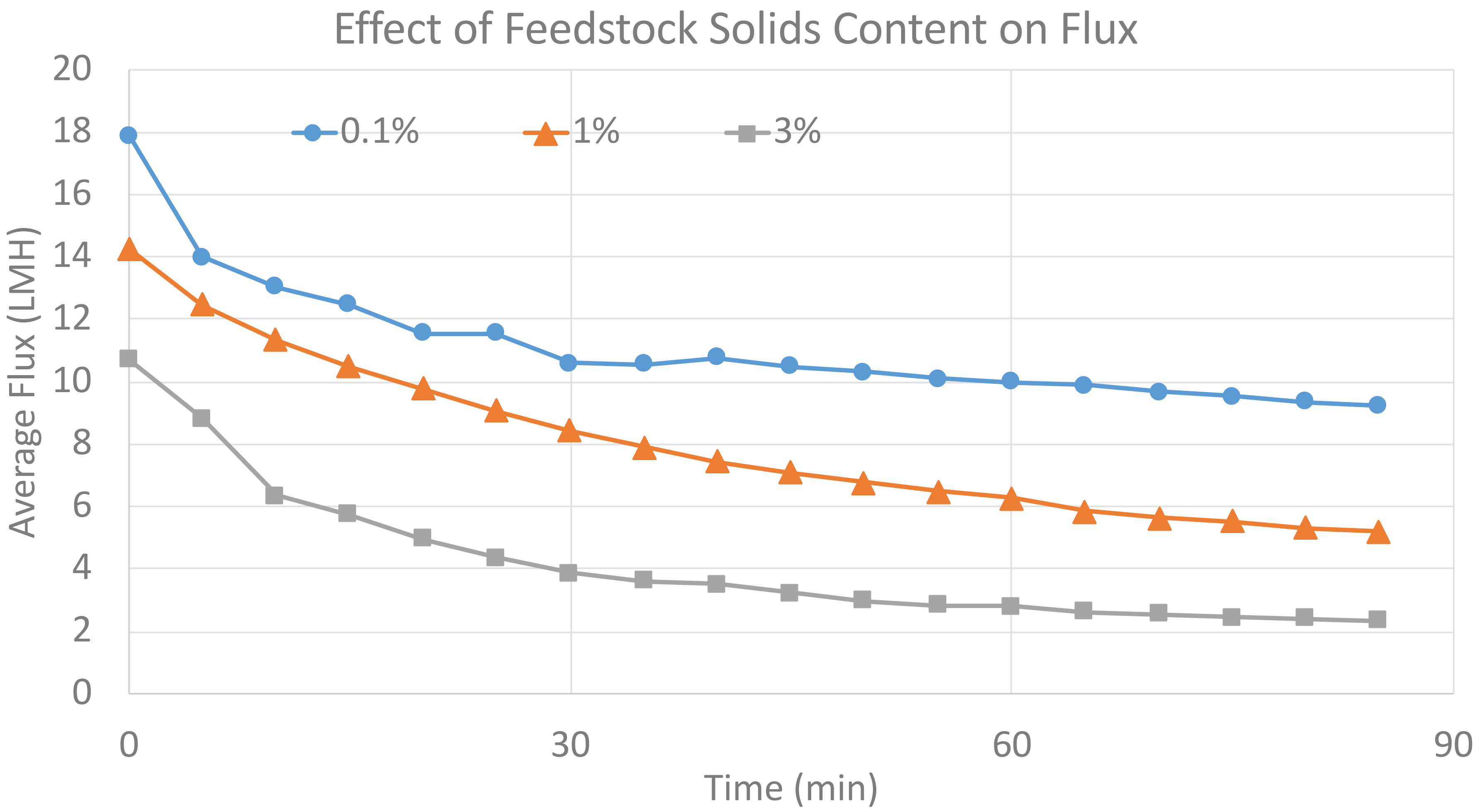
Open Cell FO System

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

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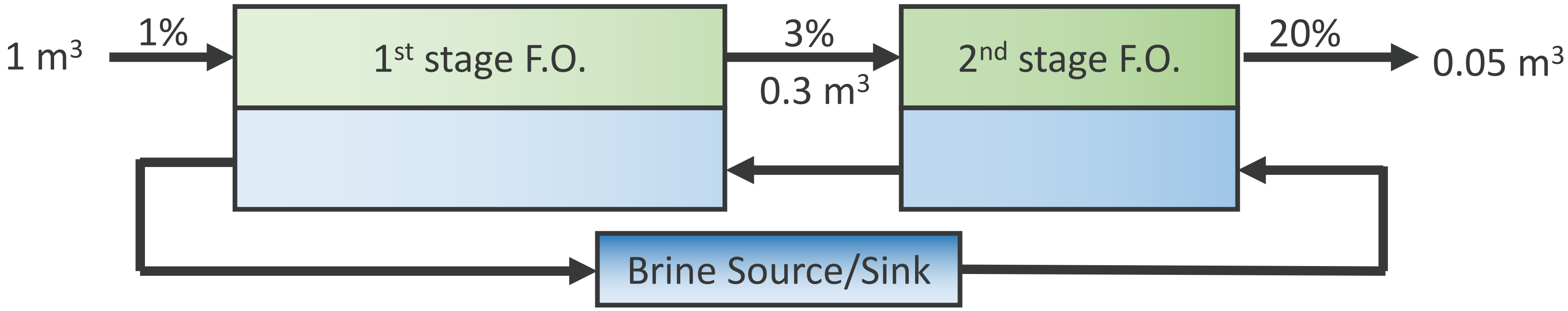

