Photosynthesis-driven microalgal system to mitigate carbon dioxide emission from power plant flue gases

DE-FE0032188

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

Robert Mroz, HY-TEK Bio, LLC;

Troy Hawkins, Argonne National Laboratory

Wen Zhang, New Jersey Institute of Technology

August 6, 2024, FECM Annual Meeting, Pittsburg, PA

Project Overview

- Funding

  DOE: $2,000,000 and Cost Share: $500,000

- Overall Project Performance Dates:

  Feb. 2023 to Feb. 2026

  BP1 (2/15/2023 to 8/14/2024; NCE to 2/14/2025), BP2 (8/15/2024 to 2/14/2026),

- 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

  Wen Zhang, New Jersey Institute of Technology

  ***DOE NETL Program Manager*: Zachary Roberts (from February 2023 to May 2024), Richard Dunst (from June 2024 to present)**

University of Maryland CENTER FOR ENVIRONMENTAL SCIENCE

HY-TEK Bio

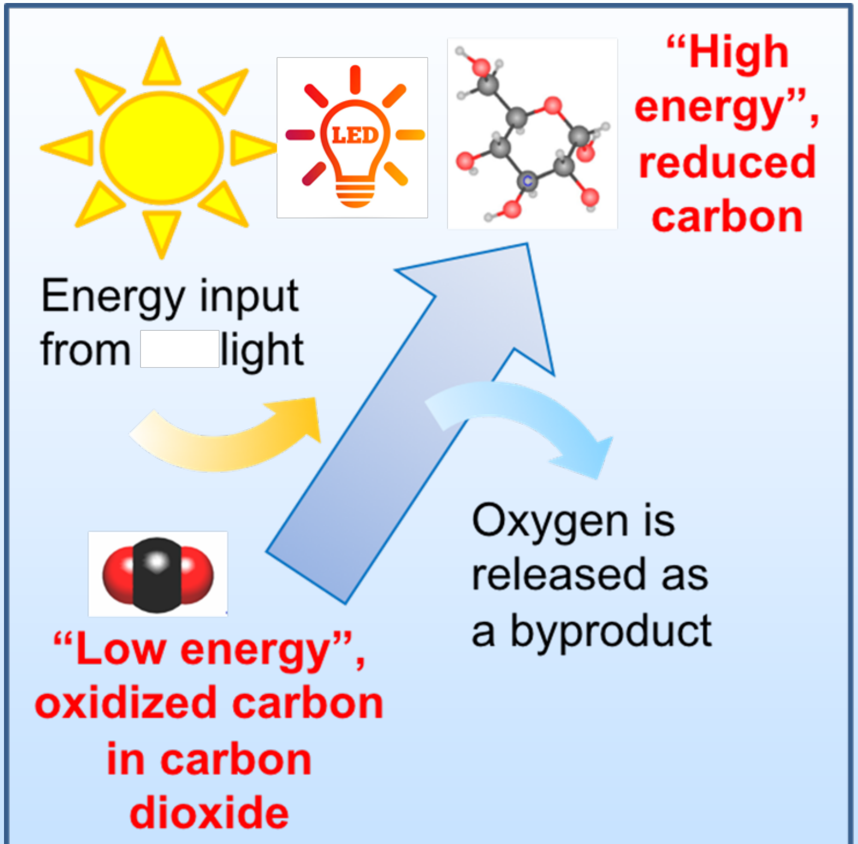
Argonne NATIONAL LABORATORY

Project Overview

– Overall Project Objectives

The objective of this project is to engineer microalgal polycultures through a photosynthesis-driven process to capture and sequester carbon dioxide (CO_2) from power plant flue gases in the form of algae biomass and carbonate precipitates.

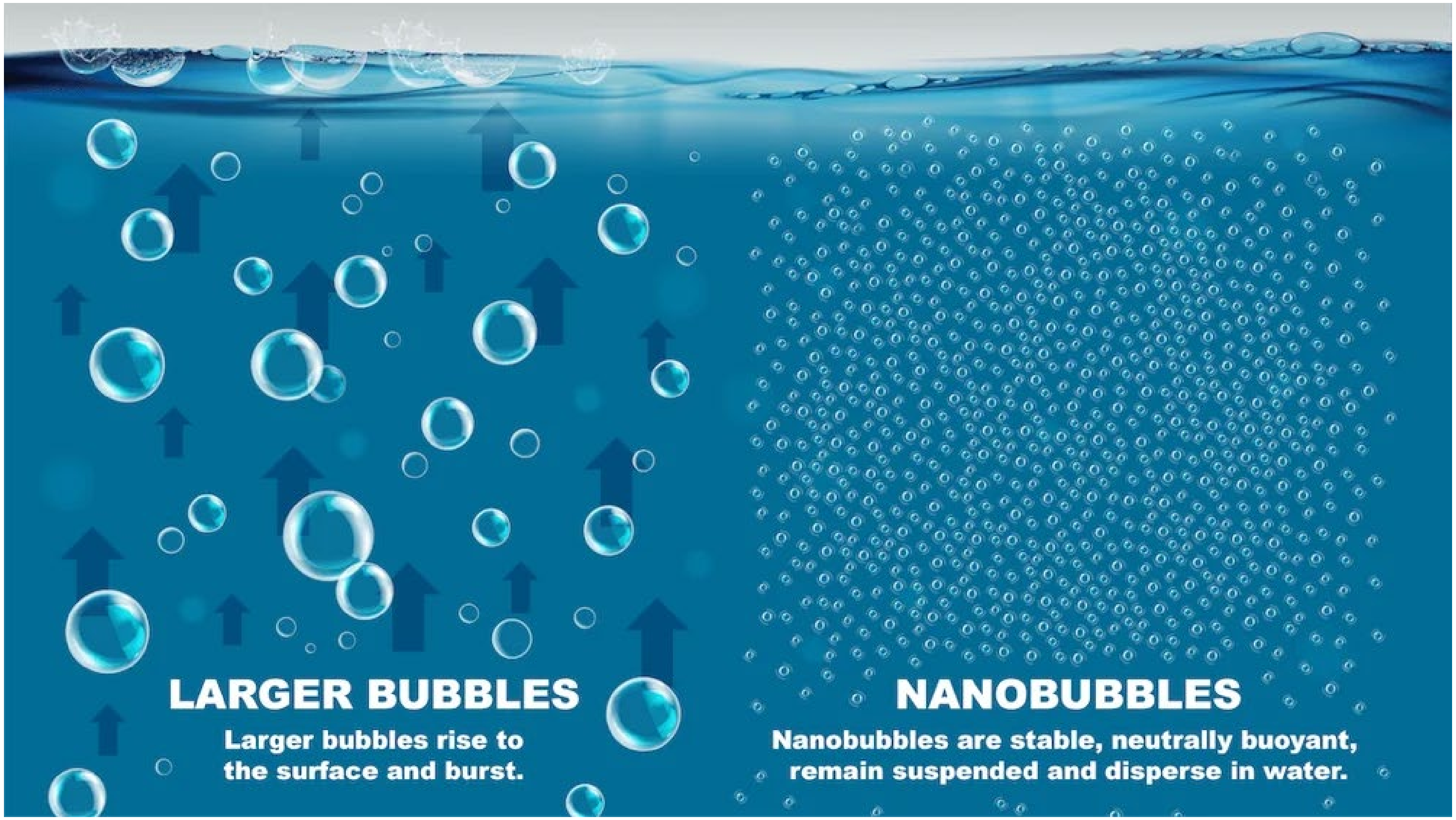
Technology Background



$$6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2$$

Williams, M.E. (July 31, 2016). Carbon-Fixing Reactions of Photosynthesis. The Plant Cell, doi/10.1105/tpc.116.tt0716. Illustrative pictures from https://www.123rf.com/.

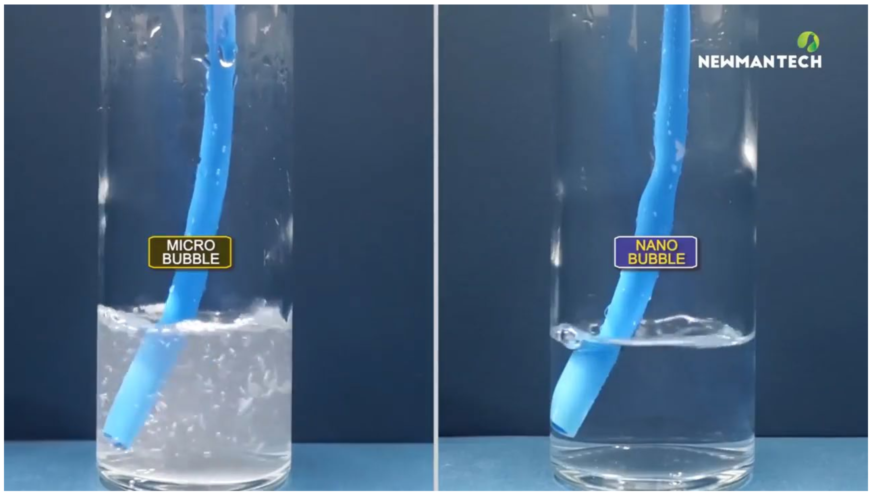
Using nanobubbles to increase carbon utilization efficiency (CUE)

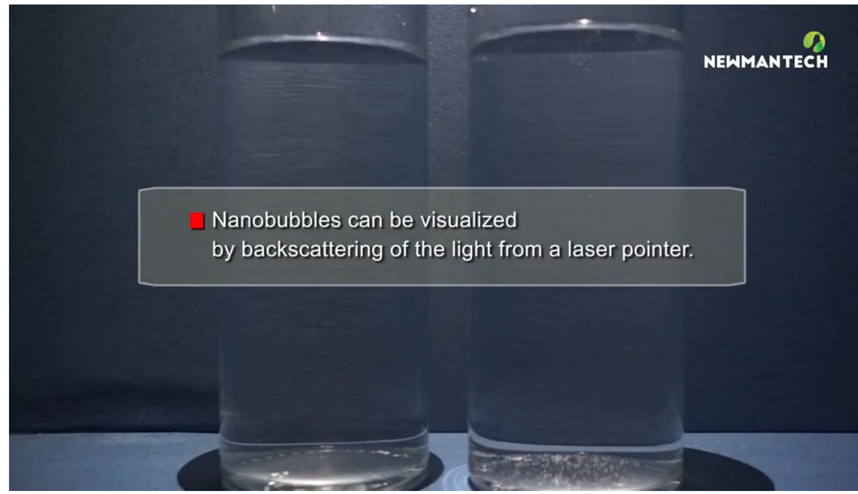


Nanobubbles have the potential to enhance the CO_2 solubility and **carbon utilization efficiency** of microalgae due to their minuscule size, high gas-liquid mass transfer efficiency, and large electrostatic interactions.

