A highly efficient microalgae-based carbon sequestration system to reduce CO_2 emission from power plant flue gas

DE-FE0031914

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Robert Mroz, HY-TEK Bio, LLC;

Troy Hawkins, Argonne National Laboratory

U.S. Department of Energy

National Energy Technology Laboratory

Aug. 28, 2023

Project Overview

– Funding

DOE: $3,000,000 and Cost Share: $750,000

– Overall Project Performance Dates:

Sep. 2020 to Sep. 2023 (NCTE to Jun. 2024)

– Project Participants:

Yantao Li, Feng Chen, Russell Hill, University of Maryland Center for Environmental Science;

Robert Mroz, HY-TEK Bio, LLC;

Troy Hawkins, Argonne National Lab

DOE NETL Program Manager: **Lei Hong** (From Jan. 2022), **Kyle Smith** (May- Dec. 2021), **Katharina Daniels** Sep. 2020 to Apr. 2021)

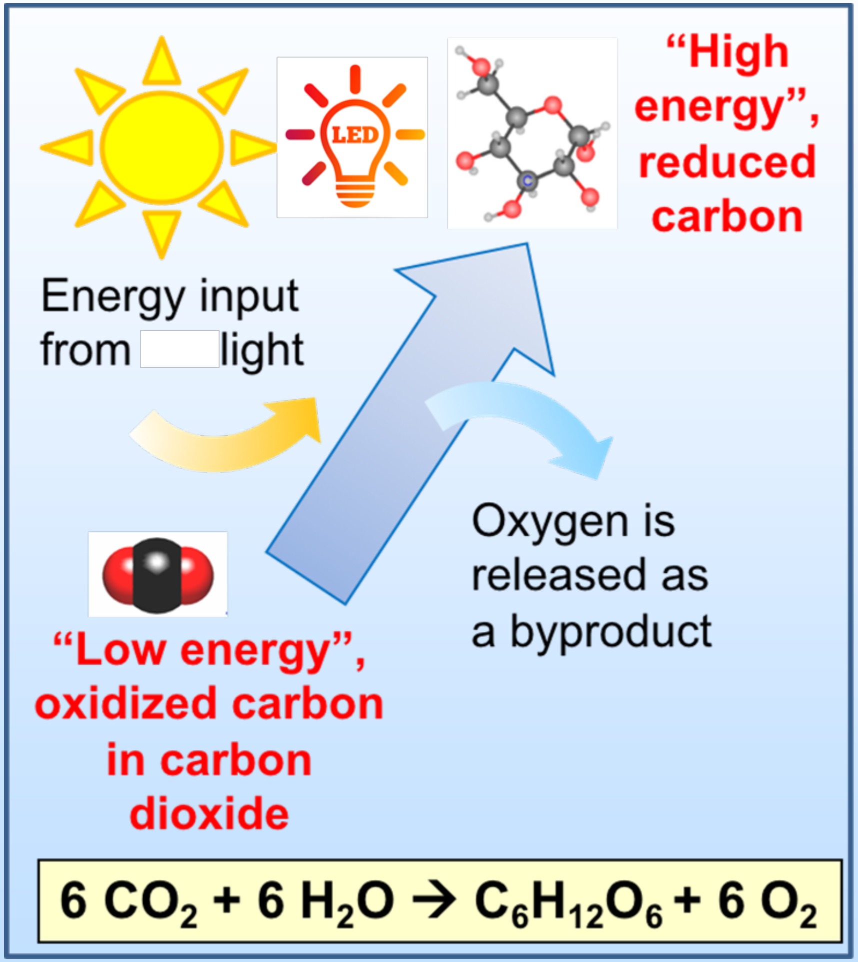
University of Maryland CENTER FOR ENVIRONMENTAL SCIENCE HY-TEK Bio Argonne NATIONAL LABORATORY

Project Overview

– Overall Project Objectives

The objective of this project is to harness the power of photosynthetic microalgae to maintain a high-pH, high-alkalinity microalgal culture to create a carbon-negative system for carbon dioxide (CO_2) conversion to value-added products from power plant flue gas.

Technology Background

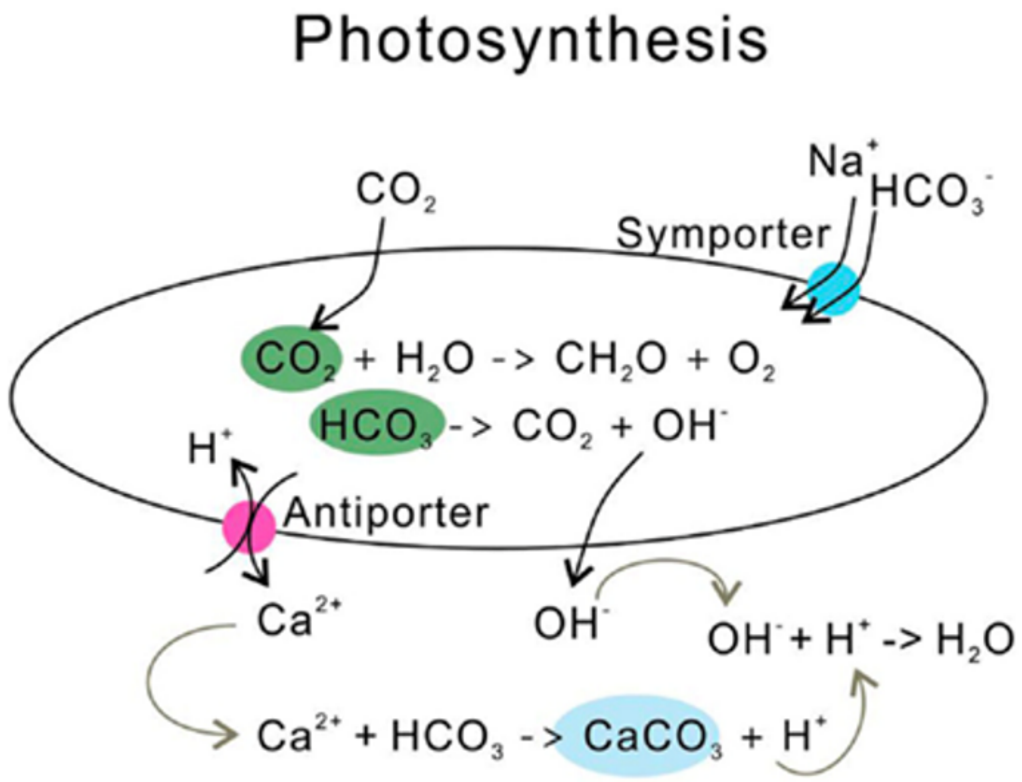


Williams, M.E. (July 31, 2016). Carbon-Fixing Reactions of Photosynthesis. The Plant Cell, doi/10.1105/tpc.116.tt0716.

100 g algal biomass produced will use 183 g CO_2.

Algal biomass for feed/biofuels.

Microalgal Carbon Capture and Biomass Production: Microalgae-driven carbonate precipitation (MadCAP)

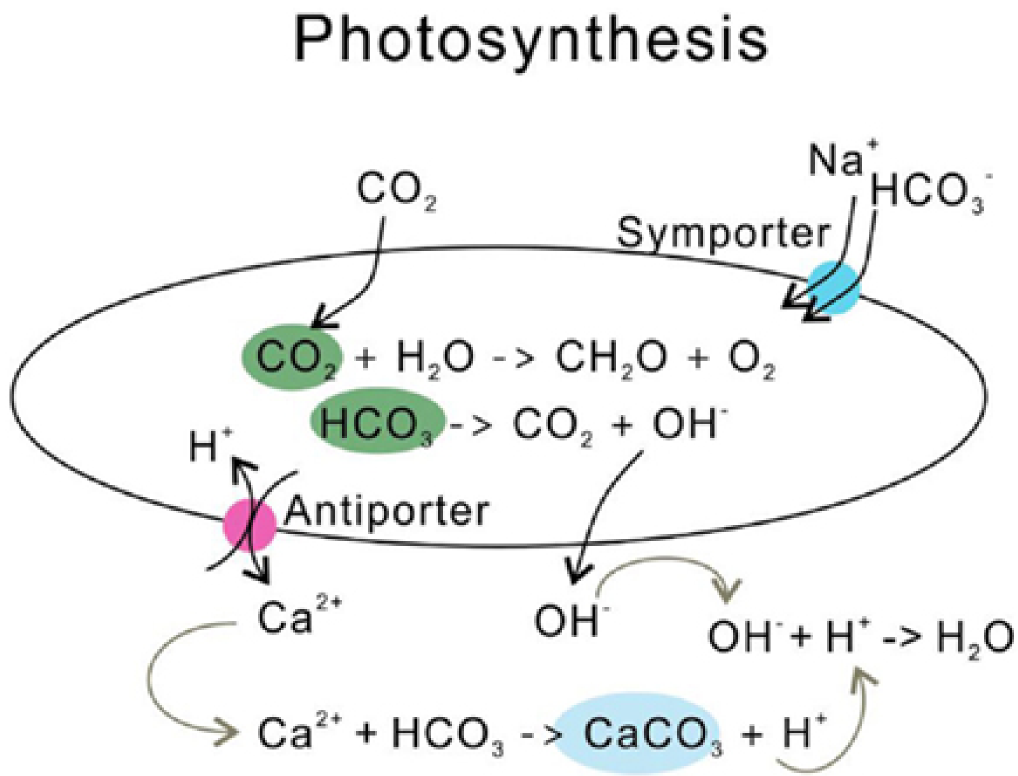


$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^- \rightleftharpoons 2H^+ + CO_3^{2-}$$