	Starting Solid (%)	Ending Solid (%)	Energy consumption (kWh/m3)
Settling Pond	0.1	1	-
Membrane	1	13	0.04
Centrifuge	13	20	1.35
Forward Osmosis 1st Stage	1	3	0.26
Forward Osmosis 2nd Stage	3	20	0.57

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

Task 5 Summary: Evaluate novel forward osmosis algae dewatering process

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- Forward Osmosis can effectively dewater algal biomass above 20% solid content with different draw solutions
- The energy consumption of forward osmosis is significantly lower than centrifuge

Budget Period	Task #	Mile-stone #	Milestone Description	Planned Completion Date	Actual Completion Date		Comments
2	5	T5.1	Dewater algal biomass >15% solid content through forward osmosis using <1.35 kwh/m^3	9/30/2019	9/1/2019		>20 % solids content achieved with minimum energy inputs – 0.26 kW/m^3

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

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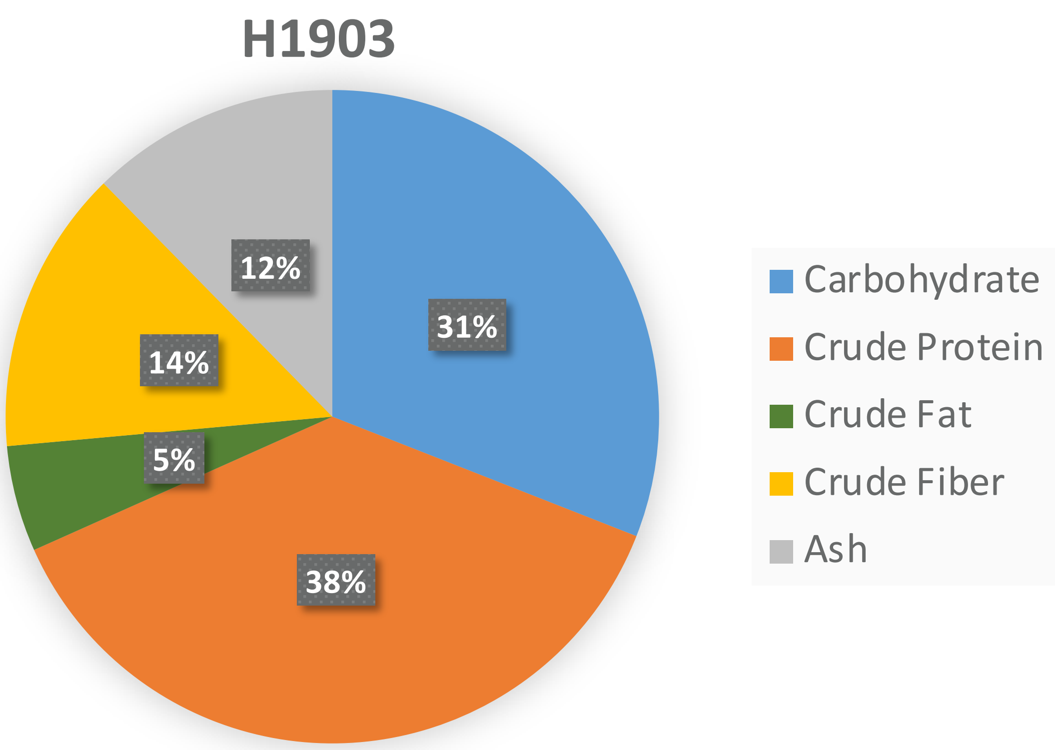
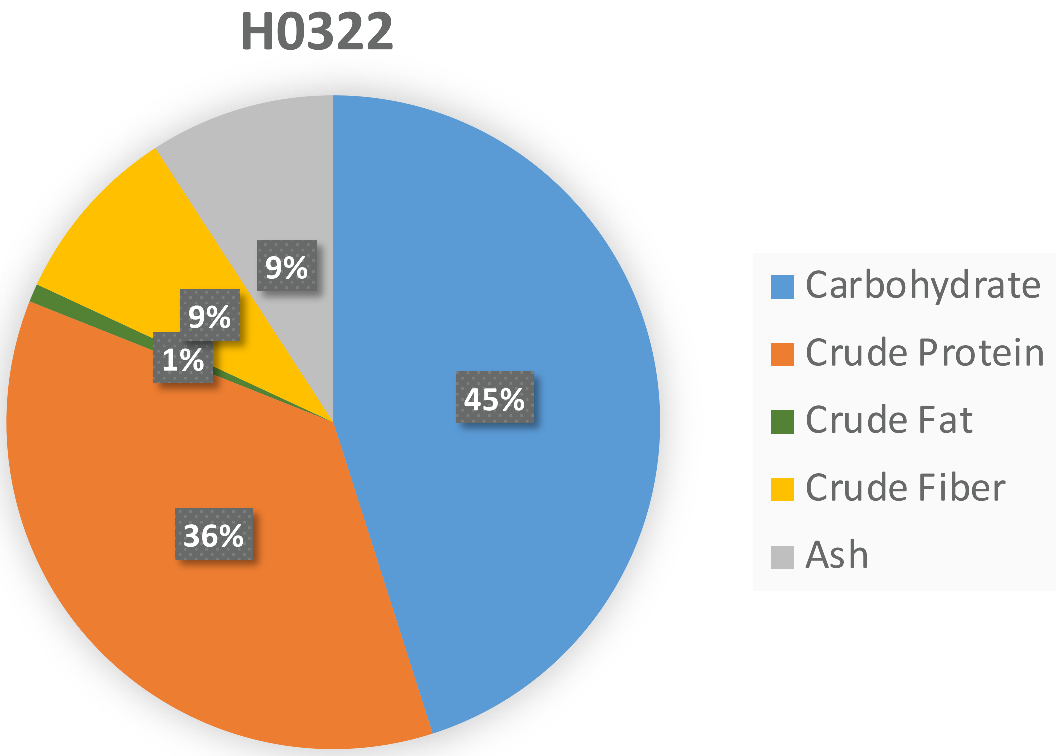
Proximate analysis of flue gas fed algal biomass