Using nanobubbles to increase carbon utilization efficiency (CUE)

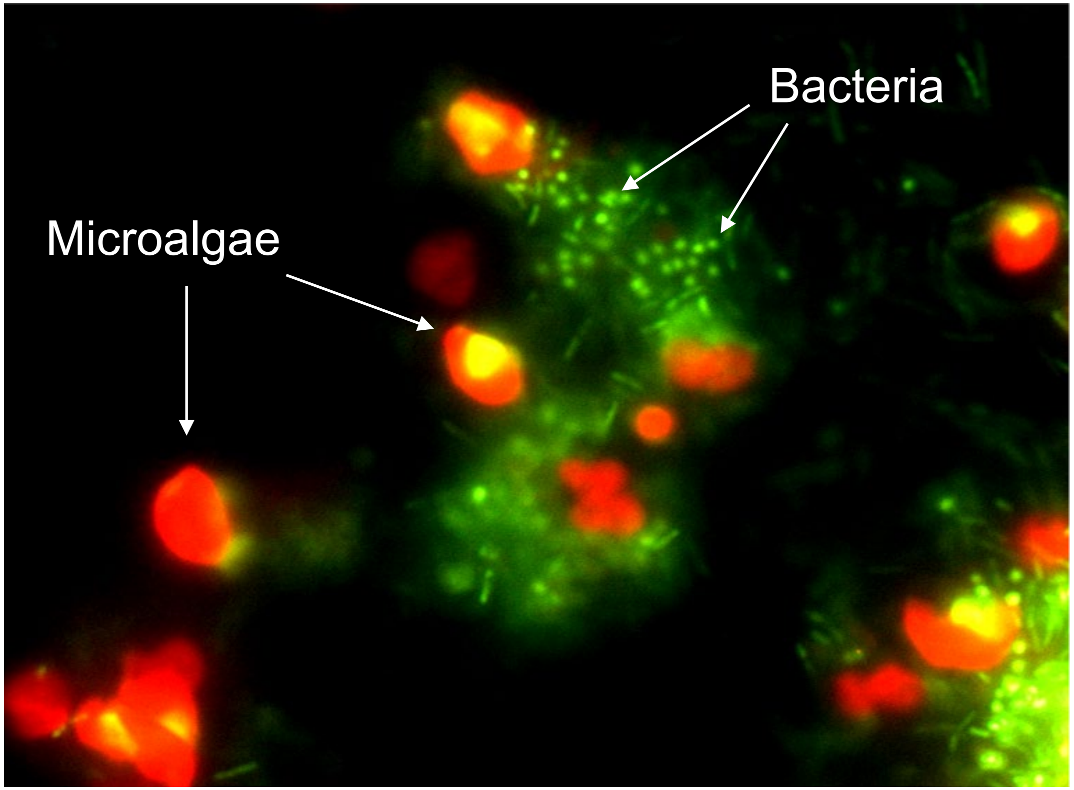
Microbubble vs Nanobubble





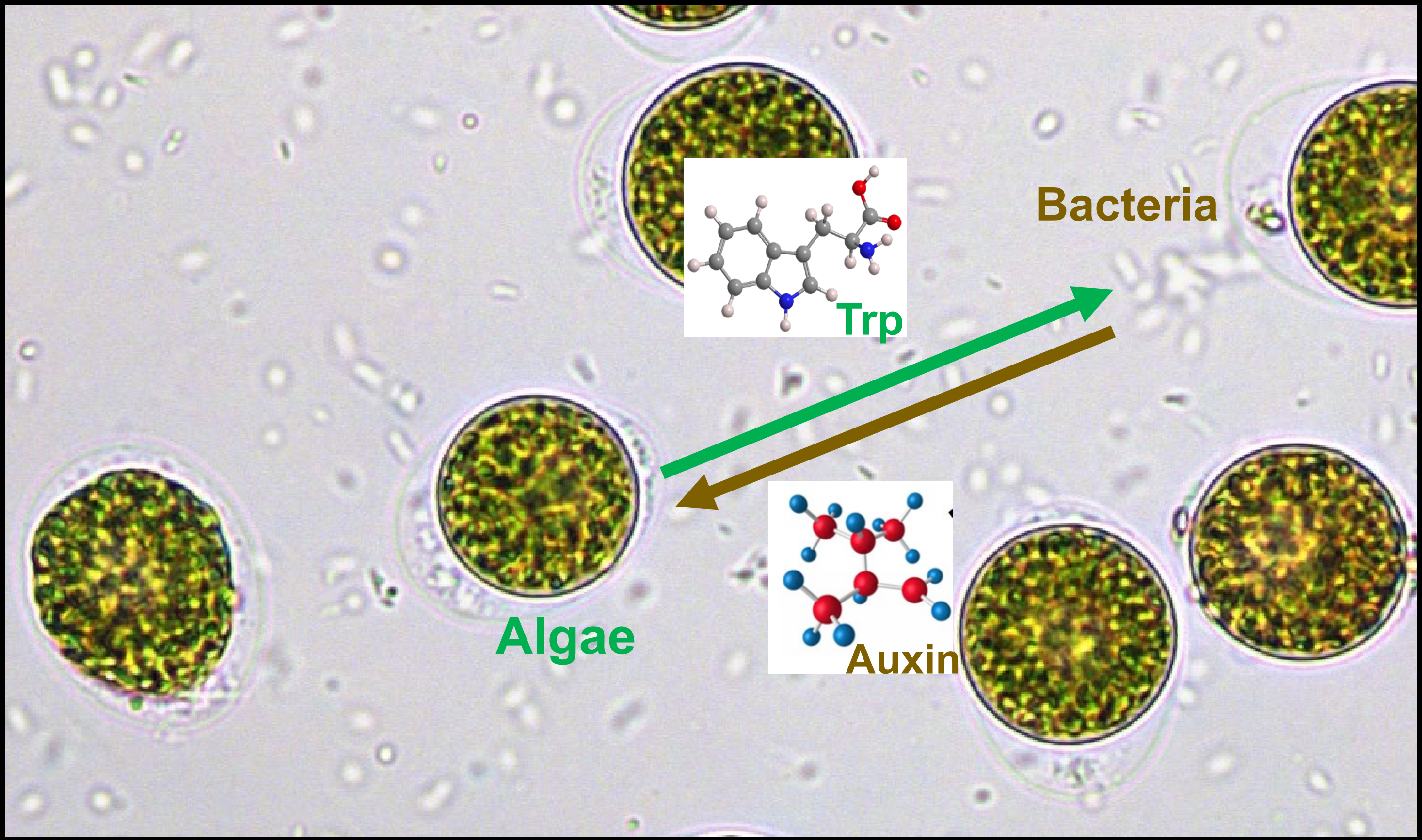
Nanobubbles have the potential to enhance the CO_2 solubility and **carbon utilization efficiency** of microalgae due to their minuscule size, high gas-liquid mass transfer efficiency, and large electrostatic interactions.

Microbiomes in algal culture systems



Complex bacteria co-exist in algal cultures and some can have beneficial effects: 1) Promote algal growth; 2) Induce calcium carbonate precipitation.

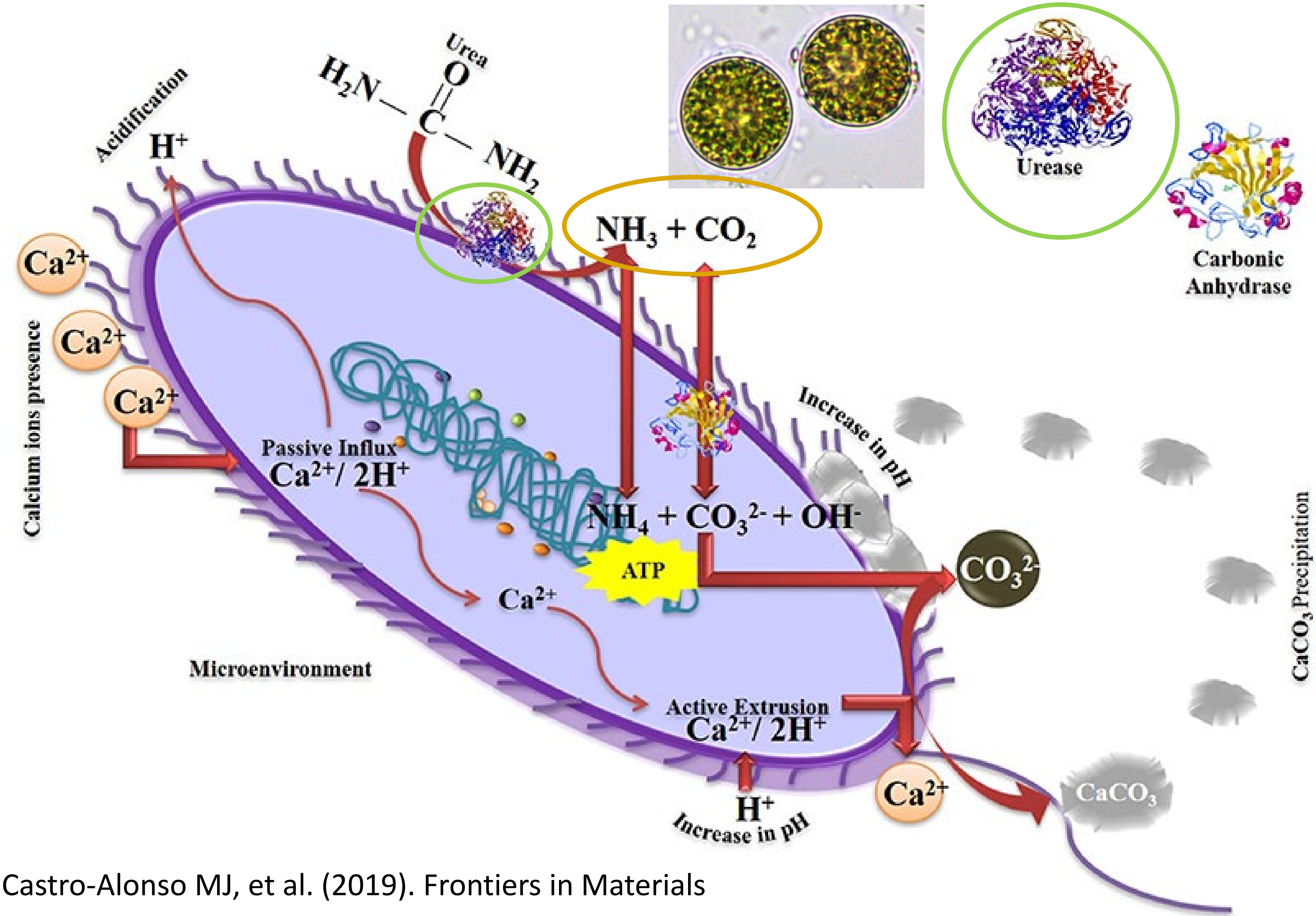
Microbial interactions in non-axenic microalgal cultures