$$Ca^{2+} + CO_3^{2-} \rightleftharpoons CaCO_3$$

Adapted from Zhu and Dittrich 2016 Frontiers in Bioeng and Biotech.
Mazzone et al., 2002 MARSci.2002.01.020105; DE-FC26-00NT40934; http://thanhphatchem.com/;

Microalgal Carbon Capture and Biomass Production: Microalgae-driven carbonate precipitation (MadCAP)



$$CO_2 + H_2\,O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + \; HCO_3^- \rightleftharpoons 2H^+$$

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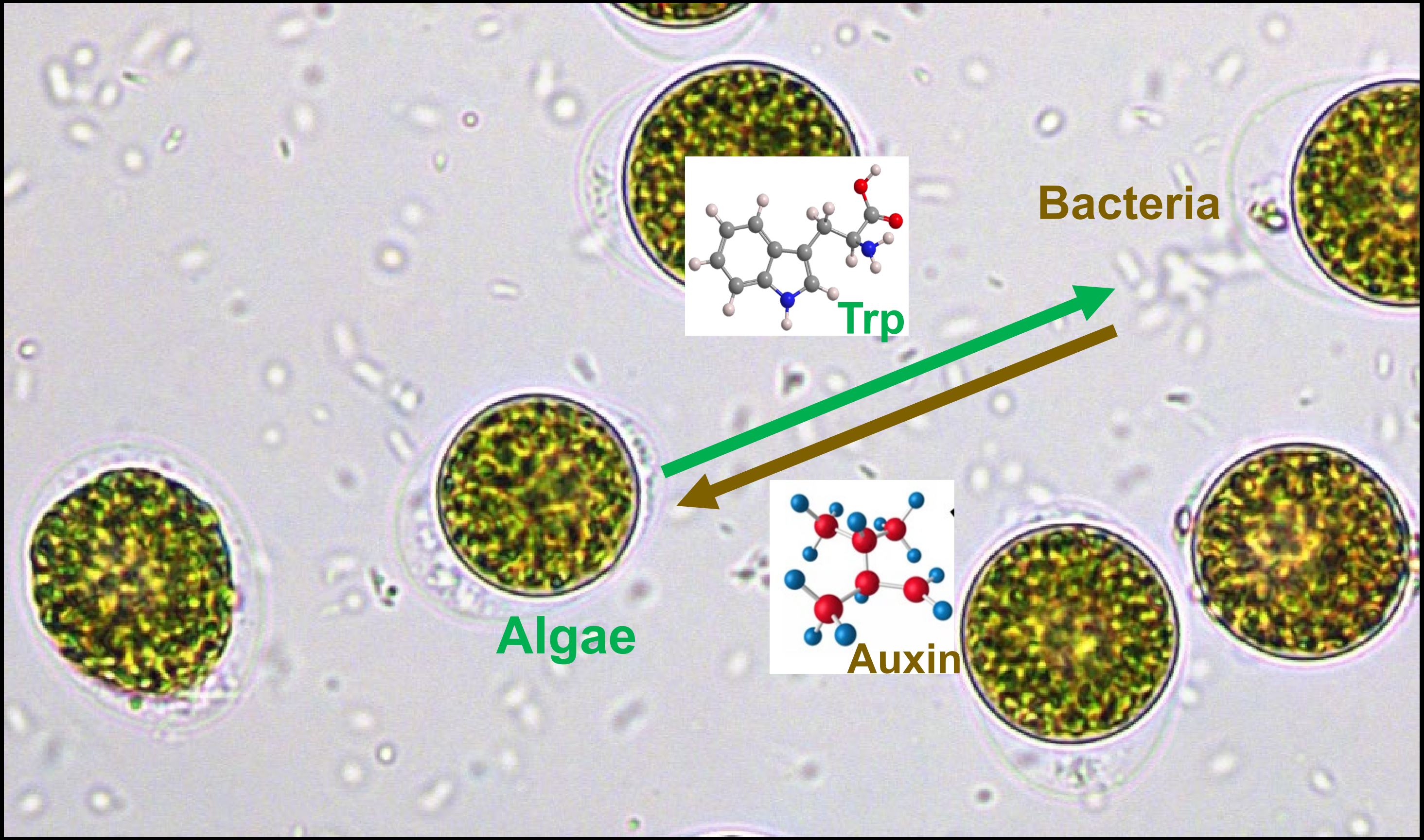
Mazzone et al., 2002 MARSci.2002.01.020105; DE-FC26-00NT40934; http://thanhphatchem.com/;

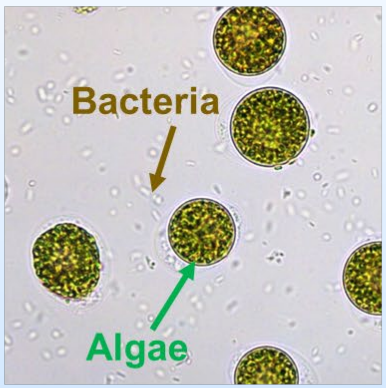
Microbial interactions in non-axenic microalgal cultures

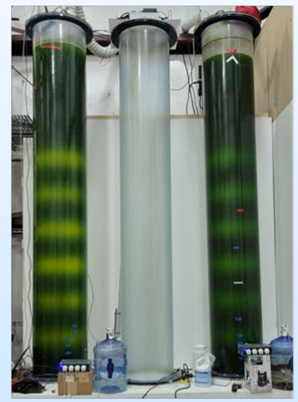


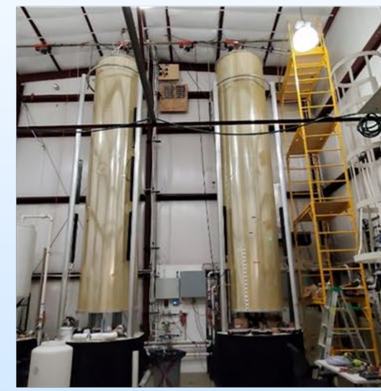
Lin, Li and Hill. Current Opinion in Biotechnology 2021, 73:300–307

Technology Background: Proposed Technology Readiness Level

Basic principle TRL 1	*Baseline* Lab scale TRL 4	Pilot scale TRL 6	*End goal* Full scale TRL 7



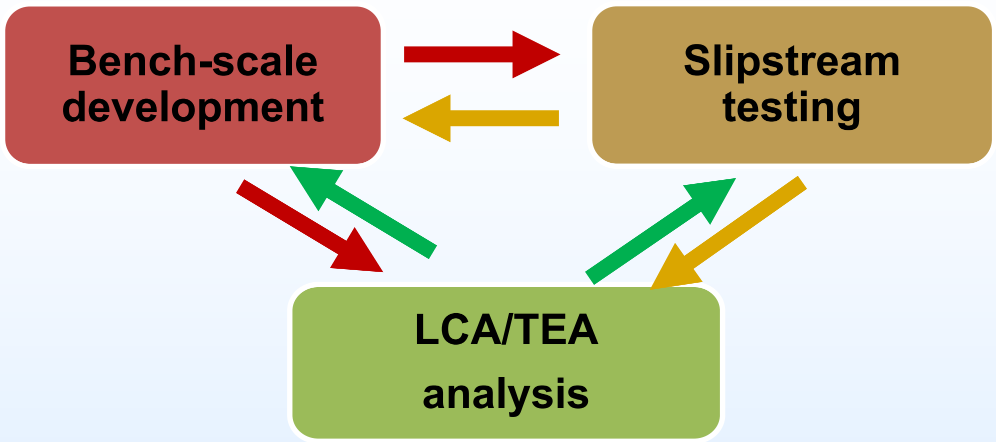




Algae-bacteria cell-cell interactions	**Lab-scale Reactors (1-10 L)**	**Pilot-scale reactors (500 L each)**	**Full-scale reactors (6,800 L each)**
10^{-15}	10^{1}	10^{3}	10^{4} (L)

