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

2023 Carbon Management Research Project Review Meeting
August 28 – September 1, 2023

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), 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

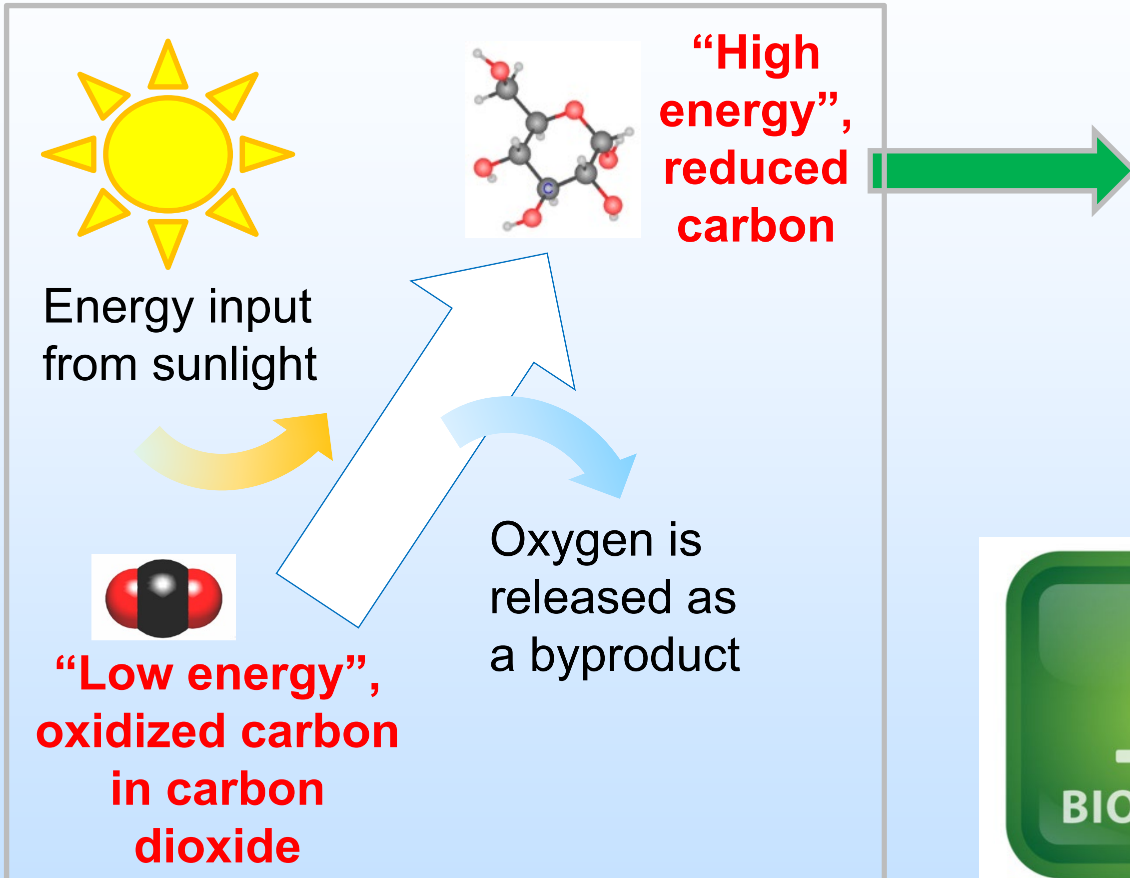
  DOE NETL Program Manager: **Zachary Roberts**