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

Heavy metals in algae grown w/ flue gas contaminants

Compare with animal feed maximum tolerable level (MTL)

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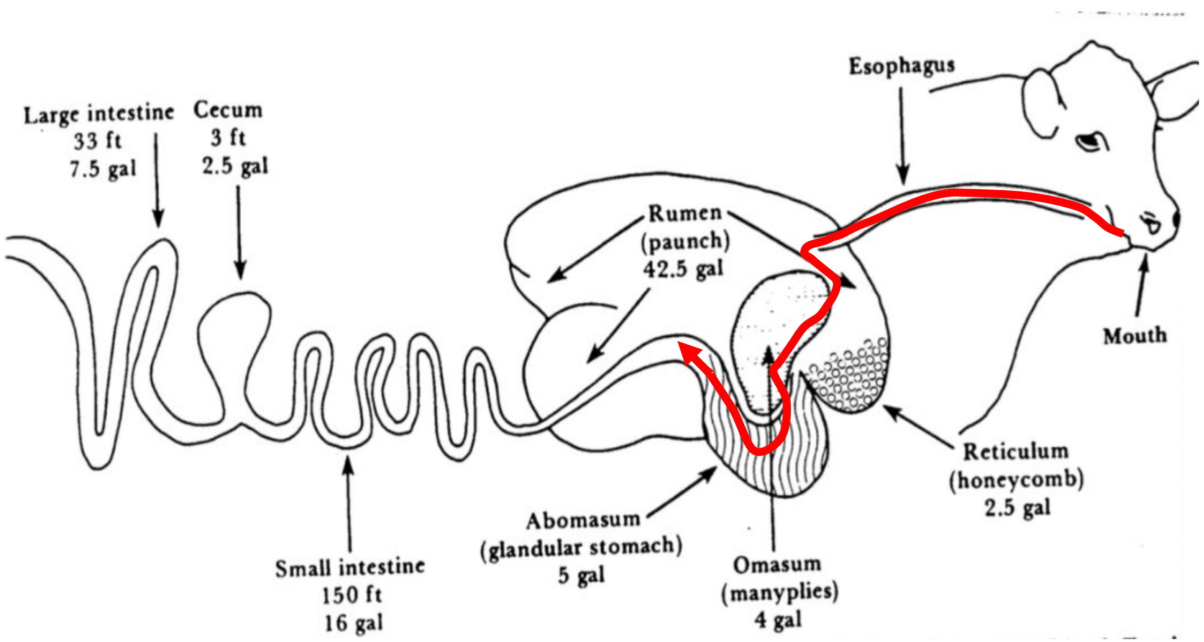
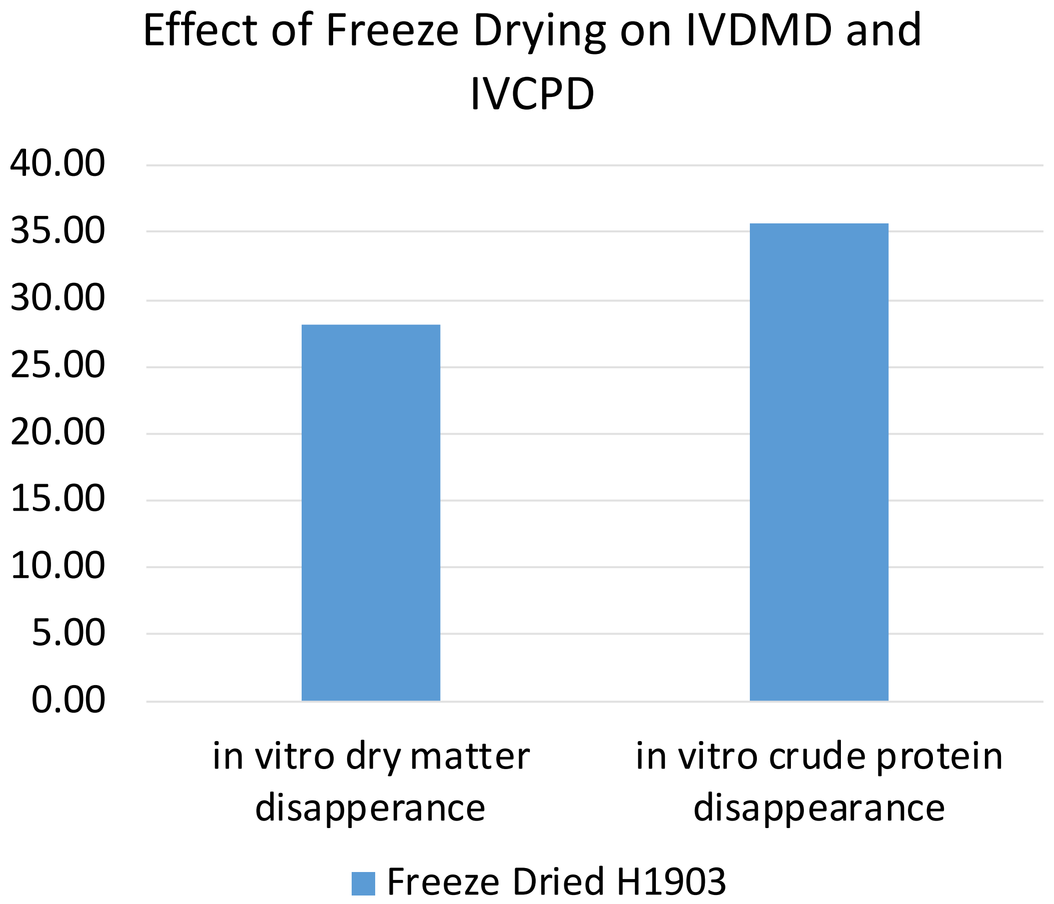
Minerals	H-1903 Cu, Cr, As, Hg, Se (ppm)	Poultry Feed MTL (ppm)	Swine Feed MTL (ppm)	Cattle Feed MTL (ppm)	Fish Feed MTL (ppm)
As	2.18	30	30	50	5
Cd	<1	10	10	0.5	10
Cr	1.16	100	100	100	3,000* as CrO
Co	<2	25	100	25	
Cu	46.6	250	250	100	100
Hg	0.5	1	2	2	1
Pb	<5	10	10	30	10
Ni	<5	250	250	50	50
Se	0.54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