System volume

Technical Approach/Project Scope



Bench-scale development of a saltwater and a freshwater algal system (UMCES)

- Subtask 2.1; 3.1; 4.1: Saltwater algal carbon sequestration system **(Li and Hill)**
- Subtask 2.2; 3.1; 4.1: Freshwater algal carbon sequestration **(Chen and Hill)**

Slipstream testing of the algal carbon sequestration system (HY-TEK Bio)

- Subtask 2.3; 3.2; 4.2: Slipstream test on strains IMET1 and HTB1 at 500 L **(Mroz)**
- Subtask 3.3; 4.3: Slipstream test on algal strains IMET1 and HTB1 at 6,800 L **(Mroz)**

Development of TEA and LCA models to evaluate and guide (Argonne)

- Subtask 2.4; 3.4; 4.4: Perform TEA and LCA analysis **(*Hawkins and Banerjee*)**

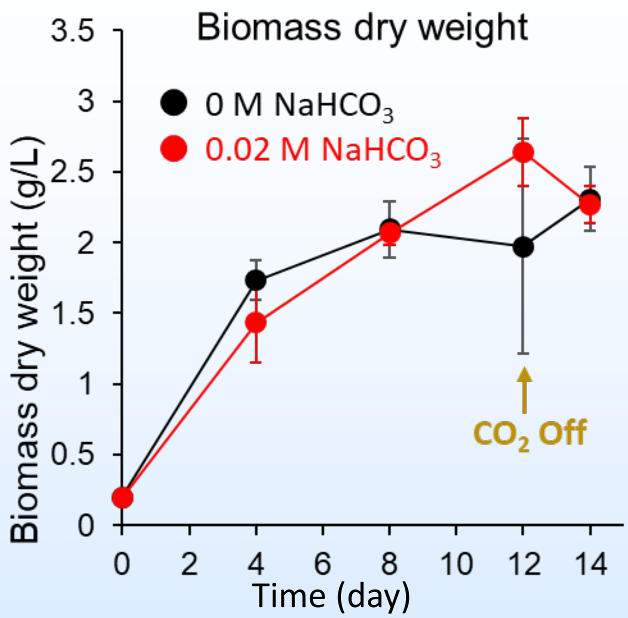
Progress- Budget Period 2 (1/1/22-3/31/23)- BP3 (4/1/23-6/30/24)

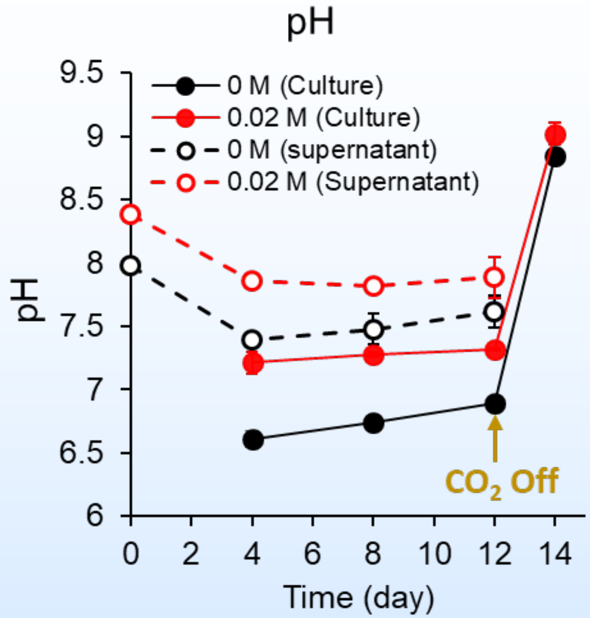
1) Bench-scale optimization of the laboratory and 500-L algal carbon sequestration system;

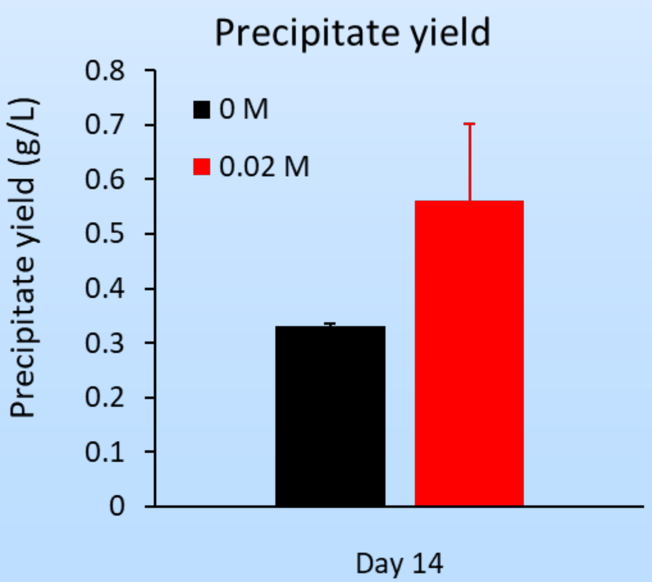
2) Use an iterative modification and validation process to scale up to slipstream testing of the algal carbon sequestration system at a 6,800-L scale on power plant flue gas; and

3) Report on updated findings of the TEA and LCA with the Monte Carlo uncertainty analysis and specific designed input/output templates for new field data.

Progress- *Nannochloropsis* IMET1 Lab culture with 10% CO_2/air





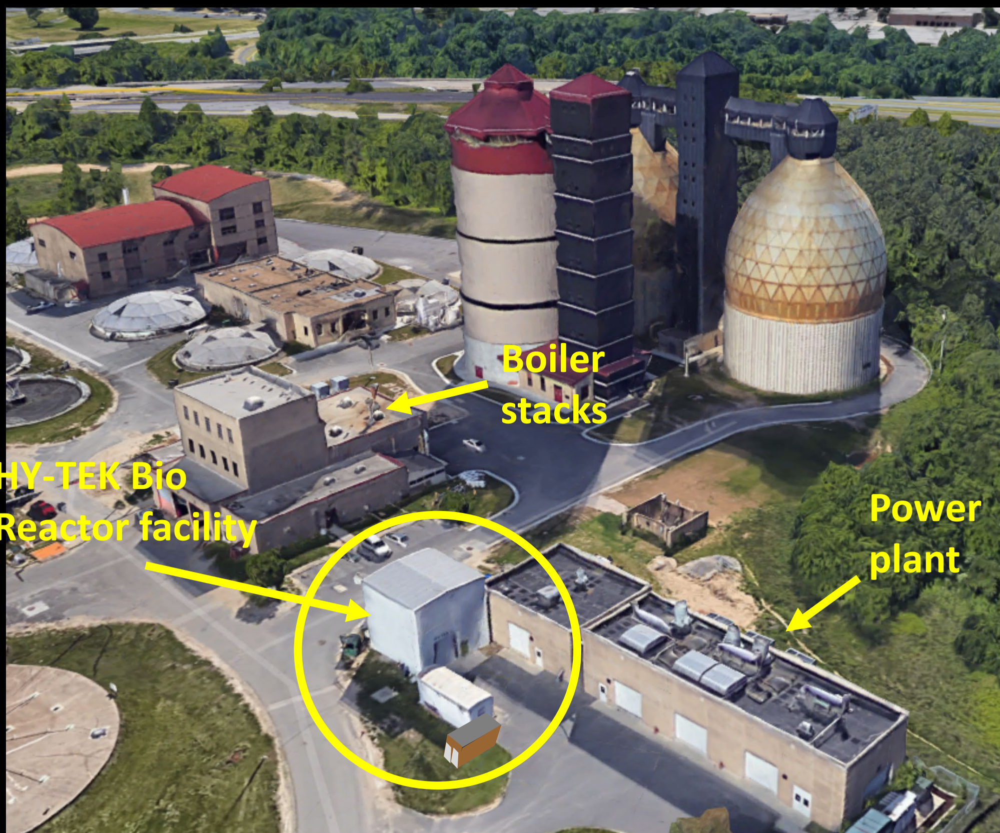


About 21% extra $CaCO_3$ precipitate formed (w/w; 0.55/2.6 (g/L)).