Project Overview

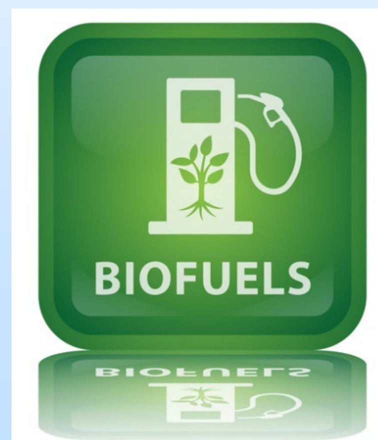
– Overall Project Objectives

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

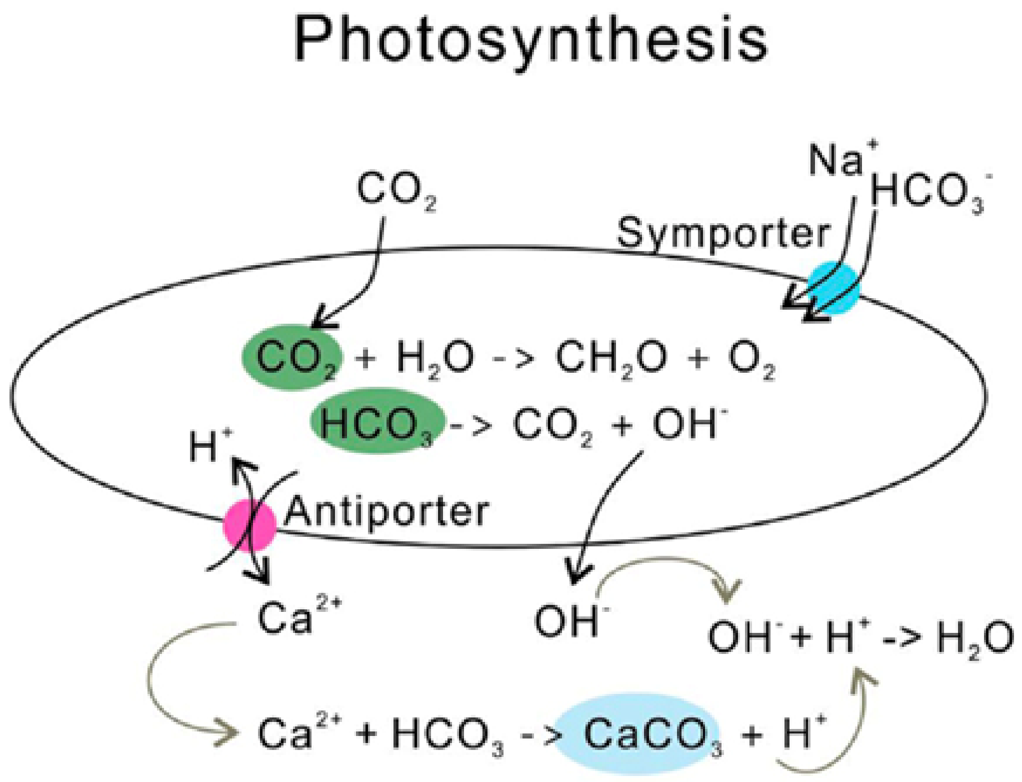


$$6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2$$



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/.

Microalgal Carbon Capture and Biomass Production: Microalgae-driven carbon dioxide mitigation (MadCom)



$$CO_2 + H_2\,O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + \; HCO_3^- \rightleftharpoons 2H^+ + CO_3^{2-}$$

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

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

Microalgae-driven carbon dioxide mitigation in nature: Whiting events

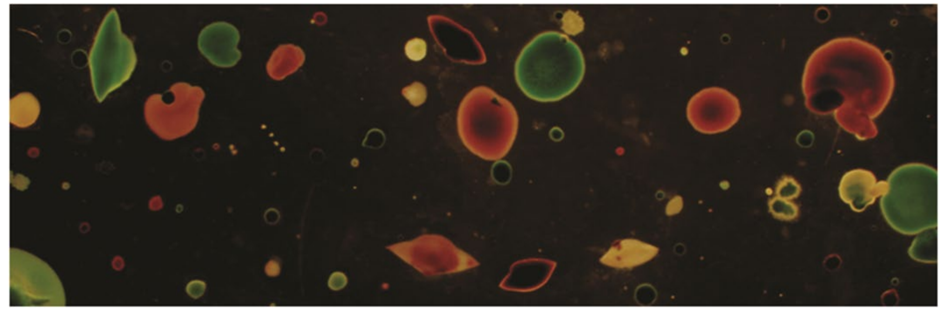
13-year data, Florida Whitings visible in MODIS images on about 14% of time each year