Task 6- Feedstuff Assessment

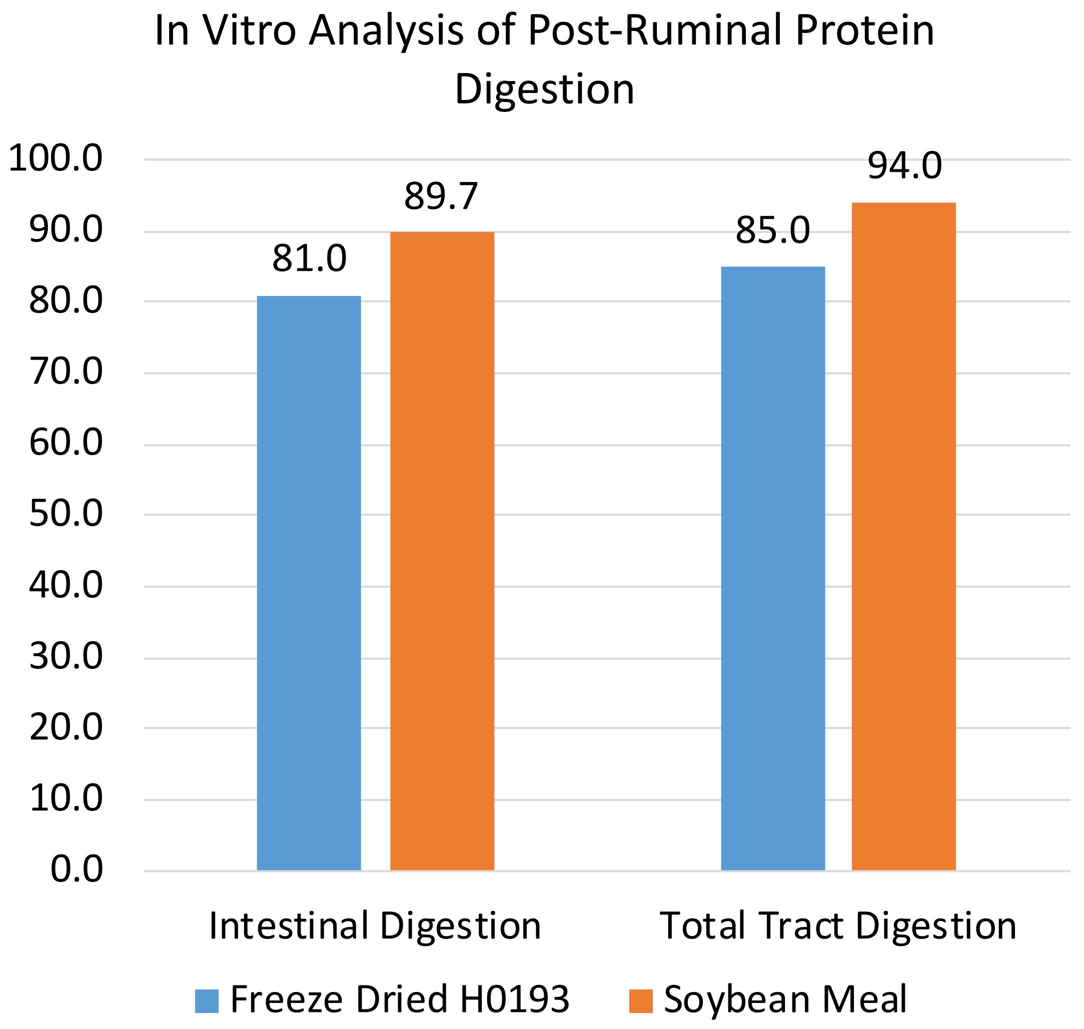
- **Algae is a High Protein Feedstuff (44% Protein)**
- **Most Algal Protein is "Bypass Protein"**
  - Rumen fluid from cannulated steer
  - Incubate samples for 24 hours