Milestone 3.1 Achieve 2 g/L biomass concentration and extra 20% carbon capture in lab cultures.

Yi-Ying Lee, Jing Wang and Li Team

HY-TEK Bio's slipstream testing site at the Back River Waste Water Treatment Plant

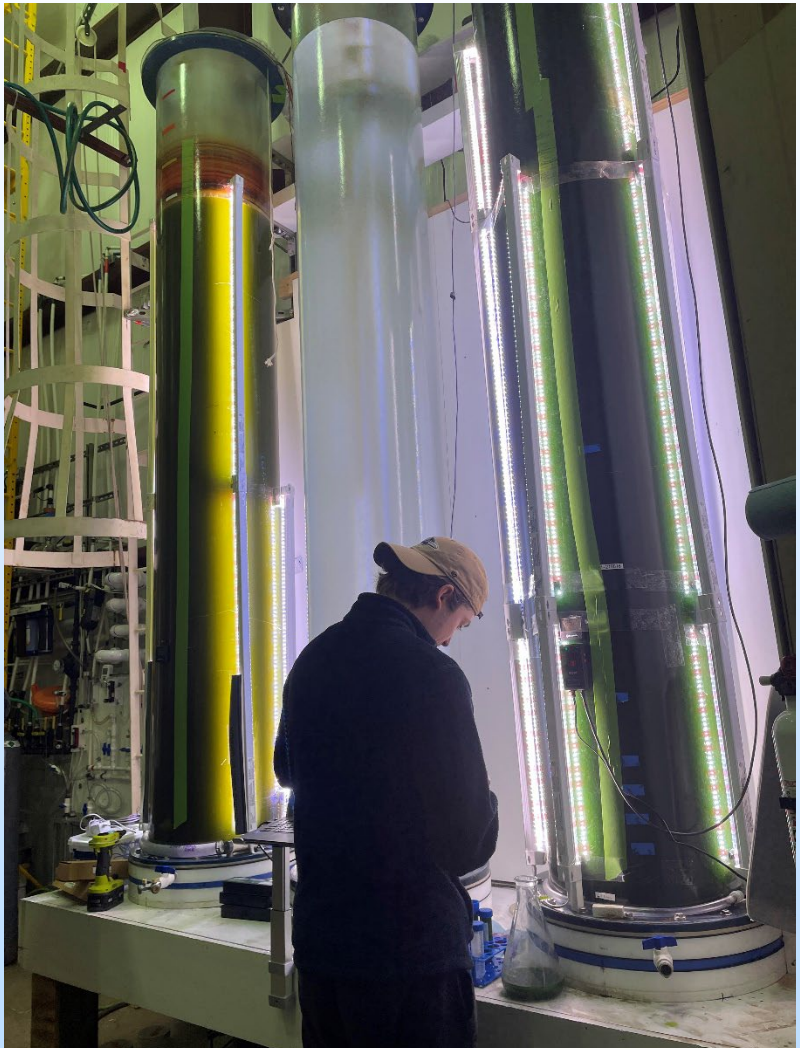


Current HTB site in operation for more than 8yrs

Robert Mroz and HY-TEK Bio Team

Progress- HY-TEK Bio 500L bioreactors

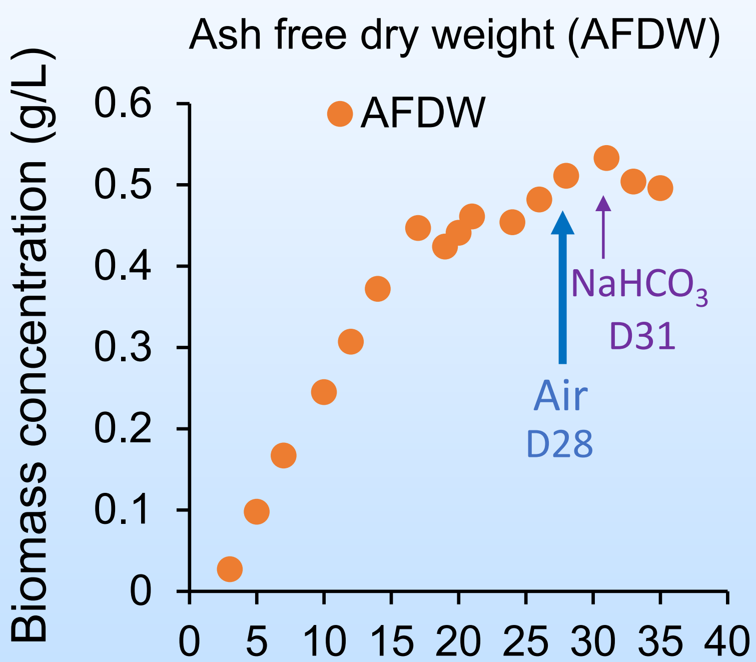
Milestone 3.2 Achieve 10-15 g/m^2/day biomass productivity concentration and extra 20% carbon capture at 500 L. M30

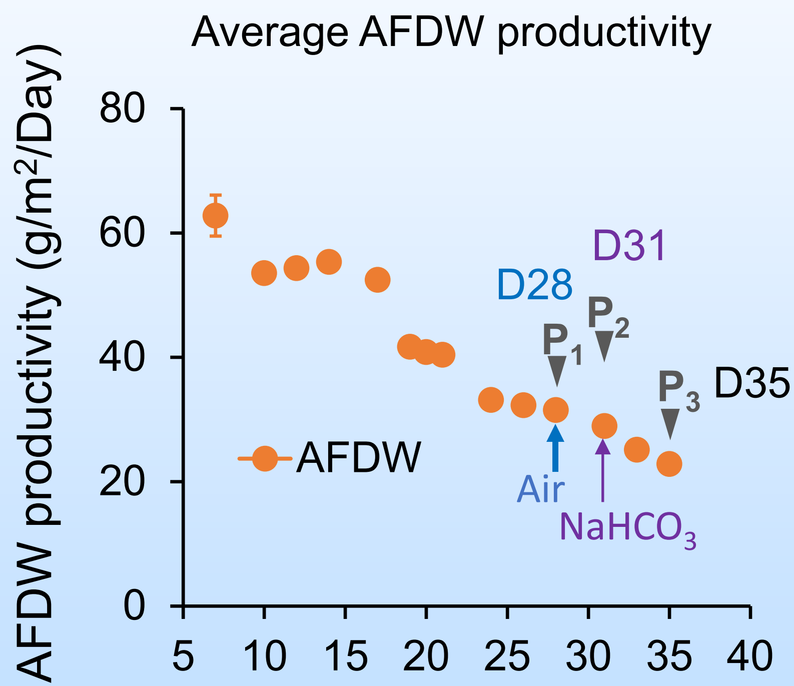


Justin Shaw, Al Dawson, Kent Nicholson, Ed Weinberg, Carolyn Mroz etc.

Progress- *N. oceanica* IMET1 in the 500L bioreactor

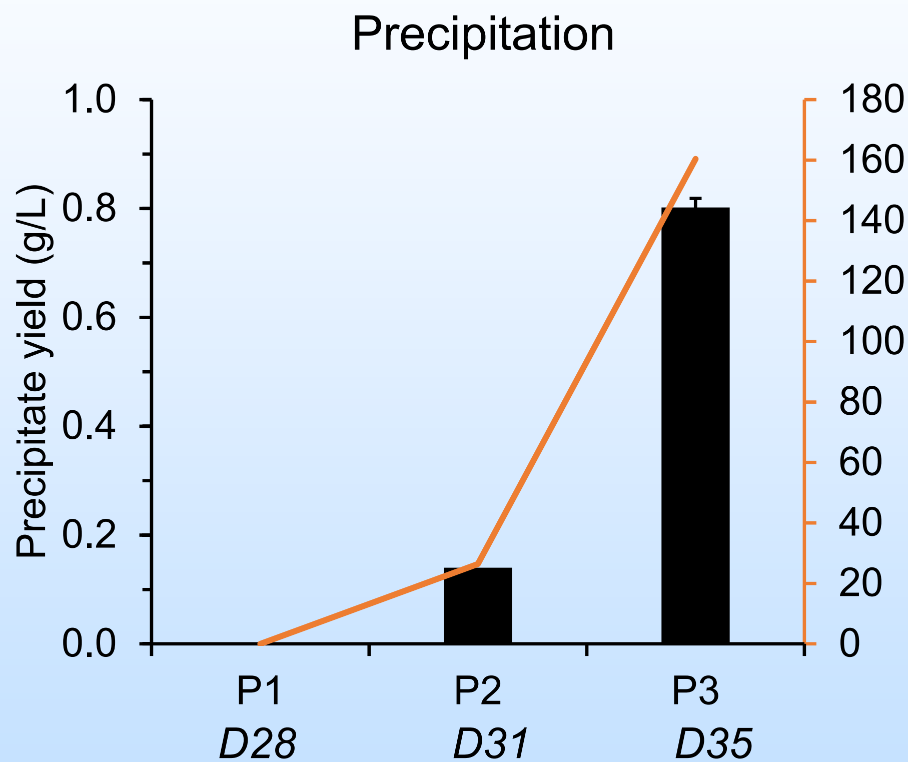
N. oceanica IMET1: D0-28 grown with 5% CO_2 (boiler flue gas); D28-35 grown with air only; D31: 0.02 M $NaHCO_3$ added to the culture