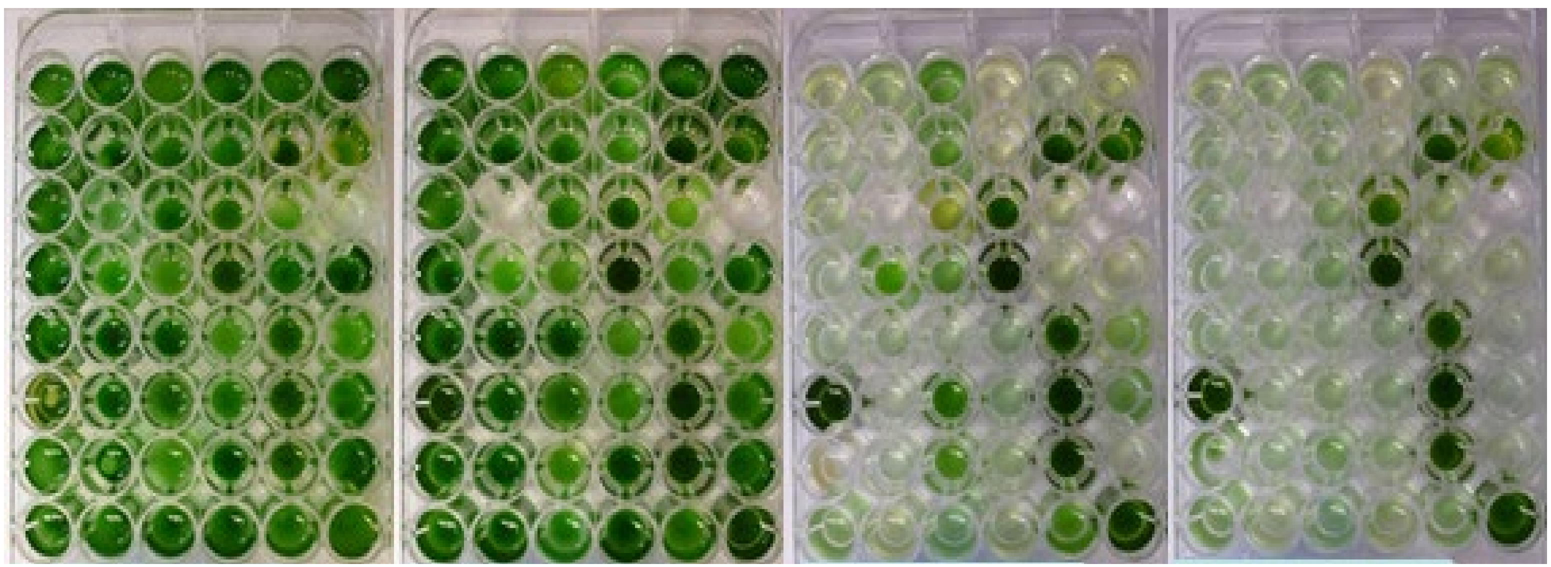
https://earthobservatory.nasa.gov/images/91807/making-sense-of-whiting-events
Escoffier, N. et al. 2022. Journal of Geophysical Research: Biogeosciences.

Marl from lake bottom (Courtesy of Larry Bean, rock collector, Livonia, Michigan.), https://www.michigan.gov/