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

Microbially Induced Calcium Carbonate Precipitation

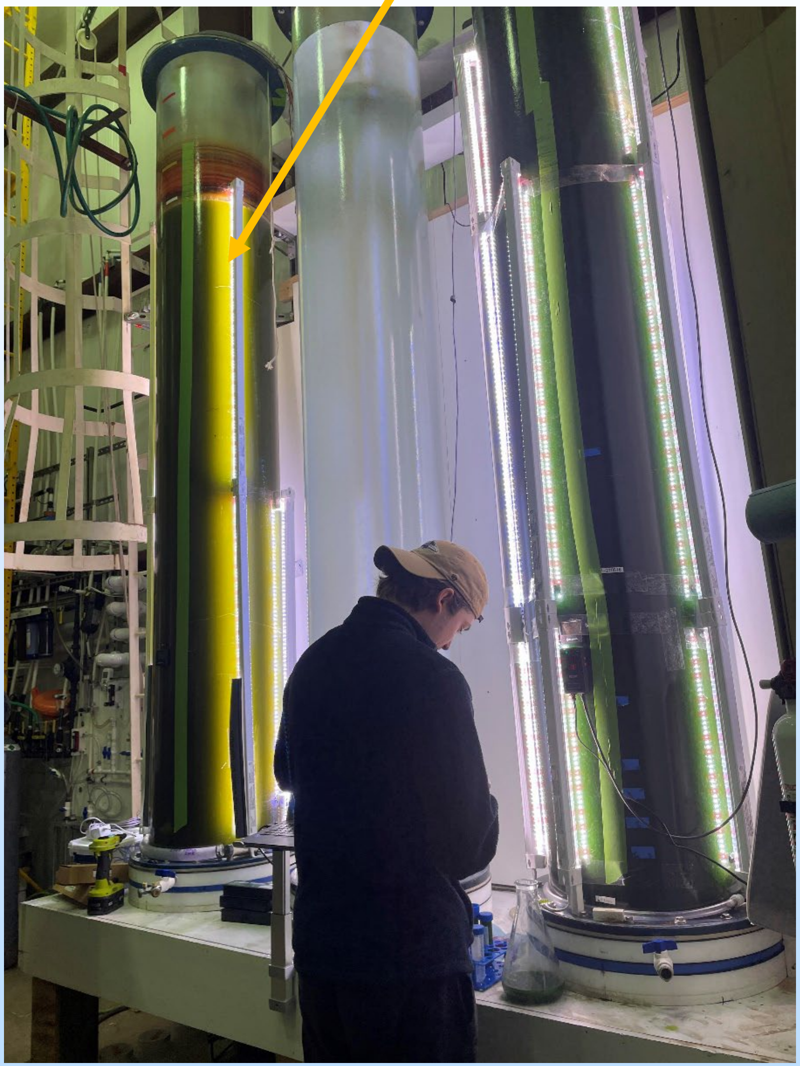
Microbially Induced Calcium Carbonate Precipitation (MICP) and Urease



Castro-Alonso MJ, et al. (2019). Frontiers in Materials

We focused on two major microalgal species

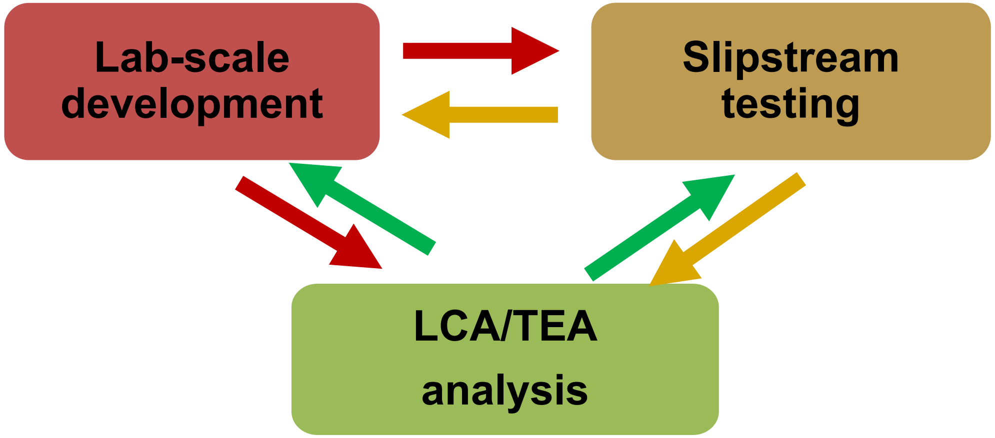
Nanaochloropsis oceanica IMET1



Scenedesmus obliquus HTB1

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

Project overview



Lab-scale development of algal system and culture microbiome optimization (UMCES)

- Subtask 2.1; 3.2: Saltwater algal system and microbiome optimization **(Li and Hill)**
- Subtask 2.2; 3.3: Freshwater algal system and microbiome optimization **(Chen and Hill)**

Development and testing of bubblers in the lab and upscaled algal systems (NJIT)

- Subtask 2.3, 3.4: Develop and optimize micro-/nano- bubblers **(Zhang)**

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

- Subtask 2.4, 3.1: Slipstream test at 9 L and 1,000 L **(Mroz)**

Development of TEA and LCA models (Argonne)

- Subtask 4.0: Perform TEA and LCA analysis **(*Hawkins*)**

Progress: Budget Period 1 Bench-scale and 9 L scale test

Subtask 2.1 **- Laboratory development of seawater *Nannochloropsis* system**

- Analyze the culture microbiome to assess changes in microbial community;
- Isolate and test urease-producing and probiotic bacterial strains;
- Measure $CaCO_3$ precipitates, culture alkalinity, and biomass yield.

Milestone 2.1 Isolate and confirm the identity of >5 urease-producing bacteria and >5 probiotic bacterial strains for *Nannochloropsis oceanica* IMET1; Date: M15

Progress: Budget Period 1 Bench-scale and 9 L scale test

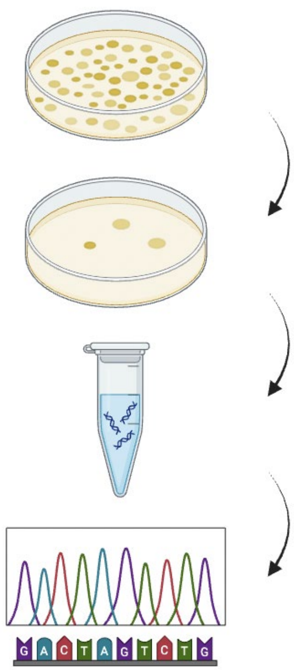
***Subtask 2.2* - Laboratory development of freshwater *Scenedesmus* system**

- Analyze the culture microbiome to assess changes in microbial community;
- Isolate and test urease-producing and probiotic bacterial strains;
- Measure $CaCO_3$ precipitates, culture alkalinity, and biomass yield.

Milestone 2.2 Isolate and confirm the identity of >5 urease-producing bacteria and >5 probiotic bacterial strains for *Scenedesmus* HTB1; Date: M15

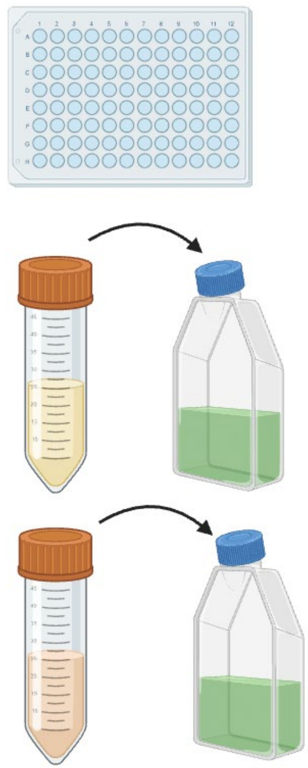
Progress: Budget Period 1 Bench-scale and 9 L scale test

Phase 1 - Isolation and identification of bacteria

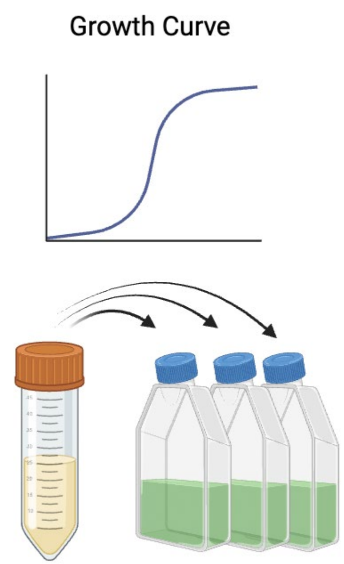


Biorender

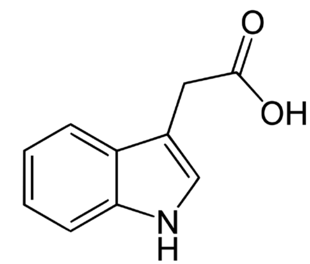
Phase 2 - Screening of multiple bacterial isolates