Task 6- Feedstuff Assessment

- **In vitro evaluation of post-ruminal digestion**
  1. Ruminal digestion
  2. Post-ruminal digestion (enzymatic)
     - Add HCl + Pepsin
     - Neutralize with NaOH
     - Add pancreatin enzyme mix (24 hr)
- **Results**
  - Algae post-ruminal protein digestion was very high > 80%
  - Algal protein availability is about 90% of soybean meal
  - Feeding value in ruminant diets will be determined by specific amino acid intestinal availability



Algae Feedstuff Pricing as a Protein Source

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- Ruminant Market
  - Based on crude protein content in beef and bypass protein quality in dairy
- Non-ruminant Market
  - Based on ability to meet amino acid (AA) deficiencies in the diet
  - H-1903 has less desirable AA composition than soybean meal
  - H-1903 has more desirable AA composition than DDG

Current value estimate for H-1903 as a protein source:

75-80 % of SBM = $260-280/ton

130-140% of DDG $195-210/ton

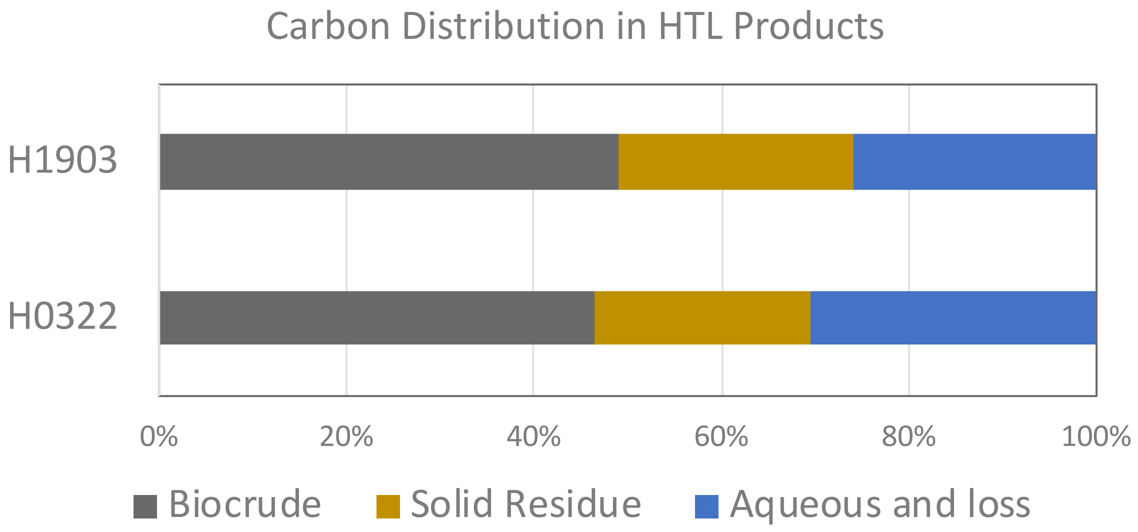
*will change with AA composition and value of PUFA

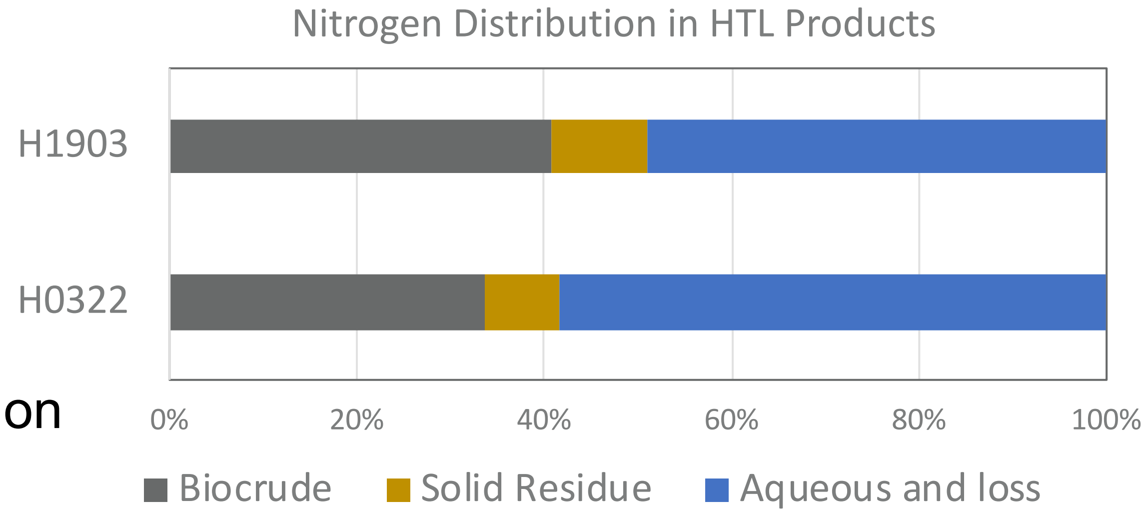
Amino Acids % DM	Crude Protein	Lysine	Threonine	Methionine	Tryptophan	Cysteine
Algae H-1903	37	1.52	1.40	0.69	0.18	0.47
Soybean Meal	48	3.00	1.86	0.67	0.68	0.71
Distillers Grain	28	0.84	1.00	0.55	0.21	0.50
Algae as % of SBM	77	51	75	102	26	66
Algae as % of DDG	132	180	140	125	86	94

Most limiting amino acids in livestock diets

Biomass elemental analysis and HTL Performance

	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 6 Summary: *Characterize algal biomass for HTL & animal feed*