Algal Strain Selection under Simulated Flue Gas

Nannochloropsis oceanica IMET1 and *Scenedesmus obliquus* HTB1 were selected

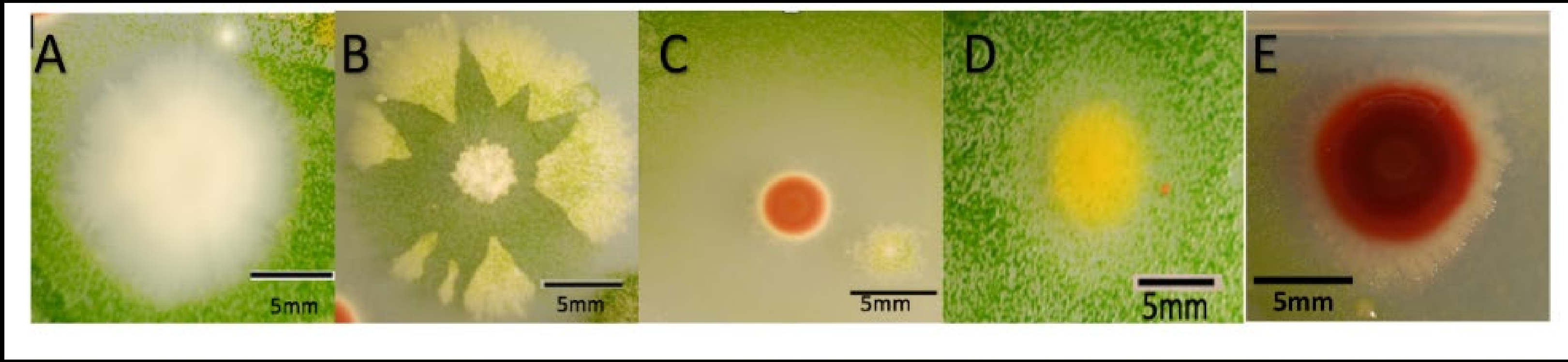




2% CO_2 5% CO_2 10% CO_2 20% CO_2

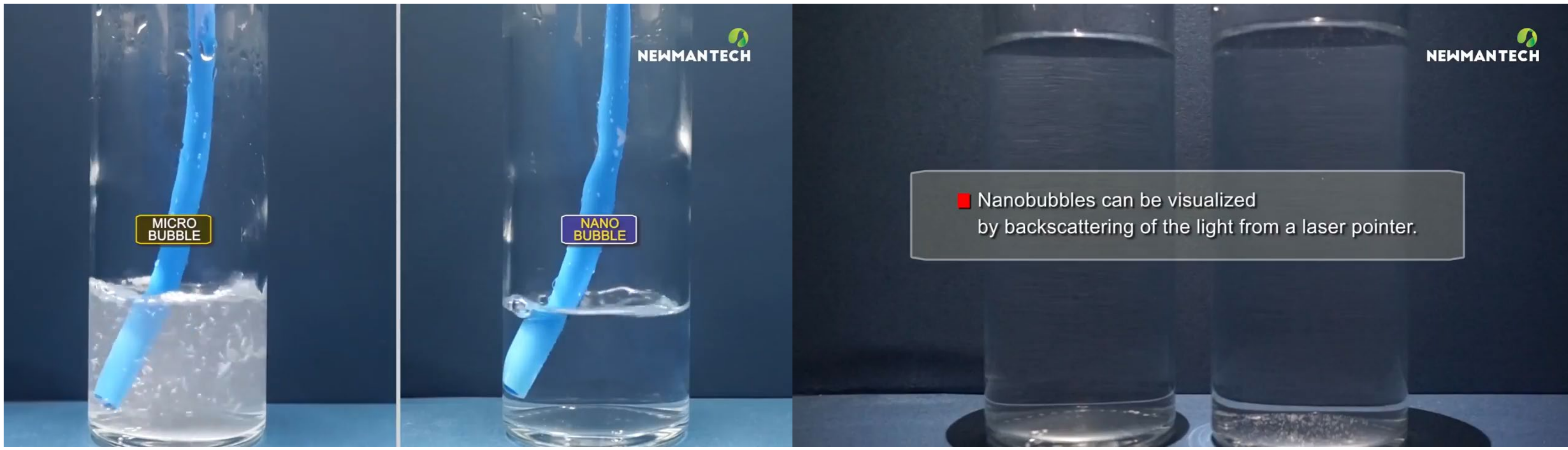
Dr. Feng Chen, UMCES

Microbial interactions in non-axenic microalgal cultures

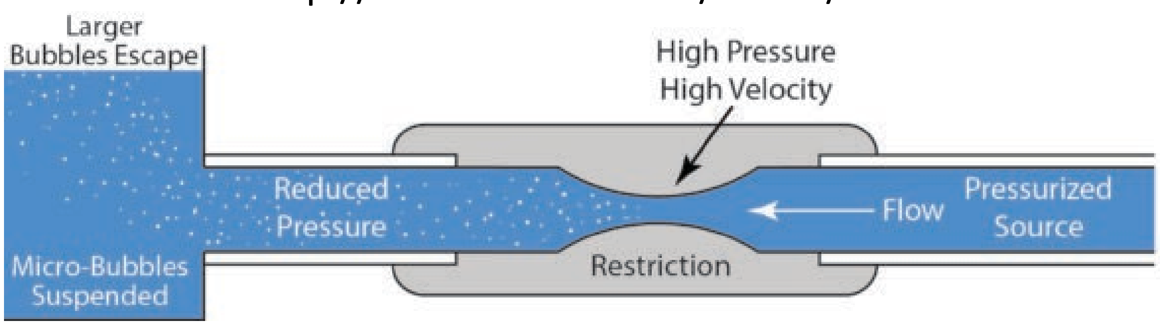


Lin, Lee, Li and Hill.

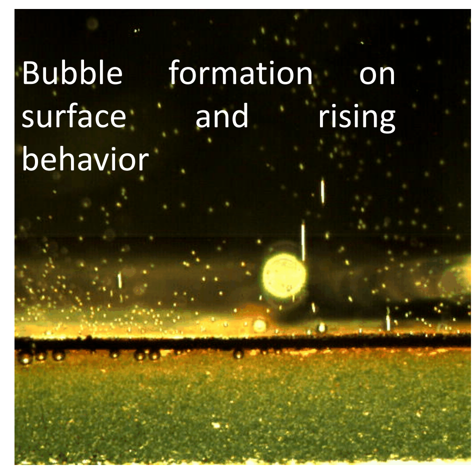
Microbubbles and nanobubbles to improve carbon utilization efficiency (CUE)



Video sources: http://newmantech.co.kr/nanoe/



https://techblog.ctgclean.com/2019/01/the-case-for-micro-bubbles-in-cavitation/

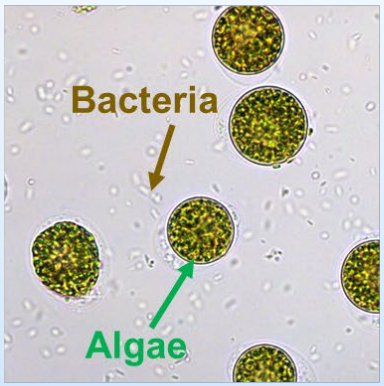


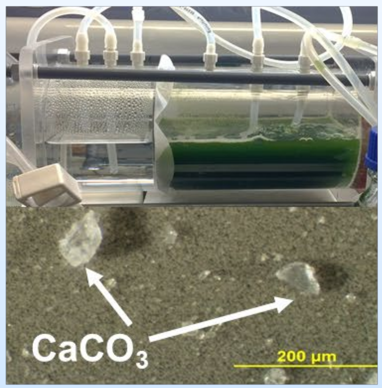
Wen Zhang and NJIT team

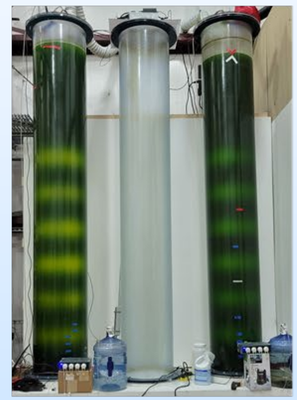
Proposed Microalgae-driven carbon dioxide mitigation TRL