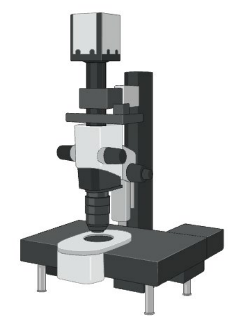


Phase 3 - Testing bacteria:algae ratios for specific isolates of interest



Phase 4 - Understanding the mechanism of growth promotion

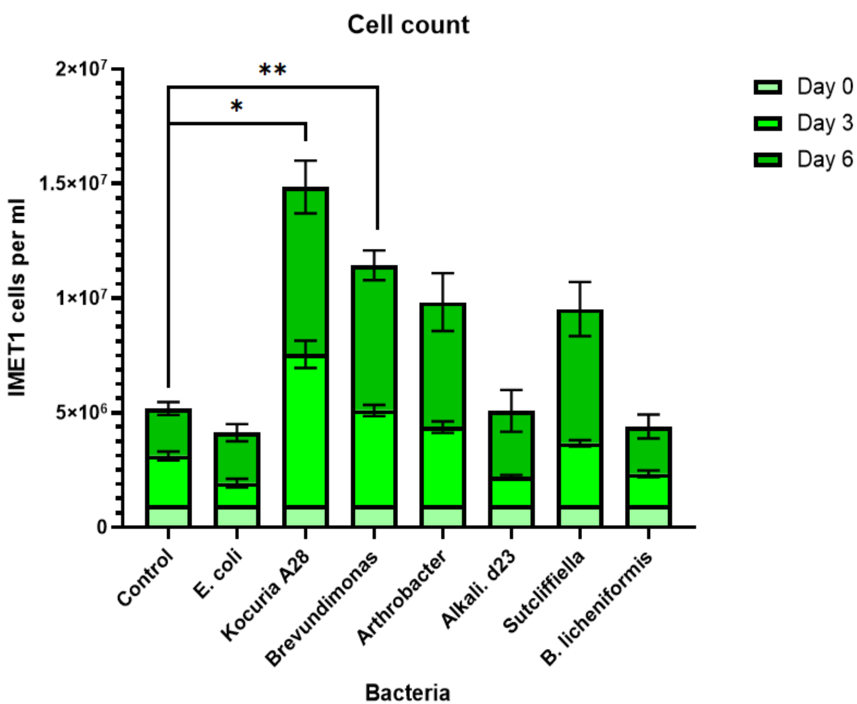


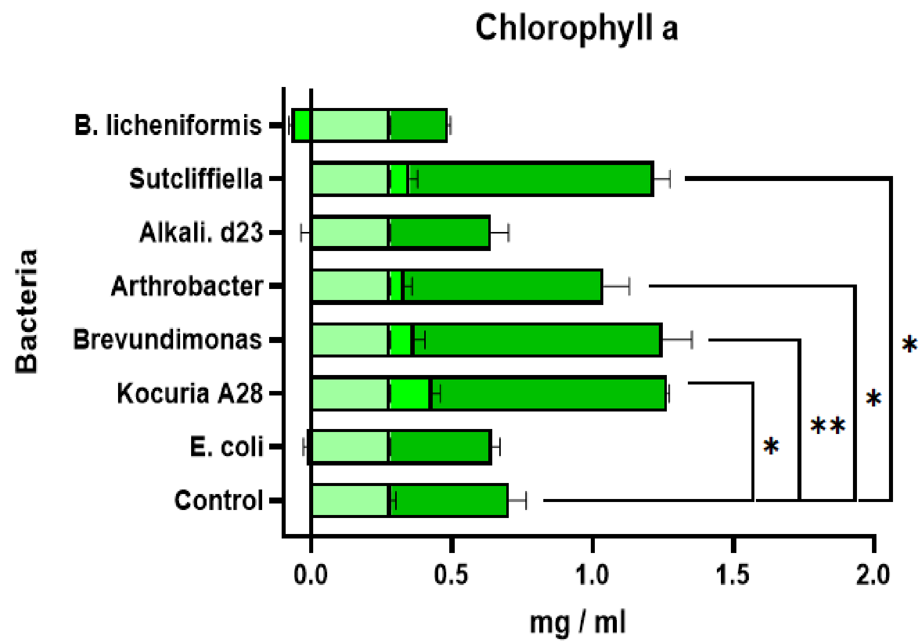


Russell Hill, Lauren Jonas, and Hill lab

Progress: Budget Period 1 Bench-scale and 9 L scale test

Nannochloropsis IMET1 Growth Promoting Isolates



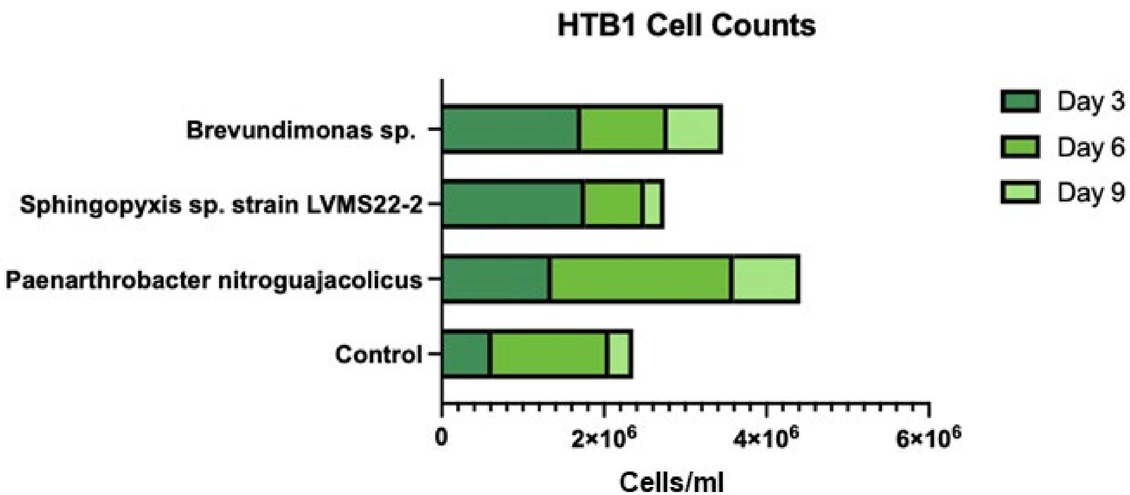


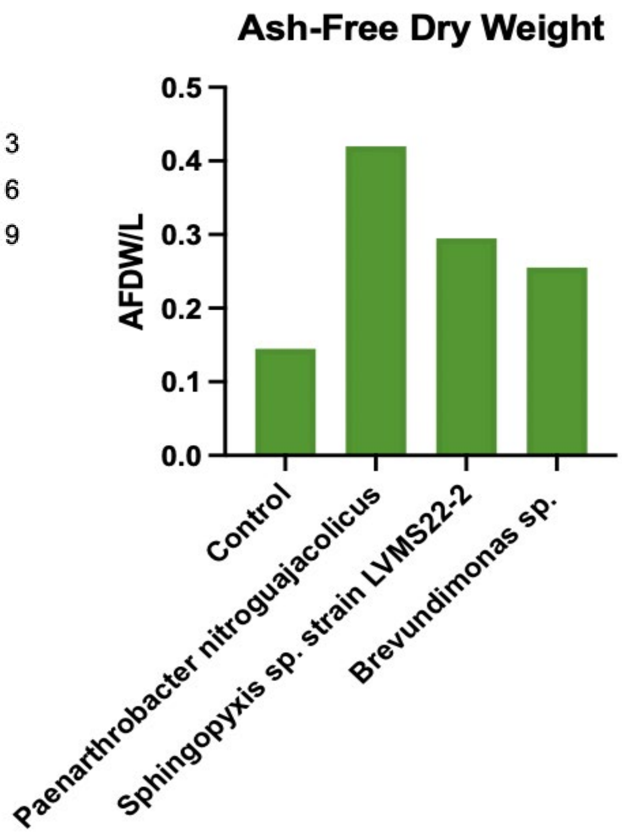
Several bacterial strains help promote the growth of IMET1

Russell Hill, Lauren Jonas, and Hill lab

Progress: Budget Period 1 Bench-scale and 9 L scale test

Scenedesmus HTB1 Growth Promoting Isolates





Russell Hill, Lauren Jonas, and Hill lab

Day 6

Progress: Budget Period 1 Bench-scale and 9 L scale test

Growth Promoting Bacteria Isolates

***Scenedesmus* HTB1**	***Nannochloropsis* IMET1**
Brevundimonas sp.	*Brevundimonas vesicularis*
Paenarthrobacter nitroguajacolicus	*Arthrobacter* sp.
Sphingopyxis sp.	*Kocuria* sp. strain A28
Kocuria rhizophila	*Sutcliffiella cohnii*
Staphylococcus sp.	*Hyphomonas* sp.
Brevundimonas sp.	*Sphingopixis* sp.

Russell Hill, Lauren Jonas, and Hill lab

Progress: Budget Period 1 Bench-scale and 9 L scale test

Five urease-producing bacteria for *Nannochloropsis* IMET1
Five urease-producing bacteria for *Scenedesmus* HTB1

Taxonomy	Identity (%)	Algae
Paenarthrobacter nitroguajacolicus	99.42	Both
Staphylococcus saprophyticus	99.28	Both
Agrobacterium tumefaciens	99.53	Both
Bosea vestrisii	99.27	HTB1
Bosea sp.	99.77	HTB1
Pseudomonas knackmussi/stutzeri	100.00	IMET1
Bacillus amyloliquefaciens	99.86	IMET1

Milestone 2.1 Isolate and confirm the identity of >5 urease-producing bacteria and >5 probiotic bacterial strains for *Nannochloropsis oceanica* IMET1; Date: M15

Milestone 2.2 Isolate and confirm the identity of >5 urease-producing bacteria and >5 probiotic bacterial strains for *Scenedesmus* HTB1; Date: M15

Russell Hill, Lauren Jonas, and Hill lab

Budget Period 1: Bench-scale and 9 L-scale field test

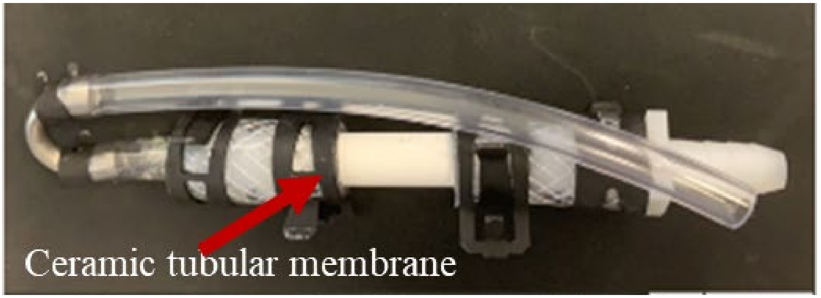
***Subtask 2.3* - Development and testing of bubblers**

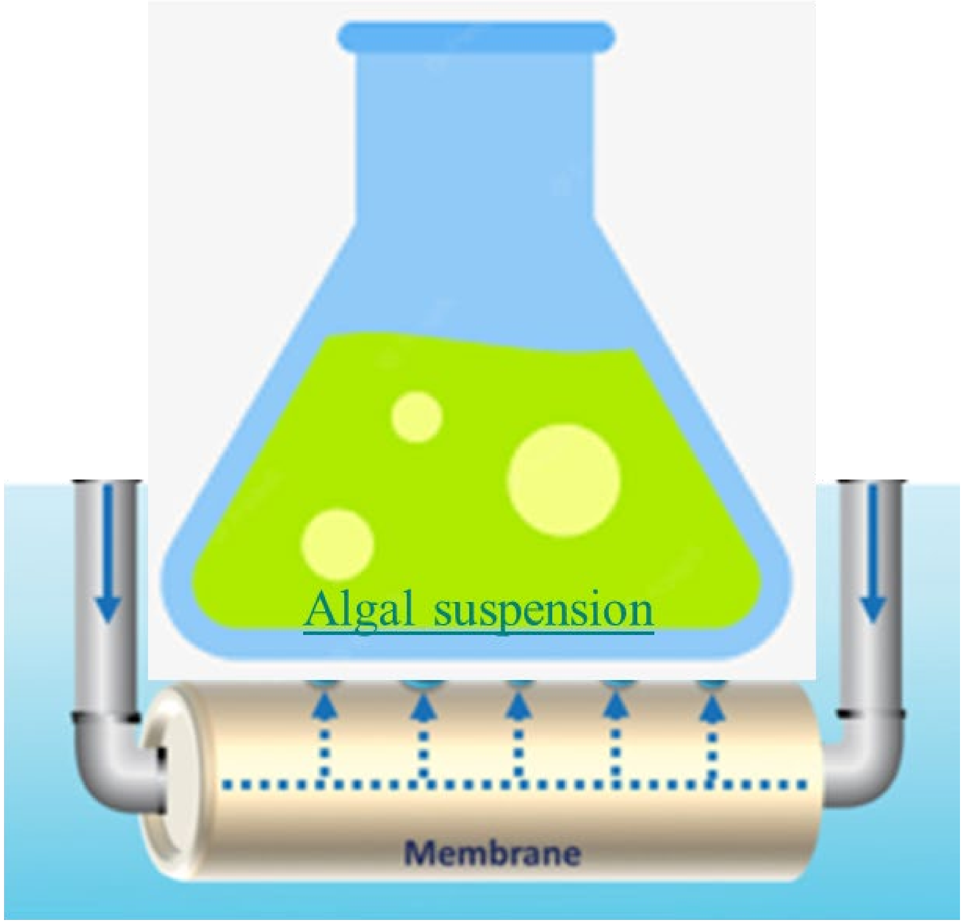
- Generate and optimize micro- and nano-bubbles of CO_2 dispersion;
- Determine key parameters such as bubble sizes and CO_2 flow or flux