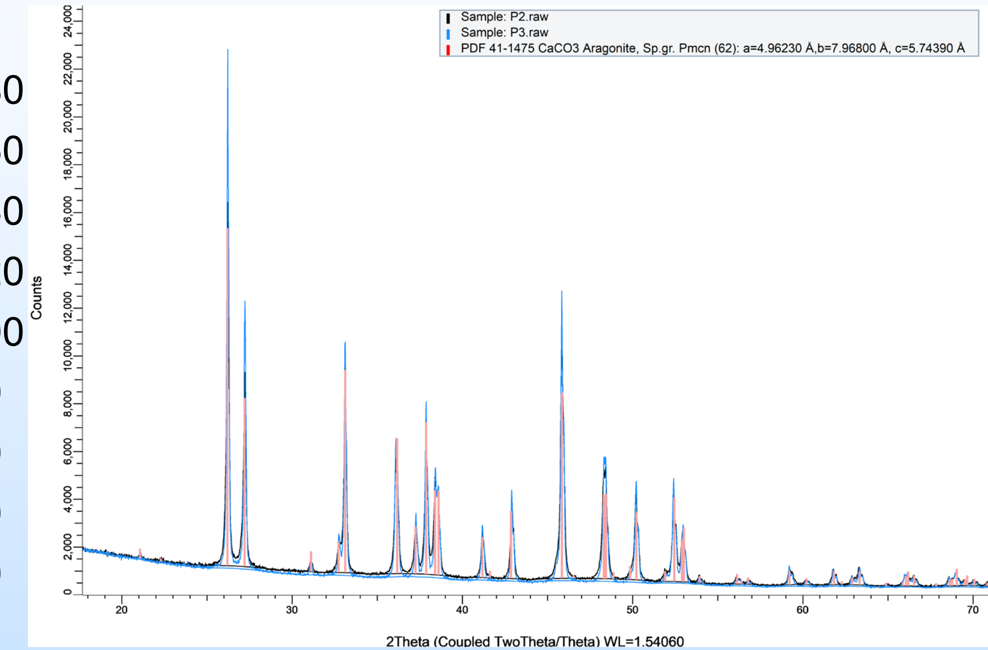


Yi-Ying Lee, Jing Wang and Li Team

Progress- *N. oceanica* IMET1 in the 500L tank



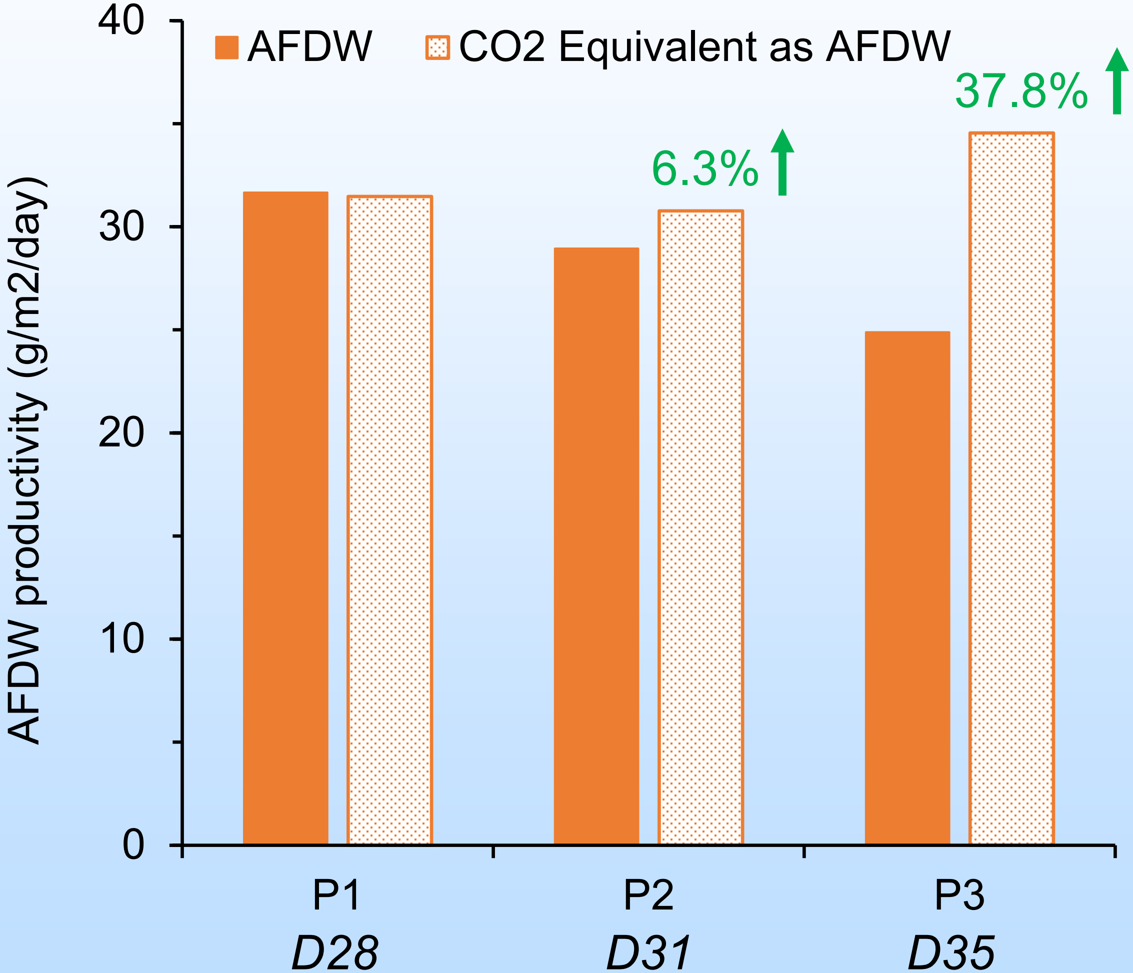
XRD confirms as aragonite ($CaCO_3$)



Assumption: To produce 100 g algae, 183 g CO_2 is needed; To produce 100 g $CaCO_3$, 44g CO_2 is needed; Therefore, stoichiometrically, CO_2 consumption to produce **416 g** $CaCO_3$ is equal to that to produce **100 g** algae.