CO_2 capture/Year

10^{-19}	10^{-3}	10^{-1}		10^{8}-10^{9} (ton)
Basic principle observed	Lab-scale TRL 3	Pilot-scale TRL 6	?	Whiting events scale



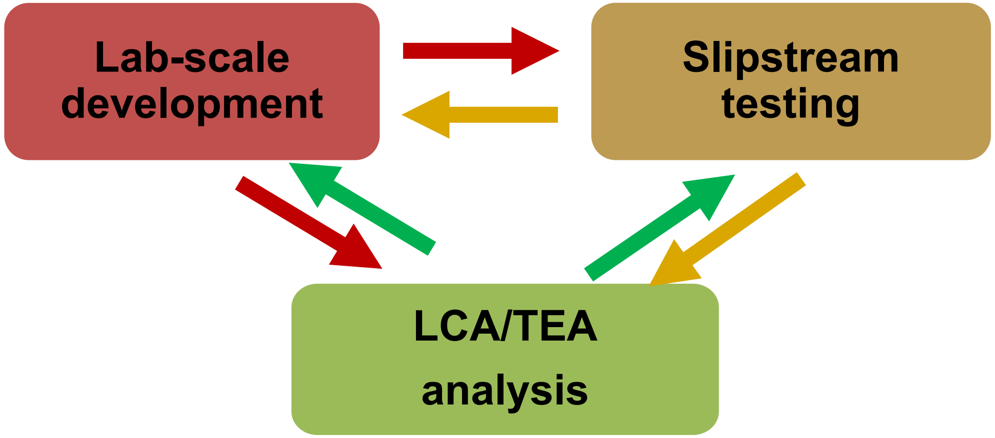




Algae-bacteria cell-cell interactions	Lab-scale Reactors	Pilot-scale reactors (1,000 L scale)	Natural Whiting events
10^{-15}	10^{1}	10^{3} (L)	10^{13}

System volume

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

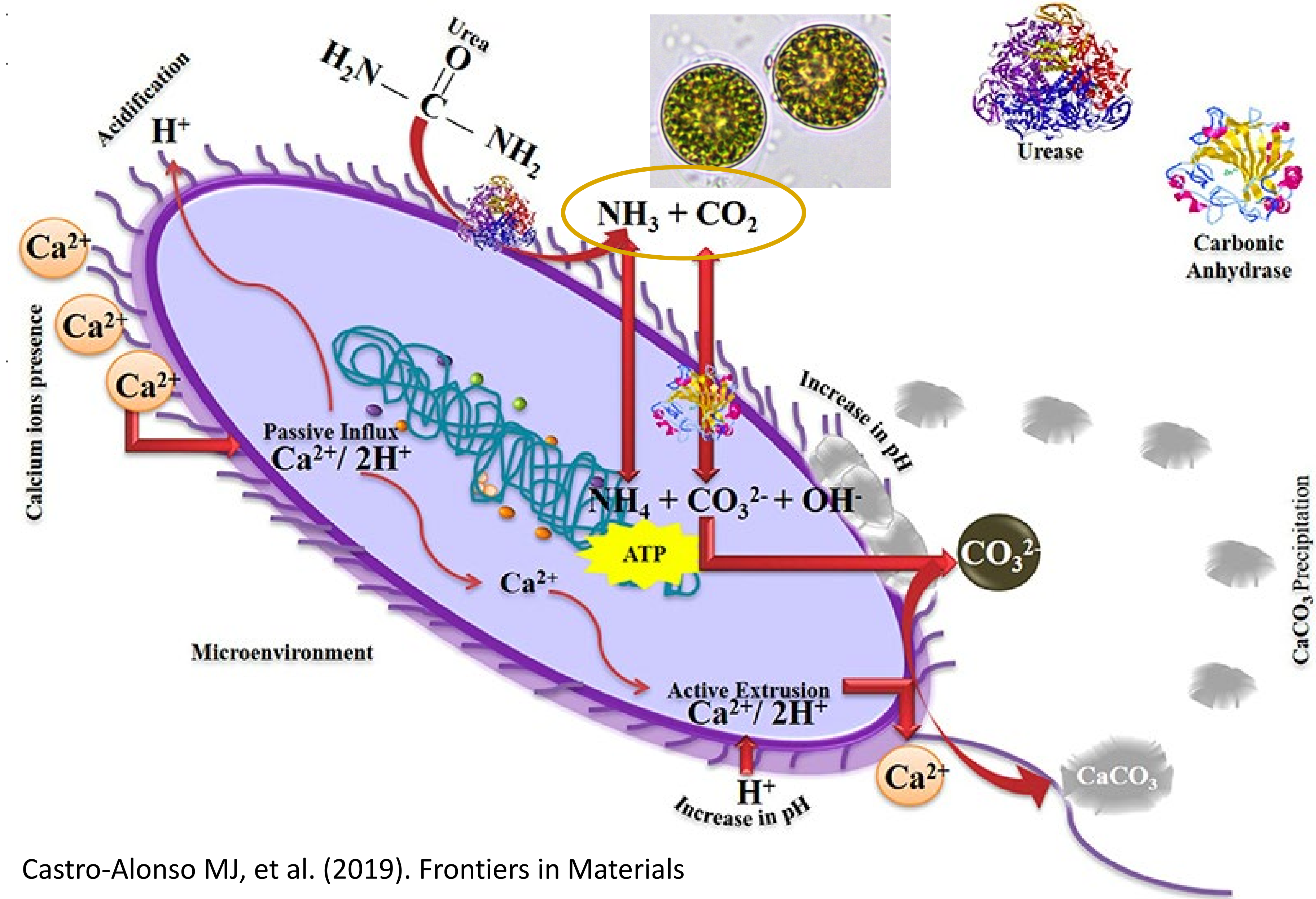
Progress: Budget Period 1 Bench-scale and 9 L scale test