Milestone 2.3 Generate CO_2 nanobubbles with concentrations of up to 1×10^8 bubbles$\cdot L^{-1}$;

Date: M12

Progress: Budget Period 1 Bench-scale and 9 L scale test



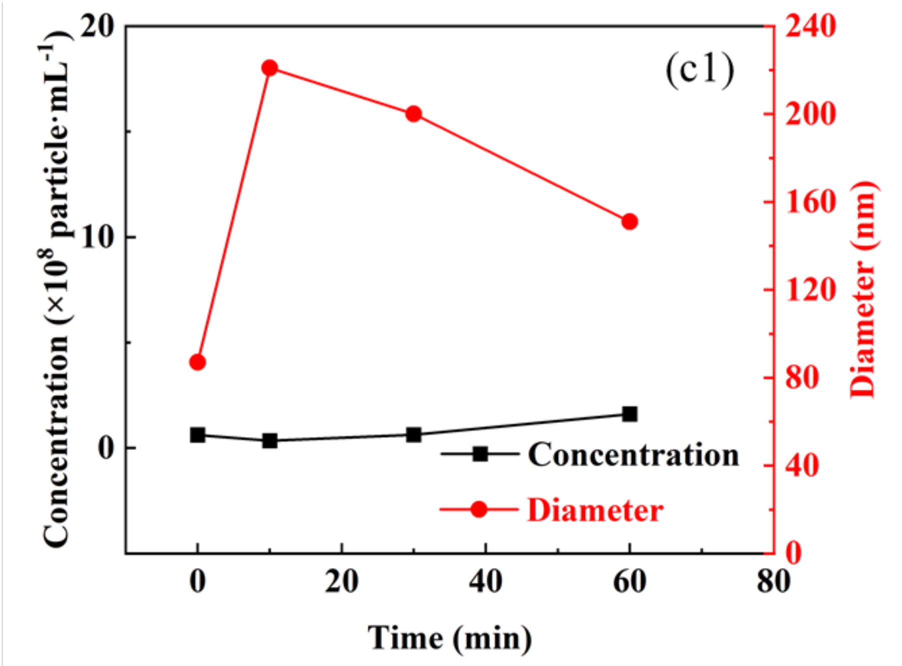


Wen Zhang's group at NJIT

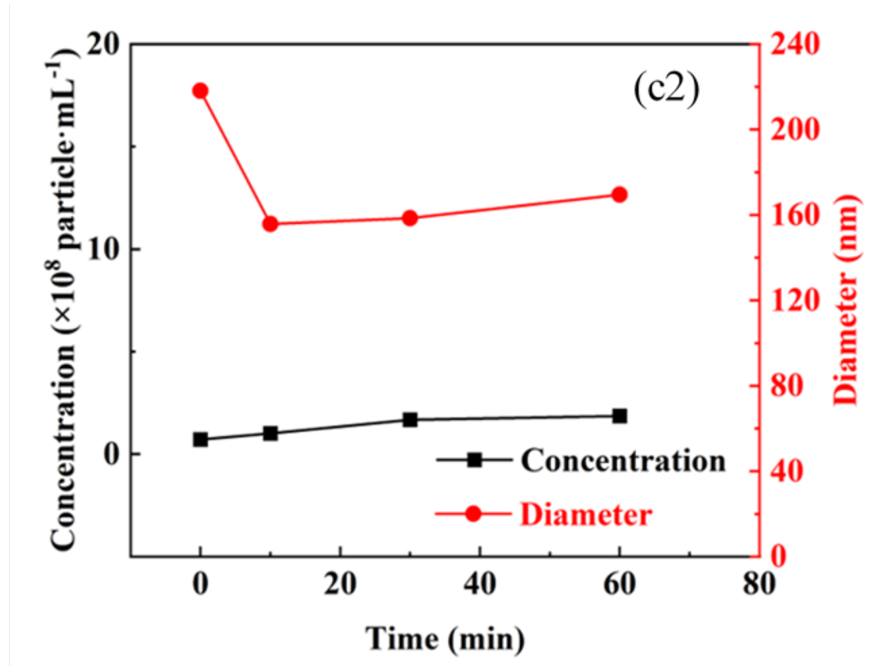
Progress: Budget Period 1 Bench-scale and 9 L scale test

Characterization of CO_2 nanobubbles in the **direct injection mode** with 10% CO_2

f/2 medium (for *Nannochloropsis*)



BG-11 medium (for *Scenedesmus*)



Wen Zhang's group at NJIT

Milestone 2.3 Generate CO_2 nanobubbles with concentrations of up to $1{\times}10^8$ bubbles$\cdot L^{-1}$

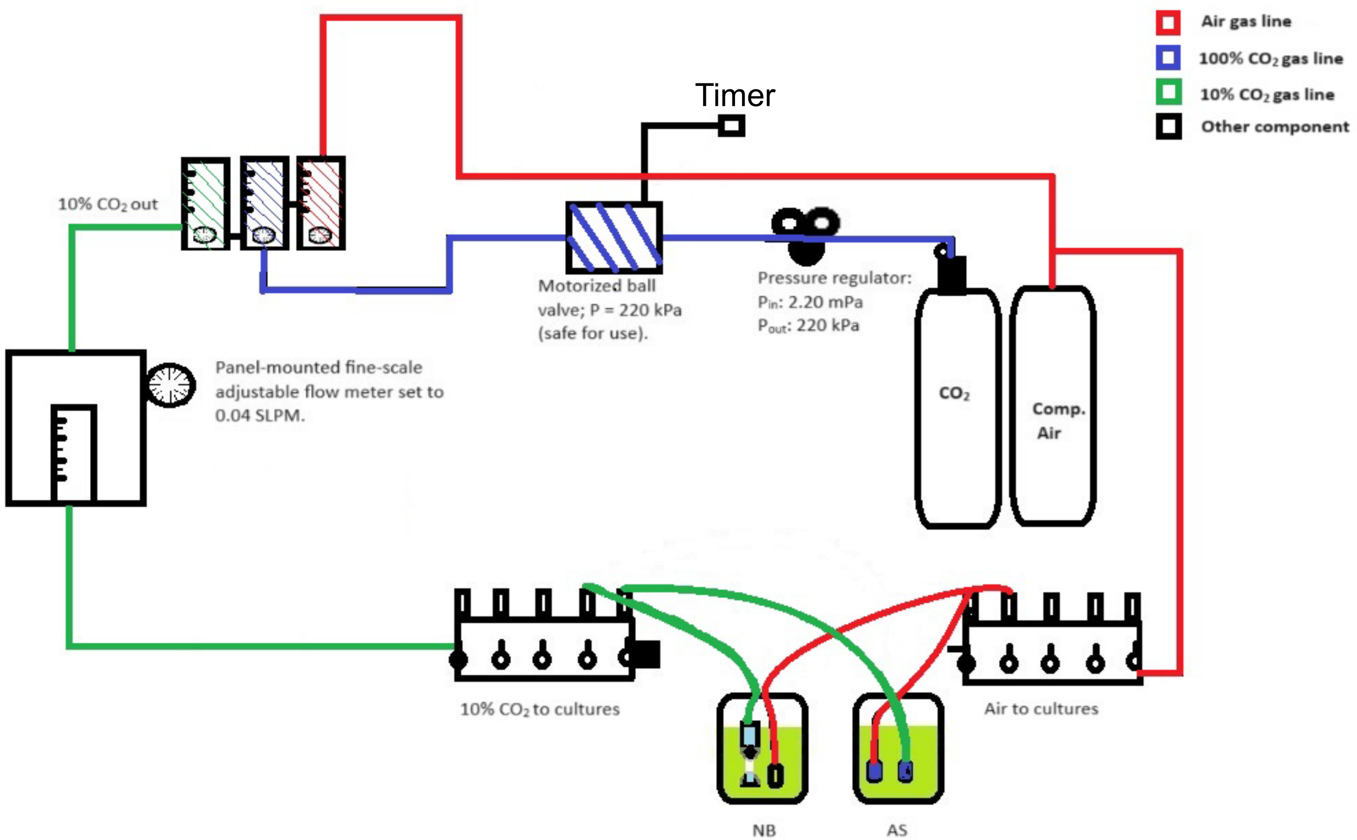
Progress: Budget Period 1 Bench-scale and 9 L scale test

BP1 Success Criteria

Determine the best combinations of urease and probiotic bacterial strains and bubbling mechanisms that facilitate an average productivity of 30 g/m^2/day and a CUE >50% (algae biomass) or >60% (algae and $CaCO_3$ precipitates) in lab culture and 9-L bioreactors.

Progress: Budget Period 1 Bench-scale and 9 L scale test

The design of the automated CO_2 sparging system



This system allows us to charge 10% CO_2 using a timer at set times. In this experiment, we set the system to charge 10% CO_2 for 5 minutes 8 times per day. Charging cultures with CO_2 multiple times per day manually can be very labor-intensive and difficult to manage for the long incubation experiments.