Progress- *N. oceanica* IMET1 in the 500L tank

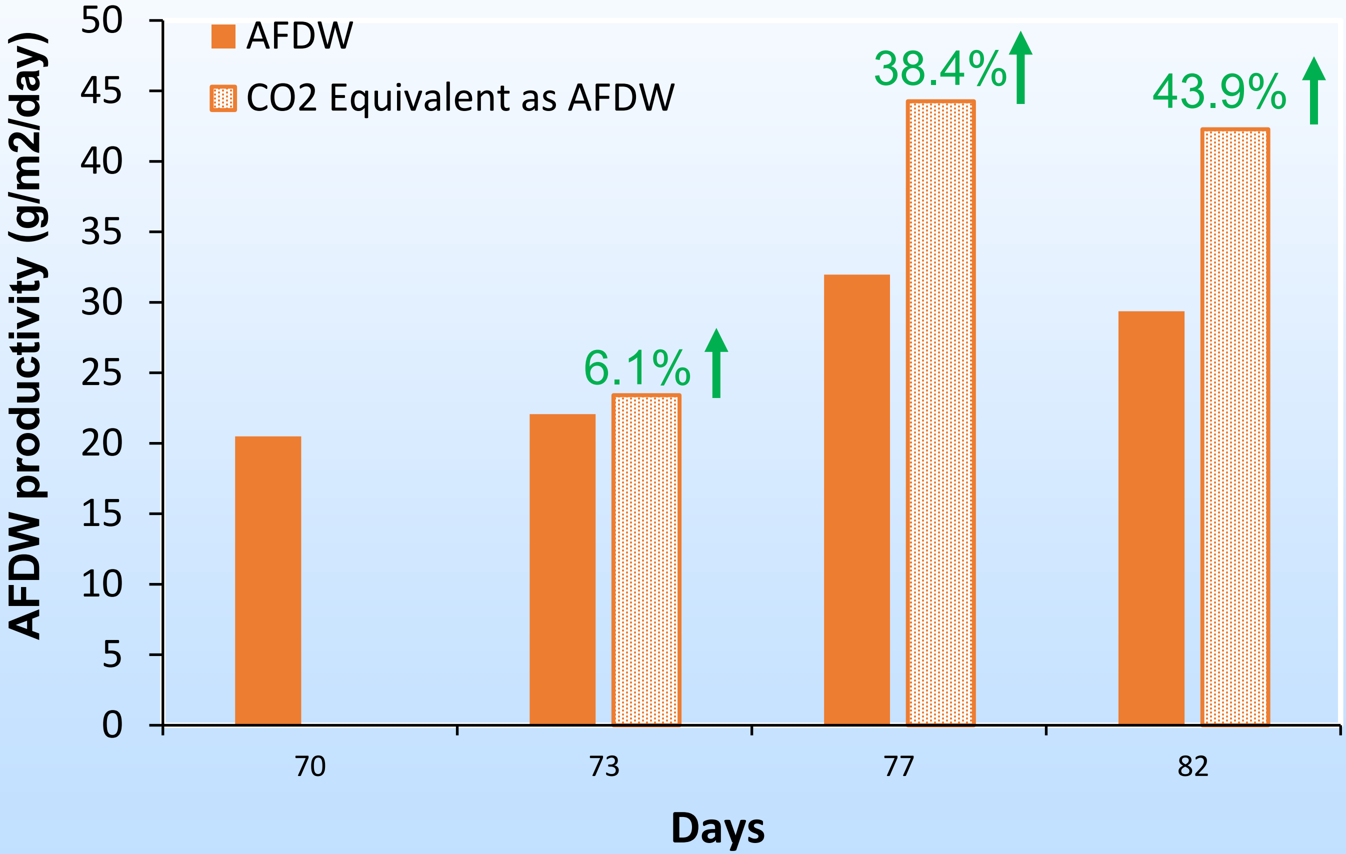
CO_2 capture equivalent based on AFDW biomass productivity
(Converting CO_2 captured as $CaCO_3$ into algae productivity)



Assumption: To produce 100 g algae, 183 g CO_2 is needed; To produce 100 g $CaCO_3$, 44g CO_2 is needed; Therefore, CO_2 consumption to produce **416 g $CaCO_3$** is equal to that to produce **100 g** algae.

Progress- Growth of *S. obliquus* HTB1 in the 500L bioreactor

CO_2 capture equivalent based on AFDW biomass productivity
(Converting CO_2 captured as $CaCO_3$ into algae productivity)

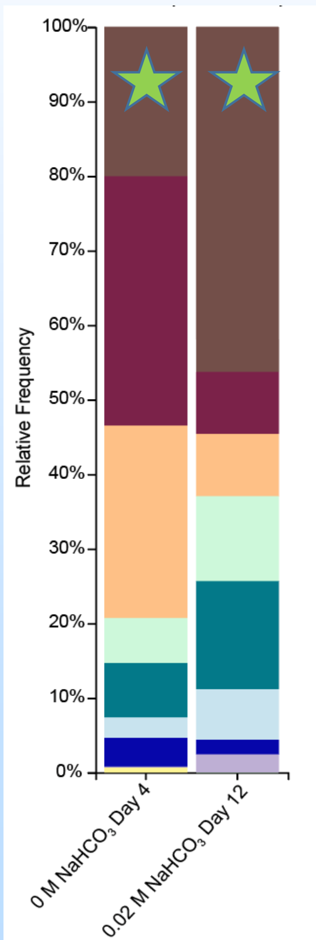


Feng Chen and Chen team

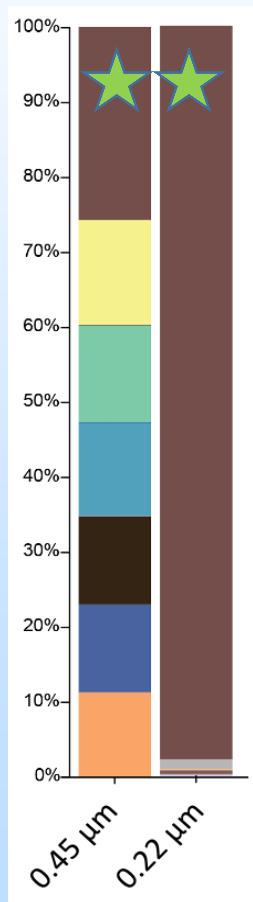
Progress- Lab Microbial Analysis *Nannochloropsis oceanica* IMET1

Closely-associated prokaryotic community (0.45 µm fraction) and free-living prokaryotic community (0.22 µm fraction) of *N. oceanica* IMET1

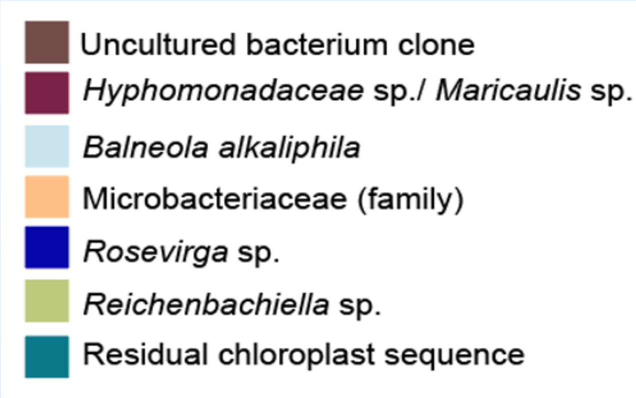
IMET1 grown at IMET (replicates)



IMET1 grown at HY-TEK 500 L reactor



"OD1" phylum



Russell Hill, Lauren Jonas and Hill Group

Progress- HY-TEK Bio work progress

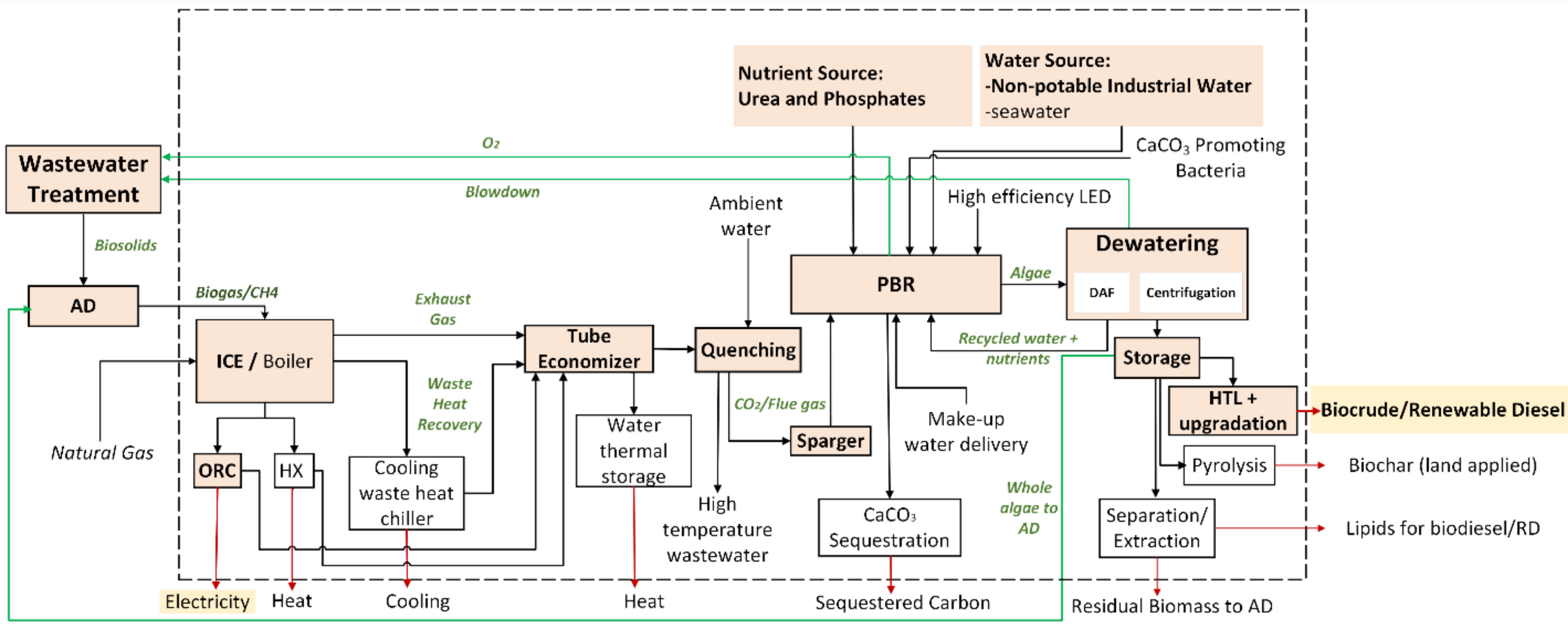
Working processes to rebuild the 6800 L photobioreactor at HY-TEK Bio.