***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.

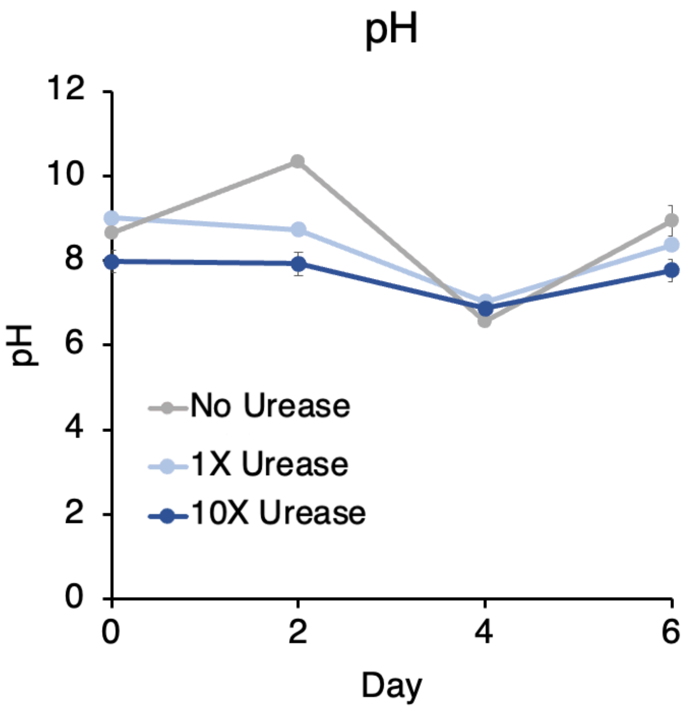
Milestone 2.2 Isolate and confirm the identity of >5 urease-producing bacteria and >5 probiotic bacterial strains for *Scenedesmus* HTB1; Date: M15

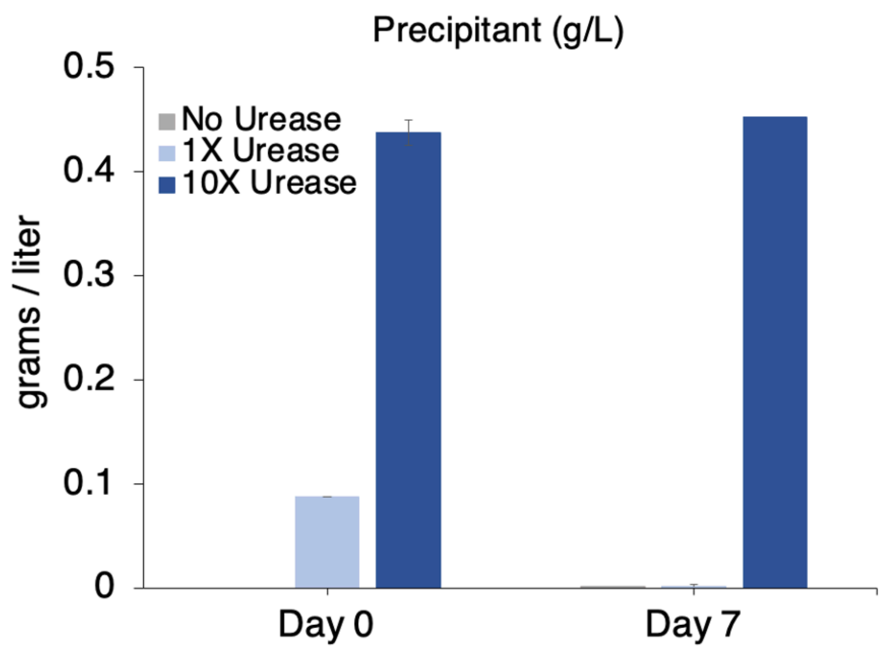
Progress: Budget Period 1 Bench-scale and 9 L scale test