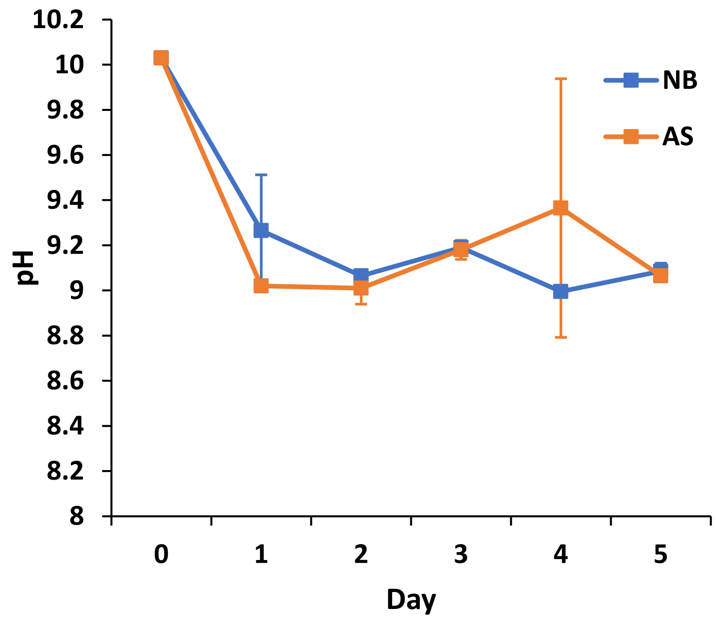
Feng Chen, Nick Gallagher, and Chen lab

Progress: Budget Period 1 Bench-scale and 9 L scale test

(n=2) Air stones (AS)

(n=2) Nanobubbles (NB)

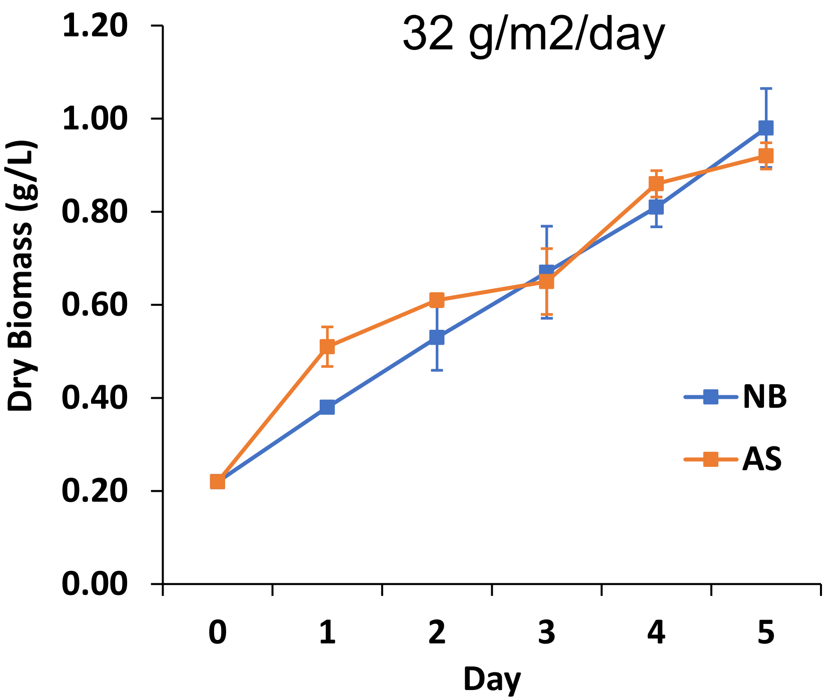
HTB1 cultures

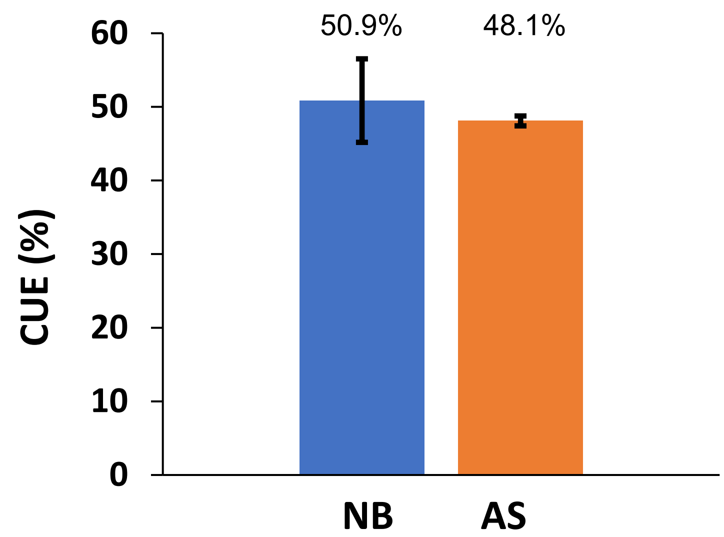


The pH remained relatively stable in both nanobubble and air stone cultures over five days of growth.

Feng Chen, Nick Gallagher, and Chen lab

Progress: Budget Period 1 Bench-scale and 9 L scale test

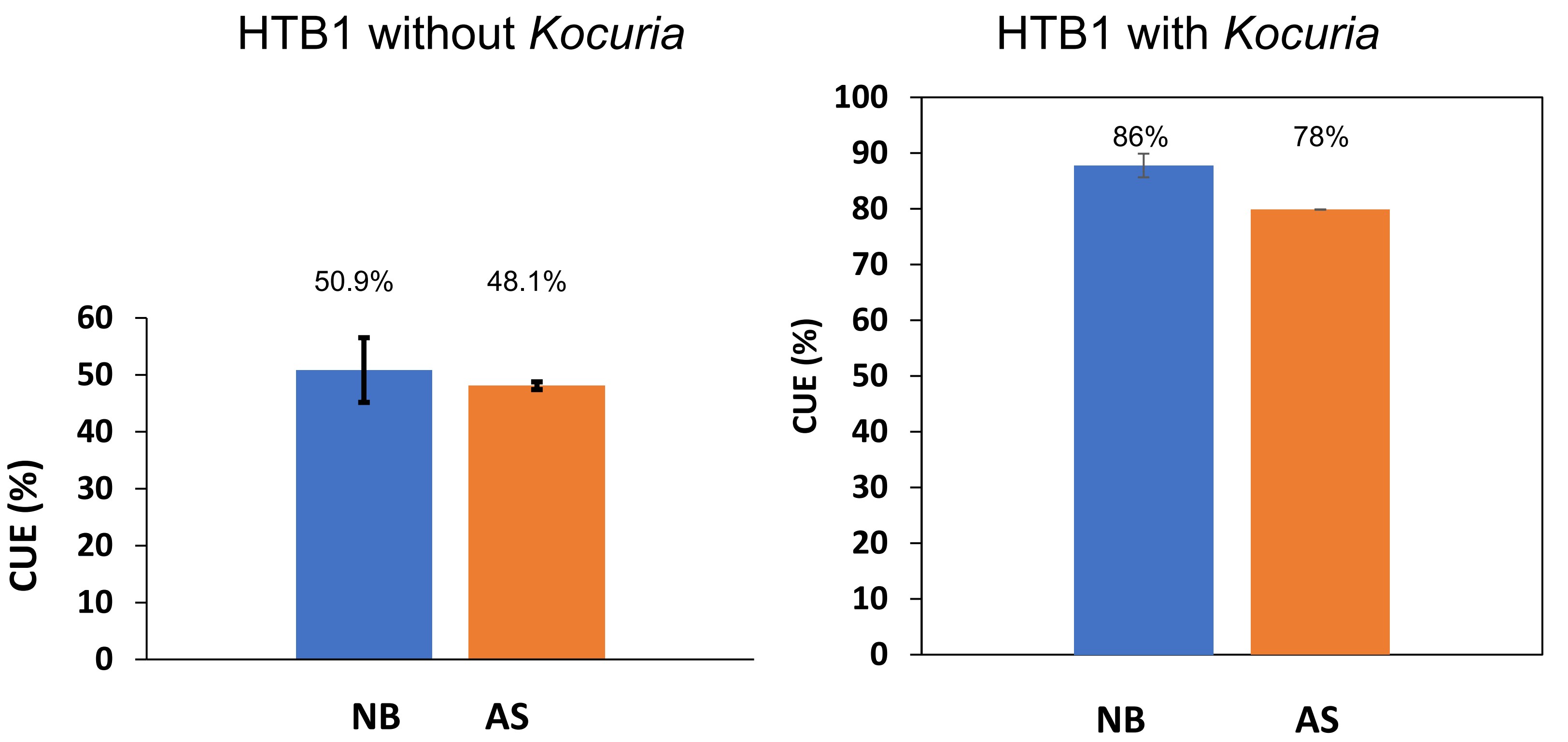




Growth of *S. obliquus* HTB1 and the carbon utilization efficiency (CUE).

Feng Chen, Nick Gallagher, and Chen lab

Progress: Budget Period 1 Bench-scale and 9 L scale test

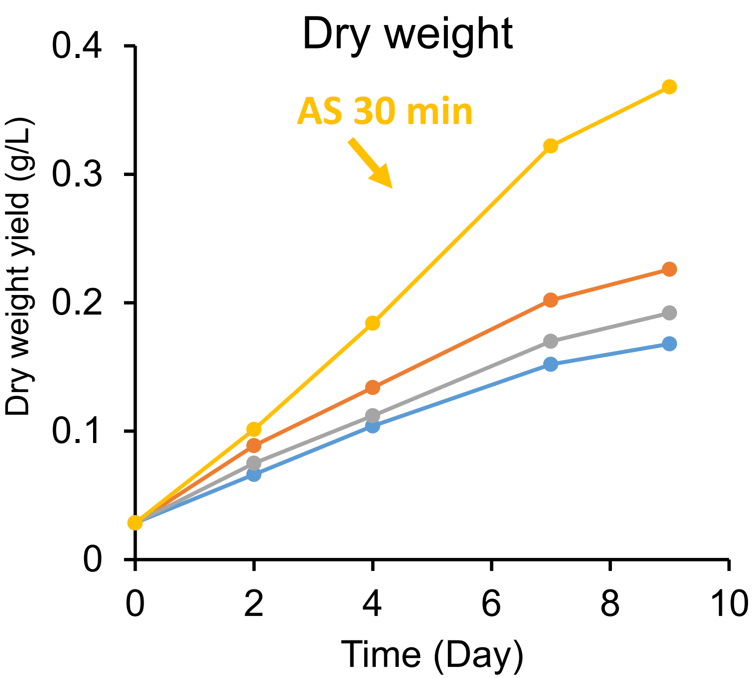


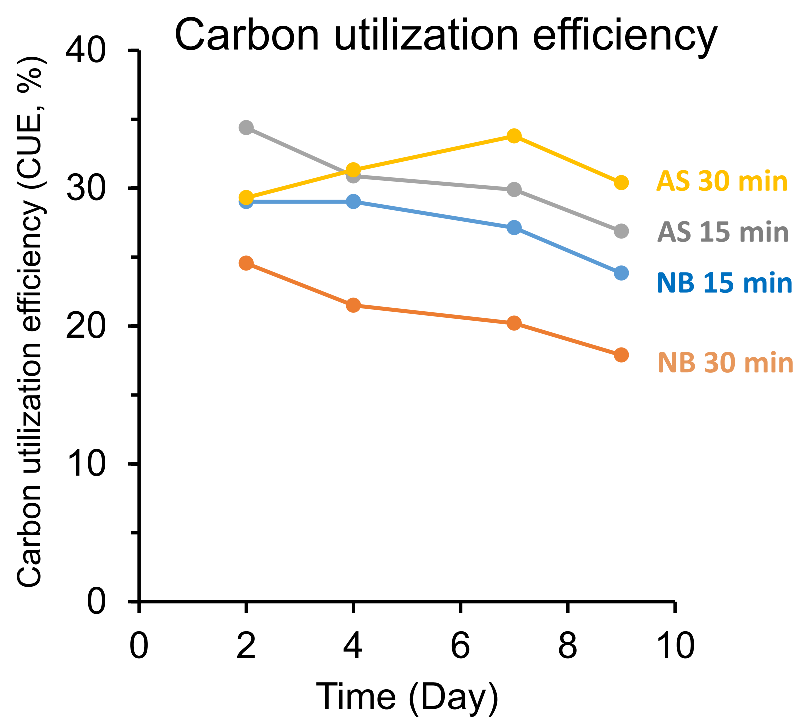
With addition of growth-promoting bacterium *Kocuria* sp., HTB grew faster and improved CUE by 35% for the NB treatment.