Progress- HY-TEK Bio 6,800L bioreactors

Robert Mroz and HY-TEK Bio Team

Progress- LCA/TEA

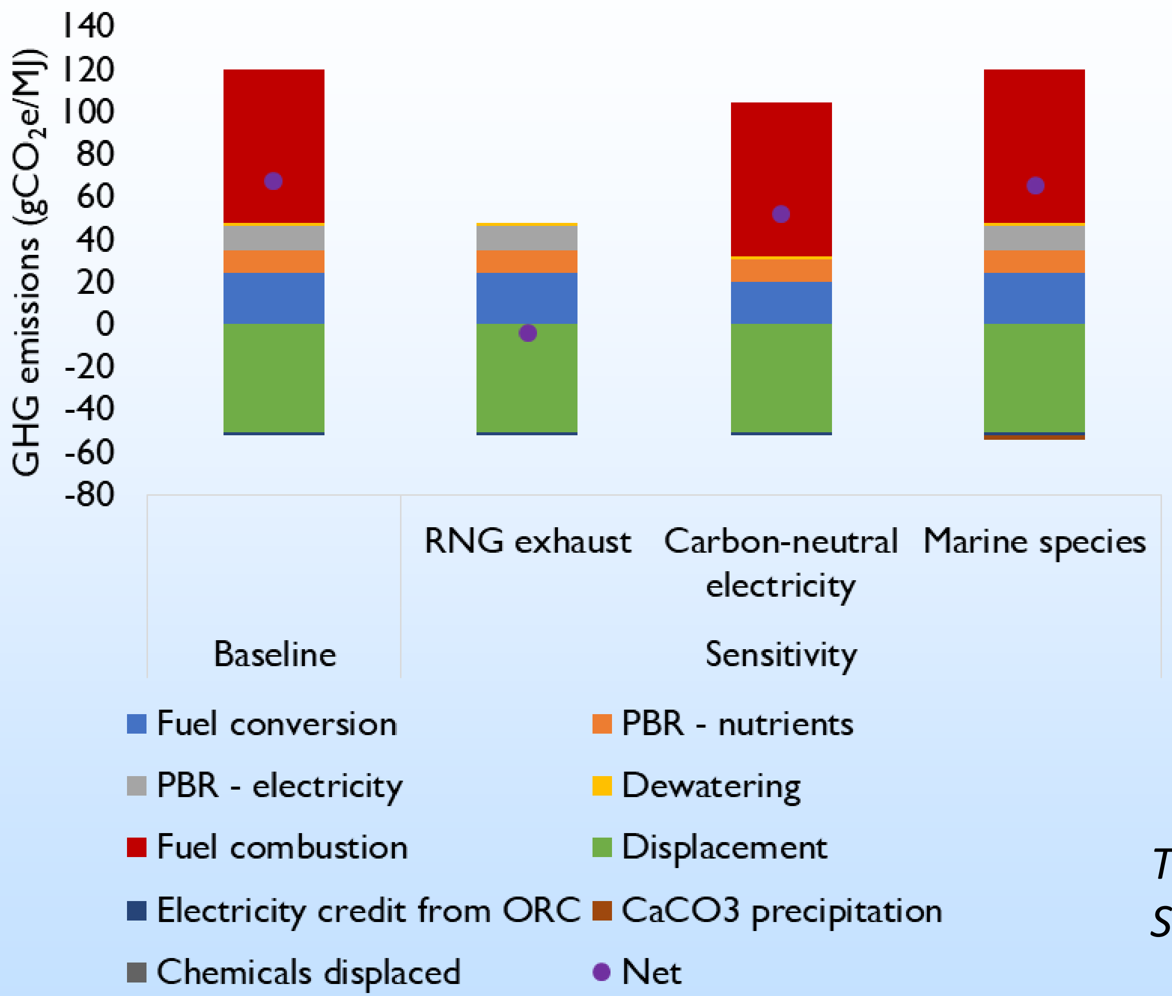
Screening LCA and TEA of Full System and Focused Analysis of Key Processes



Color indicates baseline pathways, monochromatic indicates sensitivities

Troy Hawkins, Udayan Singh, and Farah Naaz

Progress- LCA/TEA



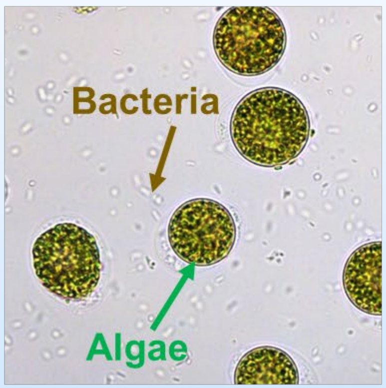
Troy Hawkins, Udayan Singh, and Farah Naaz

- **Net emissions correspond to 68 gCO_2e/MJ in the baseline algae biofuel pathway**
- **This can reduce to net-negative levels as per the CO2U NETL methodology when RNG exhaust (i.e., biogenic carbon source) and carbon-neutral electricity is used**

Technology Readiness Level at present

BP2 **BP3**

Basic principle
TRL 1

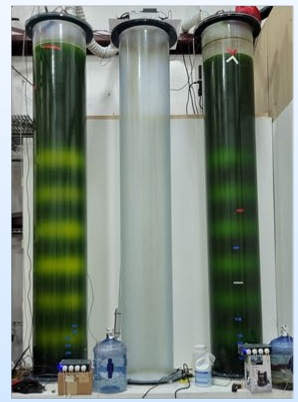


Algae-bacteria cell-cell interactions

Lab scale
TRL 4

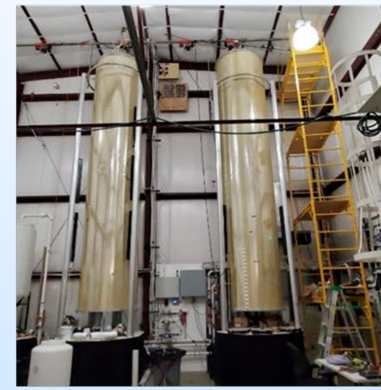
Lab-scale Reactors (1-10 L)

Pilot scale
TRL 6



Pilot-scale reactors (500 L each)

Full scale
TRL 7



Full-scale reactors (6,800 L each)

10^{-15} 10^{1} 10^{3} 10^{4} (L)

System volume

Plans for future work- BP3

Milestone Title	Planned Completion date	Actual Completion date	Verification Method	Comments
Milestone 4.1: Achieve 3 g/L biomass concentration and extra 50% carbon capture in lab cultures	Month 45 (06/30/2024)		Oral and written reports	
Milestone 4.2: Achieve 20 $g/m^2/day$ biomass productivity and extra 50% carbon capture at 500 L	Month 42 (03/31/2024)		Oral and written reports	
Milestone 4.3: Achieve 20 $g/m^2/day$ biomass productivity and extra 50% carbon capture at 6,800 L	Month 45 (06/30/2024)		Oral and written reports	
Milestone 4.4: Report on updated findings of the TEA and LCA	Month 45 (06/30/2024)		Oral and written reports	

Summary

- Our freshwater *Scenedesmus* and seawater *Nannochloropsis* systems are able to achieve >*30 g/m²/Day* AFDW biomass productivity and extra 37.8-43.9% carbon capture when grown with flue gas containing 5% CO_2 at 500 L scale for over a month (35-82 days).
- Dominant bacterial community/microbiome of the algae polyculture is stable in lab and 500 L pilot tests. Urease-producing bacteria may help precipitate more carbon.
- Updated LCA/TEA analysis shows our technology is a promising carbon capture route.