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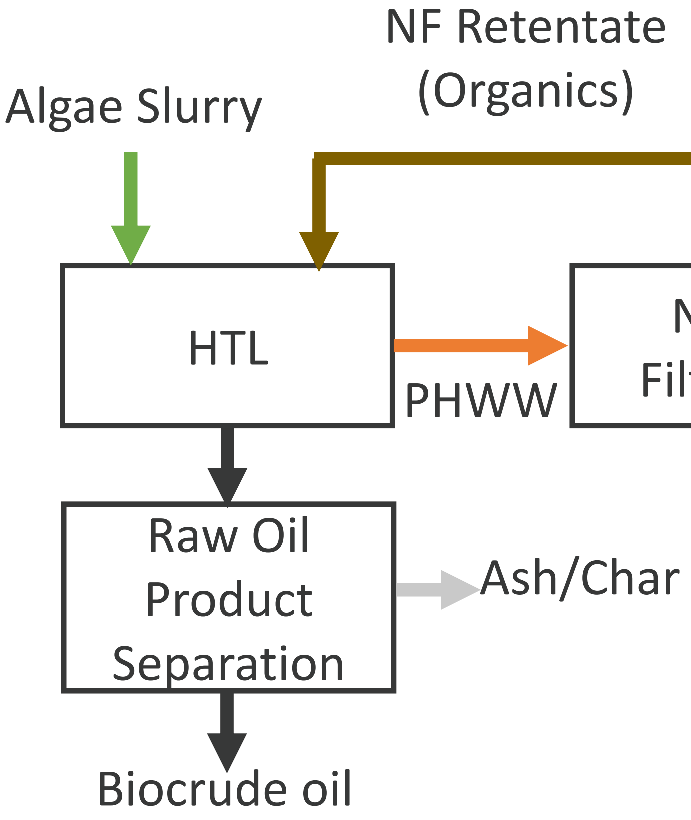
- The biomass composition analysis and in-vitro digestibility test showed simulated flue gas grown algal biomass is a suitable animal feed
- Concentrations of heavy metals in the flue gas grown algae are within animal feed maximum tolerable levels. Blending with other ingredients can be used to lower borderline values.
- H1903 species has higher HTL crude oil yield than H0322

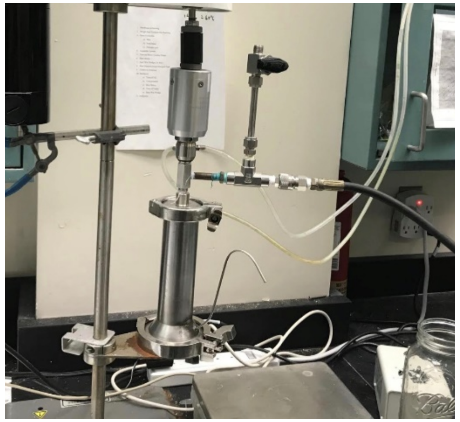
Budget Period	Task #	Mile-stone #	Milestone Description	Planned Completion Date	Actual Completion Date		Comments
2	6	T6.1	Characterize algal species that biomass heating value > 18MJ/kg and protein content > 30%	3/31/2019	3/20/2019		Completed- H1903 and H0322 sample analyzed, protein content are 38% and 36%. heating value are 22.15 and 18.66 MJ/kg
2	6	T6.2	Demonstrate a minimum in vitro dry matter disappearance of 40% for algal strains digested in rumen fluid	9/30/2019	9/18/2019		Completed, H1903 sample had >80% dry matter disappearance

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

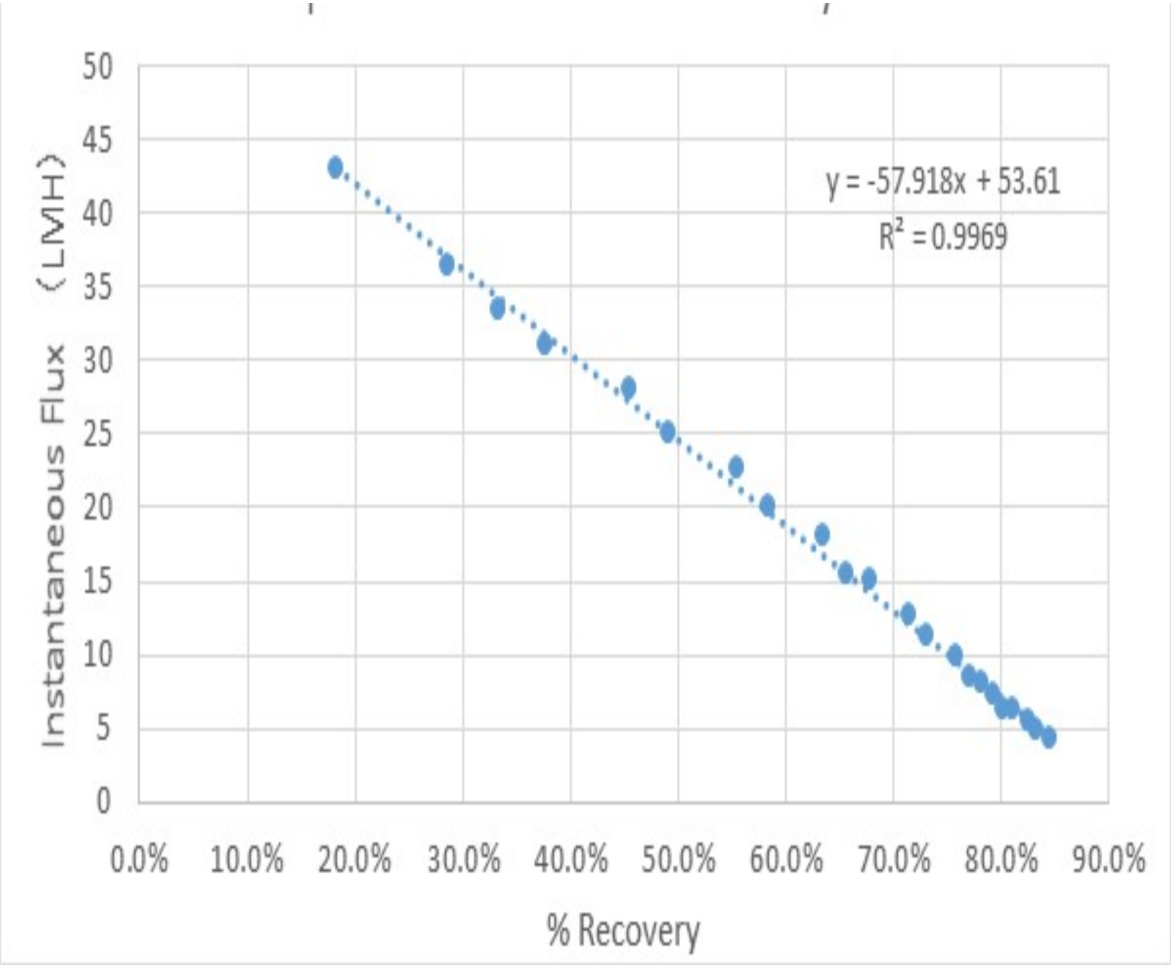
Integration of HTL with nanofiltration for carbon recycle