Feng Chen, Nick Gallagher, and Chen lab

Progress: Budget Period 1 Bench-scale and 9 L scale test

Nannochloropsis oceanica IMET1 grown with airstone (AS) or nanobubbles (NB)





For IMET1, nanobubbles do not seem to promote growth compared to air stone bubbles. CUE is in the range of 18-35%.

Yantao Li, Yi-Ying Lee and Li lab

Progress: Budget Period 1 Bench-scale and 9 L scale test

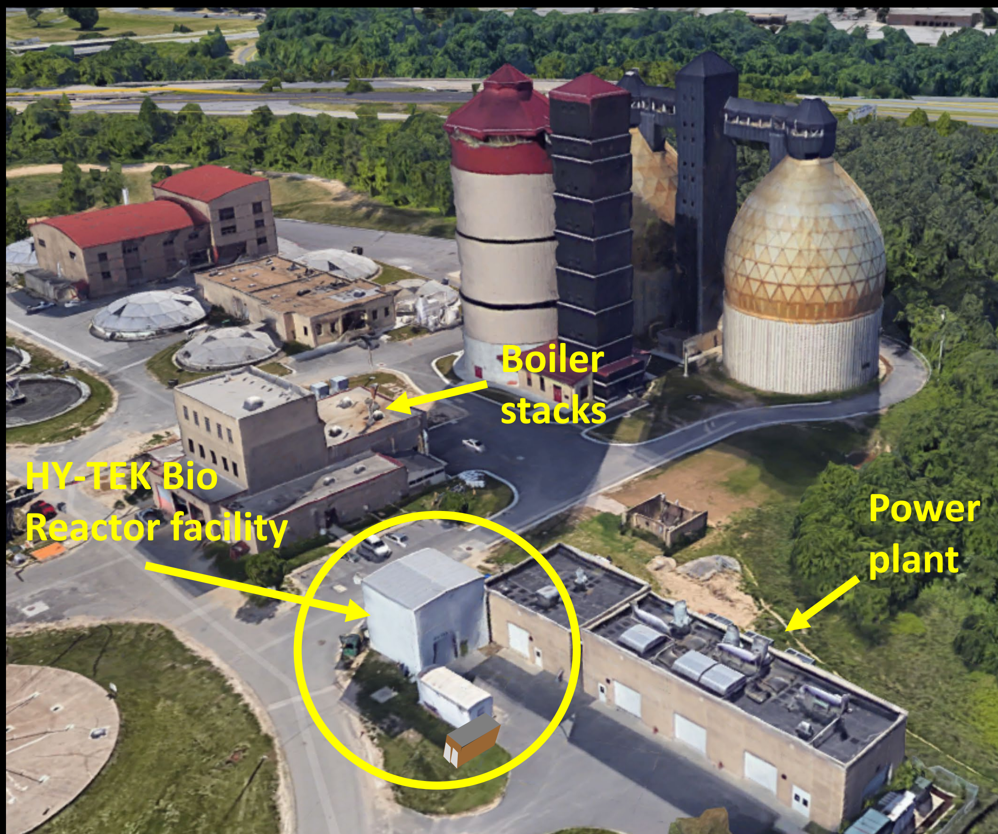
Subtask 2.4 **- Algal Culture Improvement at the flue gas site**

- Use 9-L bioreactor systems to clean flue gas with algae culture.

Subtask 2.5 **- Develop the frameworks for the TEA and LCA models**

- Develop frameworks of LCA and TEA models for sunlight-driven seawater and freshwater algal carbon sequestration systems.

HY-TEK Bio's Facility at the Back River Waste Water Treatment Plant



Current HTB site in operation for more than 8yrs

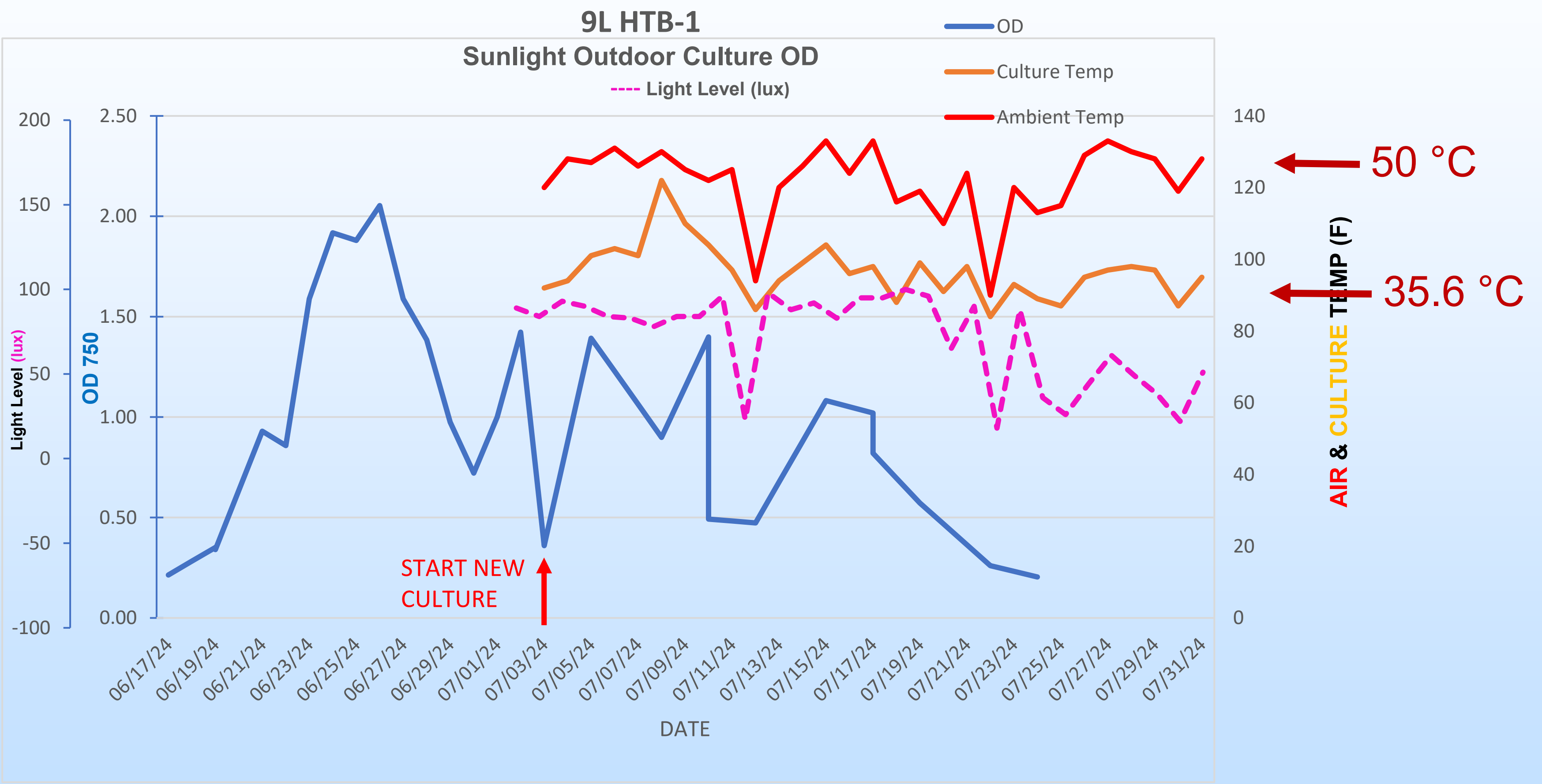
Robert Mroz's group at HY-TEK Bio

HY-TEK Bio’s Facility at the Back River Waste Water Treatment Plant

9-L Bioreactor tests

Robert Mroz’s group at HY-TEK Bio

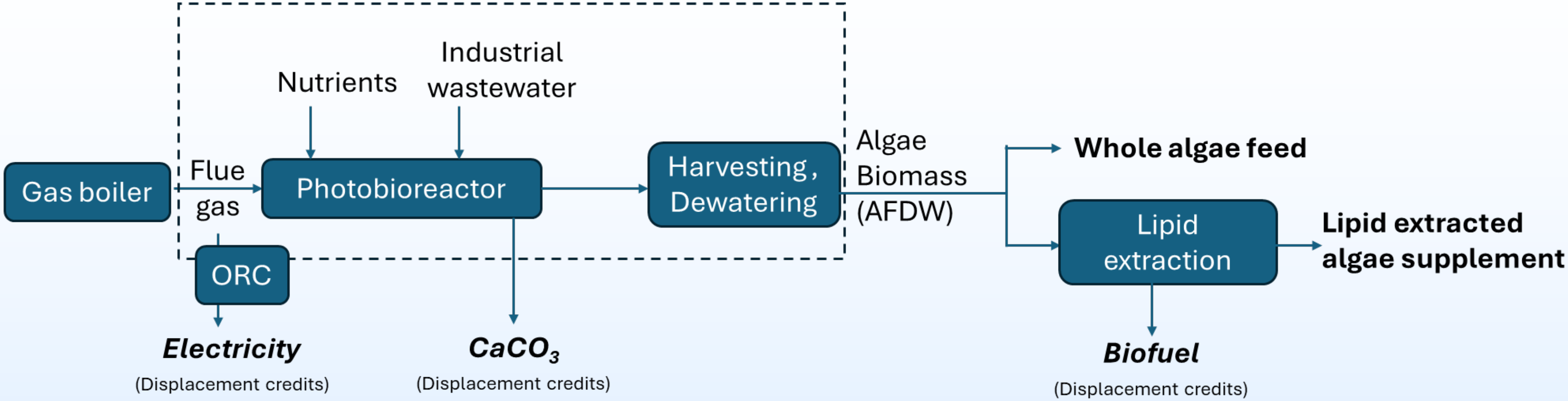
Progress: Budget Period 1 Bench-scale and 9 L scale test



Growth of HTB1 in the 9L outdoor bioreactor

Robert Mroz's group at HY-TEK Bio

Progress: Budget Period 1 Bench-scale and 9 L scale test



Screening-level LCA has been carried out for the outlined system boundary above. Based on system expansion approach, credits from calcium carbonate offset life cycle impacts for producing algae.