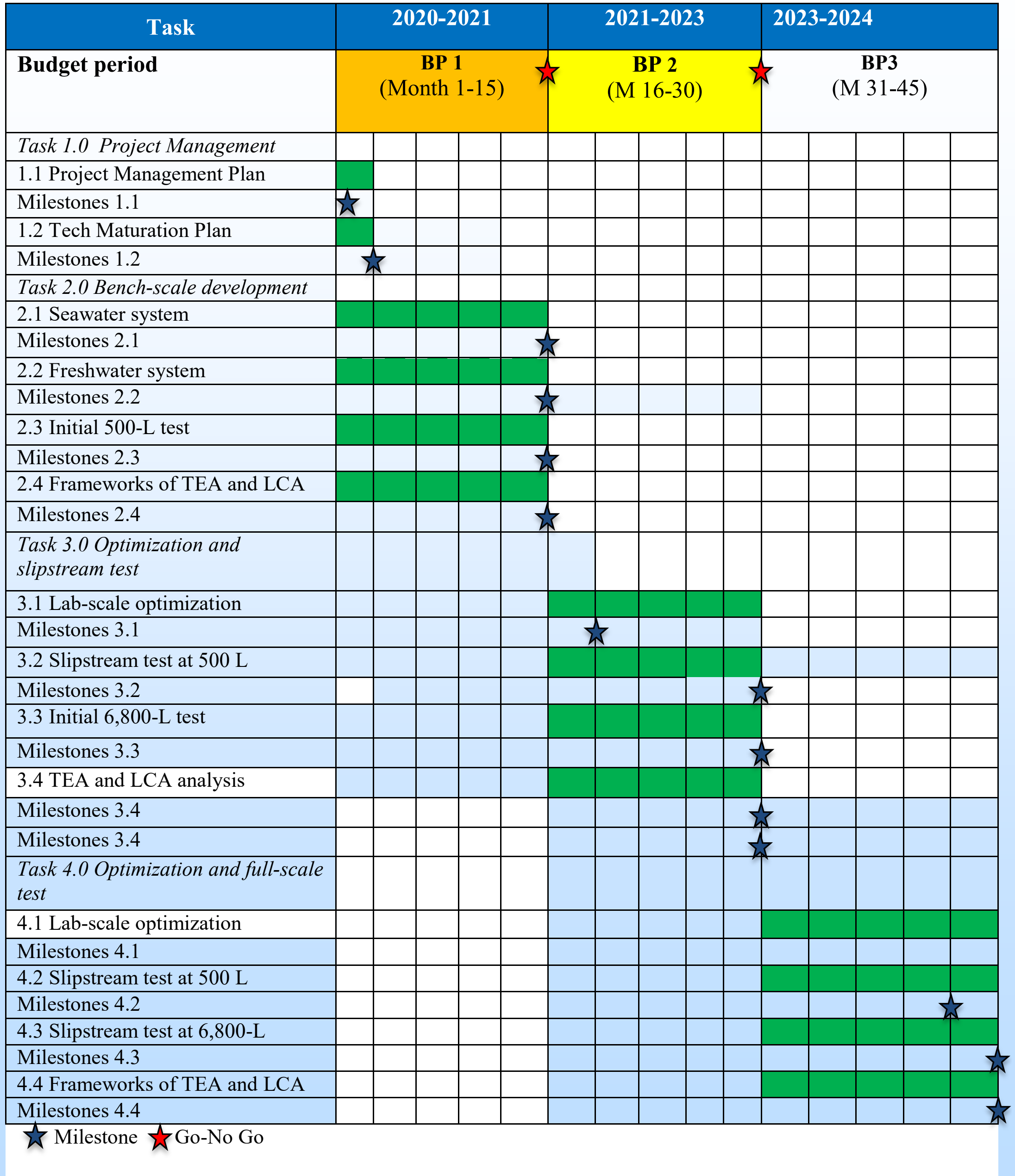
Appendix

– These slides will not be discussed during the presentation but are mandatory.

Organization Chart

No.	/Tasks	/Subtasks and PIs responsible for the task	Teams responsible
1	Project Management and Planning	• Project Management Plan ***(All PIs)*** • Technology Maturation Plan ***(All PIs)***	UMCES is the lead on this task.
2	Bench-scale development of a saltwater and a freshwater system	• Saltwater algal carbon sequestration system ***(Li and Hill, UMCES)*** • Freshwater algal carbon sequestration ***(Chen and Hill, UMCES)***	UMCES is the lead on this task.
3	Slipstream testing of the algal carbon sequestration system	• Slipstream test at 500 L scale ***(Mroz, HY-TEK Bio, LLC)*** • Slipstream test at 6,800 L scale ***(Mroz, HY-TEK Bio, LLC)***	HY-TEK Bio, LLC is the lead on this task.
4	Development of TEA and LCA models to evaluate and guide research and testing activities.	• Develop the frameworks for the TEA and LCA models ***(Hawkins and Banerjee, Argonne National Lab)*** • Perform hotspot analysis, benchmark against other carbon capture and biofuel processes, ***(Hawkins and Banerjee, Argonne National Lab)***	Argonne National lab is the lead on this task.

Gantt Chart


Task
2020-2021
2021-2023
2023-2024
Budget period
BP 1
(Month 1-15)
BP 2
(M 16-30)
BP3
(M 31-45)
Task 1.0 Project Management
1.1 Project Management Plan
Milestones 1.1
1.2 Tech Maturation Plan
Milestones 1.2
Task 2.0 Bench-scale development
2.1 Seawater system
Milestones 2.1
2.2 Freshwater system
Milestones 2.2
2.3 Initial 500-L test
Milestones 2.3
2.4 Frameworks of TEA and LCA
Milestones 2.4
Task 3.0 Optimization and slipstream test
3.1 Lab-scale optimization
Milestones 3.1
3.2 Slipstream test at 500 L
Milestones 3.2
3.3 Initial 6,800-L test
Milestones 3.3
3.4 TEA and LCA analysis
Milestones 3.4
Milestones 3.4
Task 4.0 Optimization and full-scale test
4.1 Lab-scale optimization
Milestones 4.1
4.2 Slipstream test at 500 L
Milestones 4.2
4.3 Slipstream test at 6,800-L
Milestones 4.3
4.4 Frameworks of TEA and LCA
Milestones 4.4
Milestone
Go-No Go

Algae

System Performance Data

	Units	Measured/Current Performance	Projected/Target Performance
Algae Characteristics			
Proposed Algae Strain	-	Nannochloropsis oceanica IMET1 and Scenedesmus HTB1	
Lower Heating Value @ 25ºC	kJ/kg (dry)	15	
Lipid Content[1]	wt%	20-51	
Protein Content	wt%	18-42	
Carbohydrate Content	wt%	8-30	
Algae Cultivation			
Method of Cultivation	-	PBR	
Water Source		Seawater for Nannochloropsis and freshwater for Scenedesmus	Seawater for Nannochloropsis and freshwater for Scenedesmus
Pond or PBR Surface Area	m2	0.19 (500 L)	1.16 (6,800 L)
Pond Depth or PBR Width	cm	290	586
PBR Type[2]	-	column airlift	column airlift
Pond or PBR Volume	L	500	6800
Nutrient Source - N	-	NO_3^- or urea	NO_3^- or urea or sterilized chicken manure
Nutrient Source - P	-	PO_4^{3-}	PO_4^{3-} or sterilized chicken manure
Scale of Operation – CO_2 delivered[3]	kg/hr	0.04	12-40
CO_2 Utilization			
CO_2 Source[4]	-	Commercial CO2 and simulated flue gas	Flue gas from power plant engine or boiler (BRWWTP)
CO_2 Content of Source Gas	mol%	6-8 (boiler) 10-12 (engine)	6-8 (boiler) 10-12 (engine)
Impurity or contaminant processing requirements[5]	-	clean source gas with no processing	clean source gas with no processing
CO_2 Processing Requirements[6]	-	no processing	no processing
CO_2 Concentration after Processing[7]	mol or wt%	6-8 (boiler) 10-12 (engine)	6-8 (boiler) 10-12 (engine)
Delivery Method to Pond/PBR[8]	-	Gas sparger	Gas sparger
CO_2 Pond/PBR Retention[9]	%	90	>90
***Algae* Productivity[10]**			
Peak Productivity	$g/m^2/day$	50	50
Annual Average Productivity	$g/m^2/day$	32	>20
Projected Finished Products[11]		(*Market Value*)	(*Market Size*)
Product #1: Biodiesel	-	$3/gallon	$100 B
Product #2: lutein and zeaxanthin	-	$2,000/kg	$275 M