Nanofiltration system



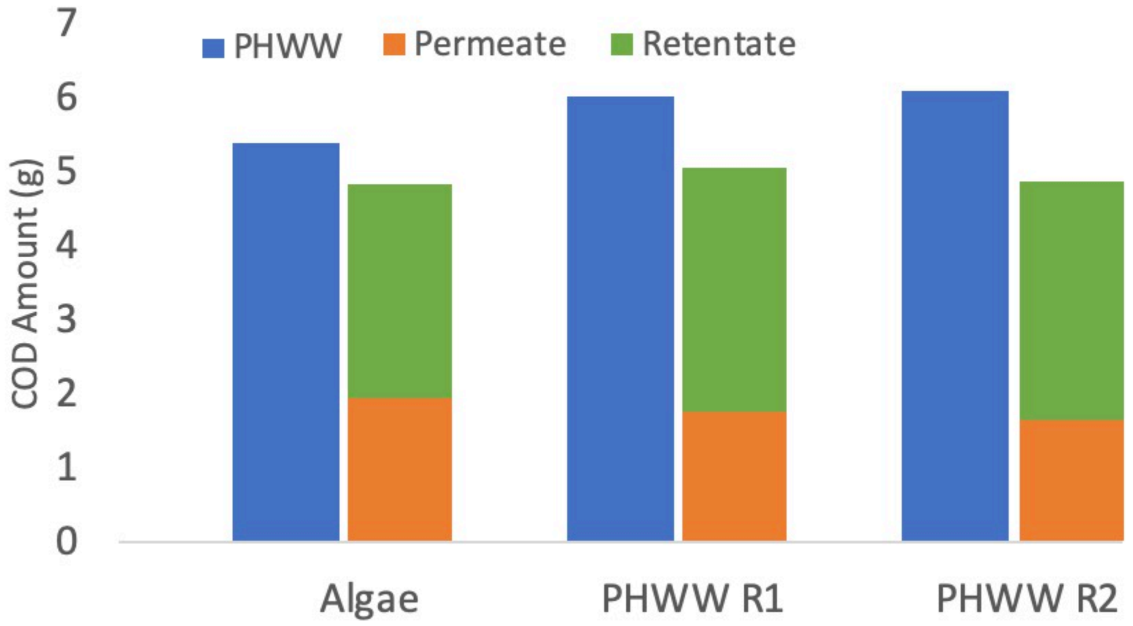
Permeate PHWW Retentate



Effect of recycling PHWW on biocrude yield & quality

	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

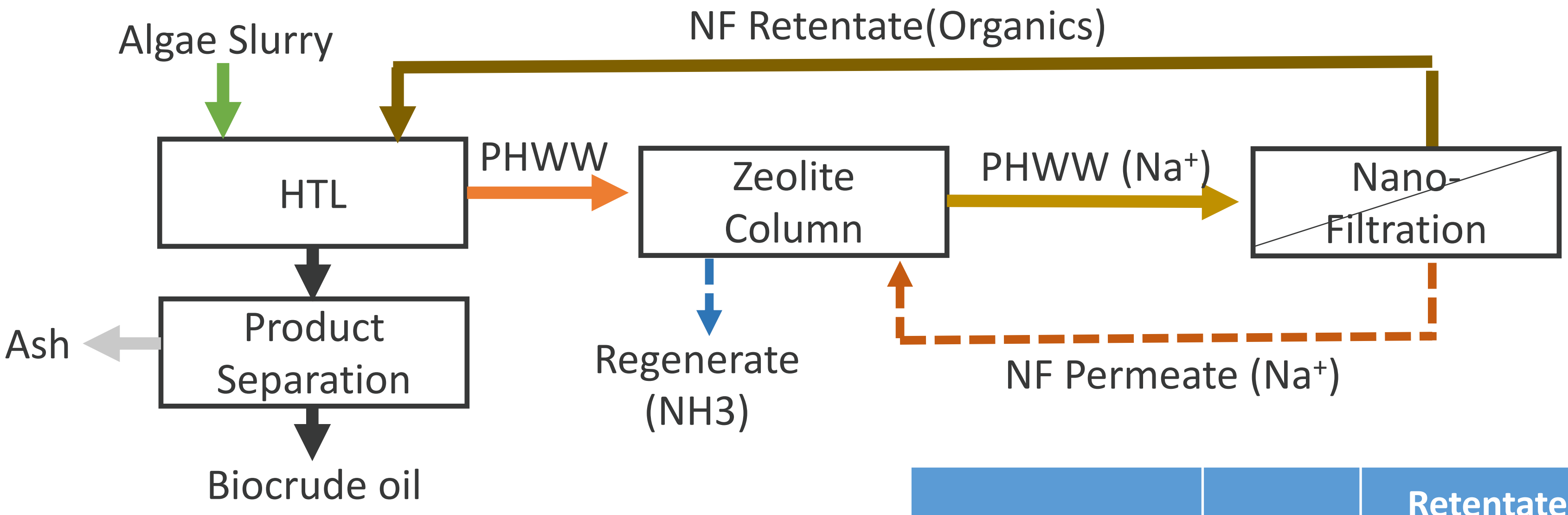
Organics Distribution (Measured as COD)