LCA metrics:

- Greenhouse gas (GHG) emissions (CO_2, CH_4, N_2O)
- Criteria air pollutant emissions (VOC, CO, NO_x, PM_{10}, $PM_{2.5}$, and SO_x)
- Fossil energy use
- Water consumption

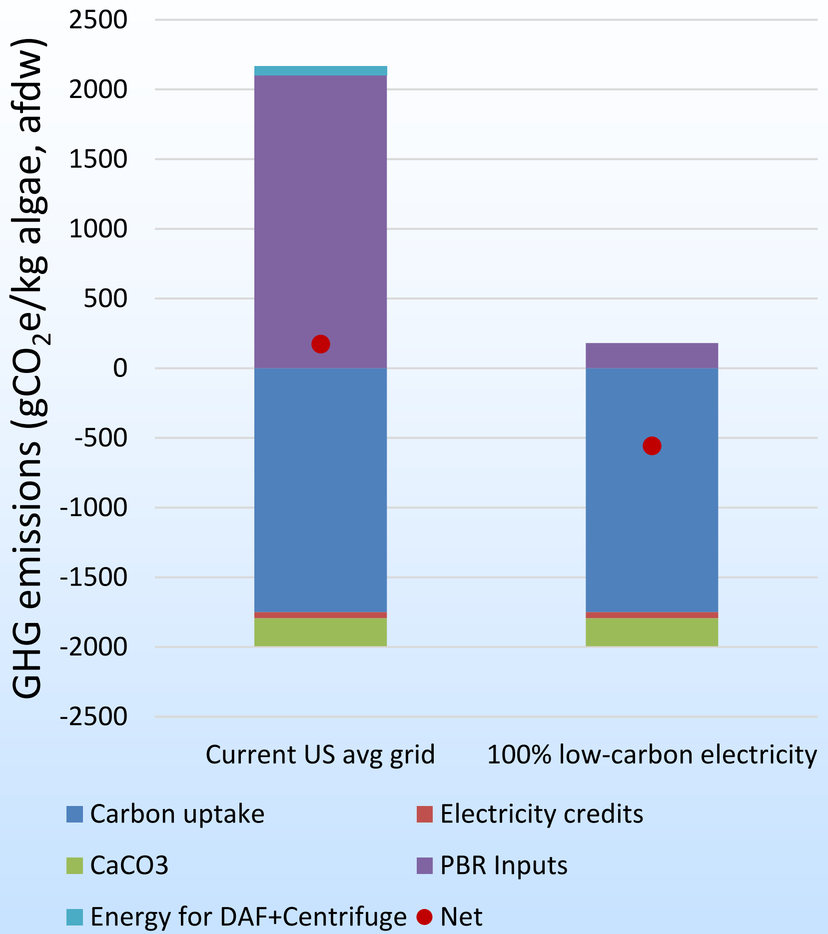
TEA metrics:

- Cost
- Return on investment
- Marginal cost of GHG avoidance

ANL Hawkins and Singh

LCA: Progress and Preliminary Findings

- LCA framework has been created using Argonne's GREET model as the background data
- Pilot data show electricity consumption of 0.93 kWh/kg algae (afdw); Water pump consumed 0.22 kW and the air compressor consumed 0.03 kW considering a water flow of 1 L/min
- Nutrient consumption: 0.42 kg-HNO_3 per kg-algae (dry) and P-nutrients equivalent to 0.041 kg-H3PO_4 per kg-algae (dry)
- Future work will update improved productivity values and investigate the impact of additional conversion steps for aquaculture feed



GHG emissions are estimated at 173 gCO_2e/kg algae when assuming current U.S. average emission factor but decarbonizing grid may bring down emissions to -557 gCO_2e/kg algae

ANL Hawkins and Singh

Plans for future work- BP1

Milestone Title	Planned Completion date	Actual Completion date	Verification Method	Comments
Milestone 2.1: Isolate and confirm the identity of >5 urease-producing bacteria and >5 probiotic bacterial strains for *Nannochloropsis oceanica*	Month 15	N/A	Via Quarterly Reports submitted to DOE Project Officer	100% completion
Milestone 2.2: Isolate and confirm the identity of >5 urease-producing bacteria and >5 probiotic bacterial strains for *Scenedesmus obliquus*	Month 15	N/A	Same as above	100% completion
Milestone 2.3: Generate CO2 nano-/micro-bubbles with concentrations of up to 1×10^8 bubbles$\cdot L^{-1}$	Month 12	2/14/2024	Same as above	100% completion
BP1success criteria: Determine the best combinations of urease and probiotic bacterial strains and bubbling mechanisms that facilitate an average productivity of 30 $g/m^2/day$ and a CUE >50% (algae biomass) or >60% (algae and $CaCO_3$ precipitates) in lab culture and 9-L bioreactors.	Month 18	N/A	Same as above	70% completion

Six-month NCTE requested, and no extra fund requested.

Summary

- **Obtained >5 urease-producing bacteria and >5 probiotic bacteria for *Nannochloropsis* and *Scenedesmus*, respectively.**
- ***Scenedesmus* culture with nanobubbles from simulated flue gas, reached a CUE greater than 50%.**
- **With addition of probiotic bacteria (Kocuria sp.), HTB1 improved growth and the CUE reached 86% with nanobubbles.**
- **Next step is to set up algal culture in 9 L outdoor bioreactors at the flue gas site (HY-TEK Bio's facility) to monitor the growth and CUE.**

Appendix

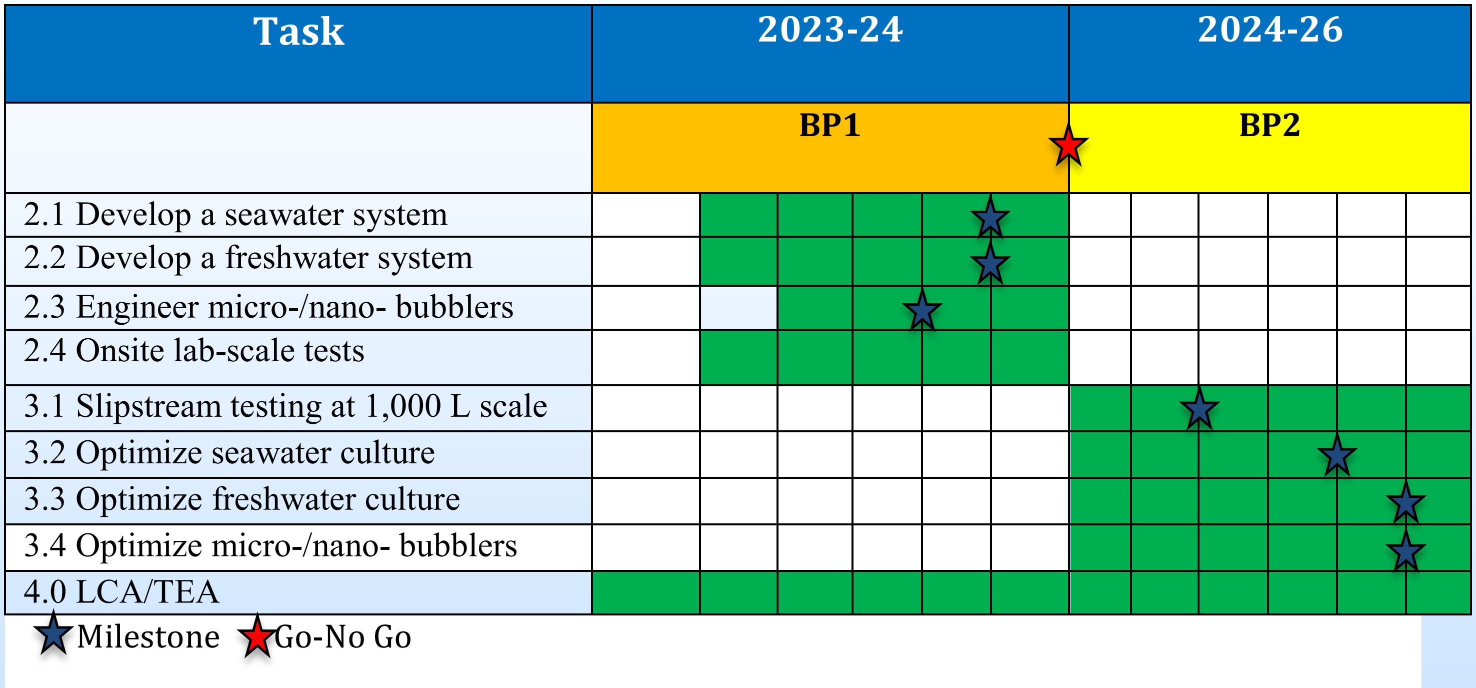
– These slides will not be discussed during the presentation but are mandatory.

Organization Chart

No.	/Tasks	/Subtasks and PIs responsible for the task	Teams responsible
1.1 1.2	Project Management and Planning	• Project Management Plan ***(Li working with all PIs)*** • Project Reporting ***(All PIs)***	UMCES is the lead on this task.
2.1, 2.2, 3.2, 3.3.	Bench-scale development of a saltwater and a freshwater system and culture microbiome optimization	• Saltwater algal carbon sequestration system ***(Li and Hill)*** • Freshwater algal carbon sequestration ***(Chen and Hill)***	UMCES is the lead on this task.
2.3, 3.4	Development and testing of bubblers in the lab and upscaled algal systems	• Optimization of microbubbles and nanobubbles in lab cultures ***(Zhang)*** • Bubbler optimization at 1,000 L scale ***(Zhang)***	NJIT is the lead on this task.
2.4, 3.1	Slipstream testing of the algal carbon sequestration system at the Back River wastewater treatment plant	• Bioreactor test on site (at the wastewater treatment plant) at 9 L scale ***(Mroz)*** • Slipstream test at 1,000 L scale ***(Mroz)***	HY-TEK Bio is the lead on this task.
4.0	Development of TEA and LCA models to evaluate and guide research and testing activities.	• Develop the frameworks for the TEA and LCA models ***(Hawkins)*** • Perform contribution analysis, benchmarked against other conventional algae processes ***(Hawkins)***	Argonne National Lab is the lead on this task.

Gantt Chart

Project Schedule (Gantt chart)*



* Start date was Feb. 15, 2023; each block represents one quarter (3-month). At the end of the first BP, there is a Go-No Go decision point.