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

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

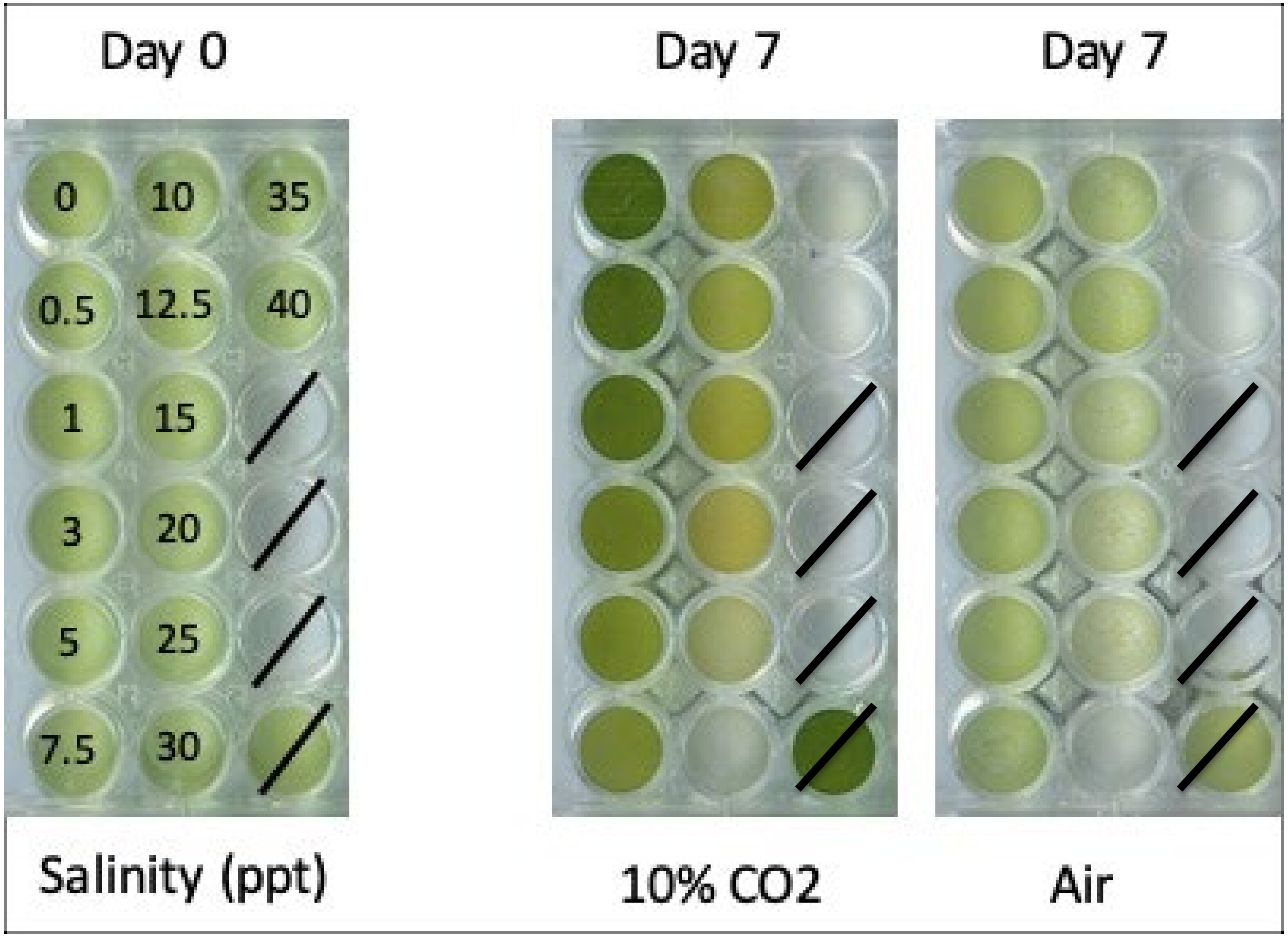




Russell Hill, Lauren Jonas and Hill Group

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

***Scenedesmus* HTB1 tolerates varying salinity gradients and produces carotenoids**



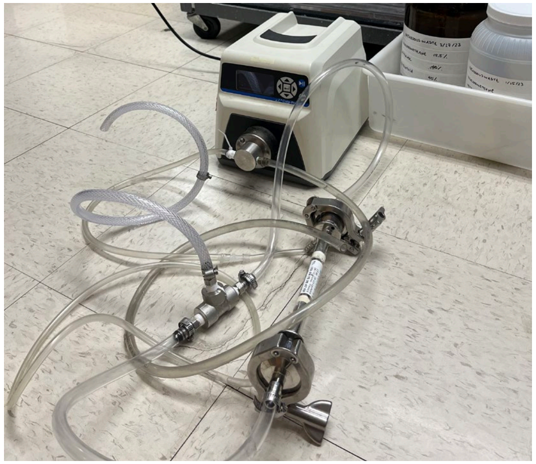
Feng Chen and Chen team

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

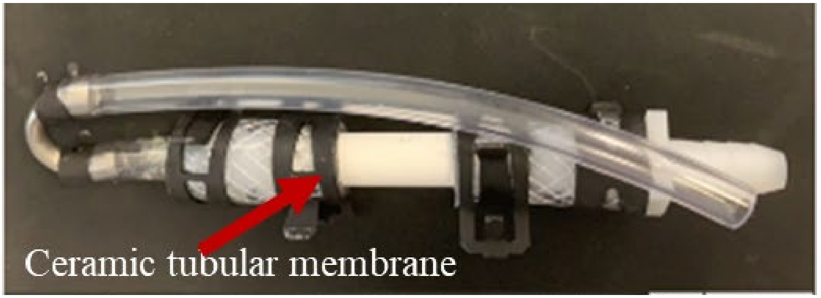