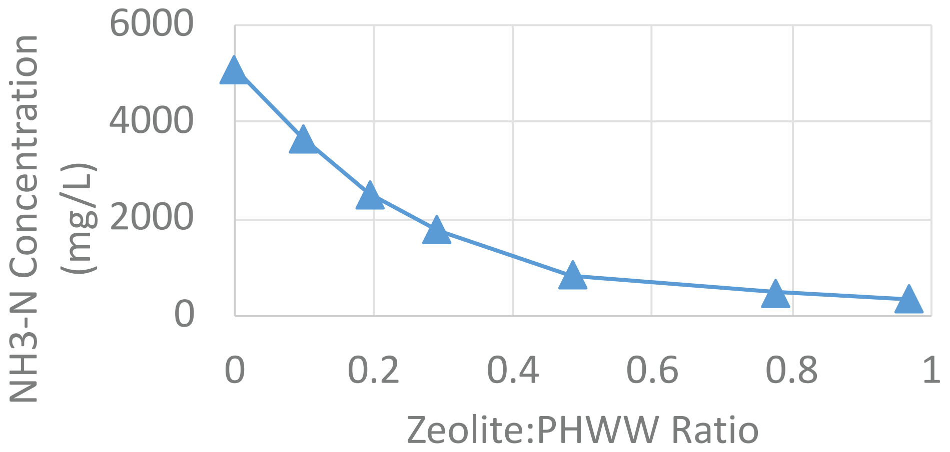
- 6% increase in biocrude yield w/ PHWW recycle
- Small N increase in the biocrude oil

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

Alternatives to reduce NH3 in recycled PHWW



- 94% ammonium removal achieved in batch zeolite test
- Zeolite treatment reduced N content of biocrude but also slightly reduced yield



	Algae	Retentate Recycle Run 1	Retentate Recycle Run 2	Zeolite Treated R1	Zeolite Treated R2
Biocrude Oil Fraction	0.349	0.368	0.371	0.350	0.356
HHV (MJ/kg oil)	33.7	36.3	35.7	36.6	35.7
N (%)	5.63	5.59	5.72	5.06	5.15

Task 7 Summary: *Demonstrate ability to concentrate & recycle HTL aqueous phase (PHWW)*

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- Successfully demonstrated nanofiltration can recover 59.1% organic in PHWW
- Recycling concentrated organics to HTL increased crude oil yield by 5.4 and 6.1 % in first and second recycle runs
- On-going work to enhance nitrogen separation from organics

Budget Period	Task #	Mile-stone #	Milestone Description	Planned Completion Date	Actual Completion Date		Comments
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%

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

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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 - $ 0.60 /gge
Nutrient Removal: $ 3.70 - $ 7.20 /gge
Fuel Selling Price: $ 2.00 - $ 3.50 /gge

TOTAL Revenue $ 5.70 - $ 11.30/gge

Project Success Criteria for Each Budget Period

Decision Point	Date	Success Criteria
G/N-1 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 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 Go/No-Go Budget Period 3	9/30/2020	Integrated Application of Project Technologies w/ Projected Cost of Algal Biomass < $470 /dry ton

Projection of remaining work in BP2

- Continuing use of wastewater (PHWW) in CO_2 capture tests
- Continuing tests of organic and nitrogen separation in PHWW with nanofiltration
- Submit Q4 progress report (Due Oct. 30, 2019)

BP3 Project Tasks

- ***Task 8- Evaluate the potential of sewer network flue gas distribution***
  - Identify sewer system modifications to accommodate flue gas transport.
  - Develop flue gas transport model for case study.
  - Measure flue gas transfer efficiency in field demonstration test
  - Estimate cost of flue gas transport via sewer network and compare with dedicated pipeline.
- ***Tasks 9- Techno-Economic Analysis***
  - Preliminary TEA Evaluation
  - Lab tests to quantify relationship between light intensity and algae productivity and outdoor experiments external to GH to achieve 35 g/m2/day productivity and 70% CO2 capture efficiency
  - Measure animal performance using algae feed
  - Refined TEA Incorporating Project Results.
- ***Tasks 10- Life-Cycle Assessment***
  - Refine and Customize LCA Model
  - LCA Hotspot Evaluation
  - Refined LCA Model Incorporating Project Results.

Questions and Comments…

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