***Subtask 2.3* - Development and testing of bubblers**

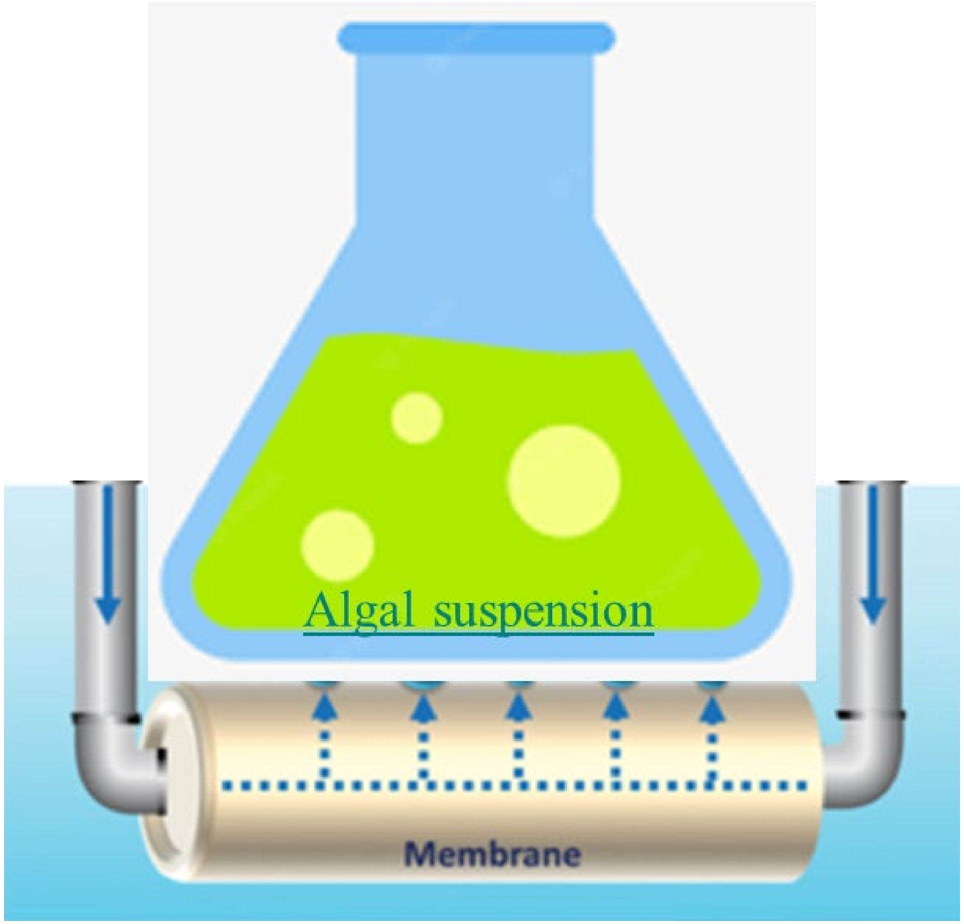
- Generate and optimize micro- and nano-bubbles of CO_2 dispersion;
- Determine key parameters such as bubble sizes and CO_2 flow or flux

Milestone 2.3 Generate CO_2 nanobubbles with concentrations of up to 3×10^{14} bubbles·L^{-1} and sizes ranging from 300 nm to 1 µm in diameter and microbubbles with concentrations of up to 1×10^{8} bubbles·L^{-1} and sizes ranging from 10 to 100 µm; Date: M12



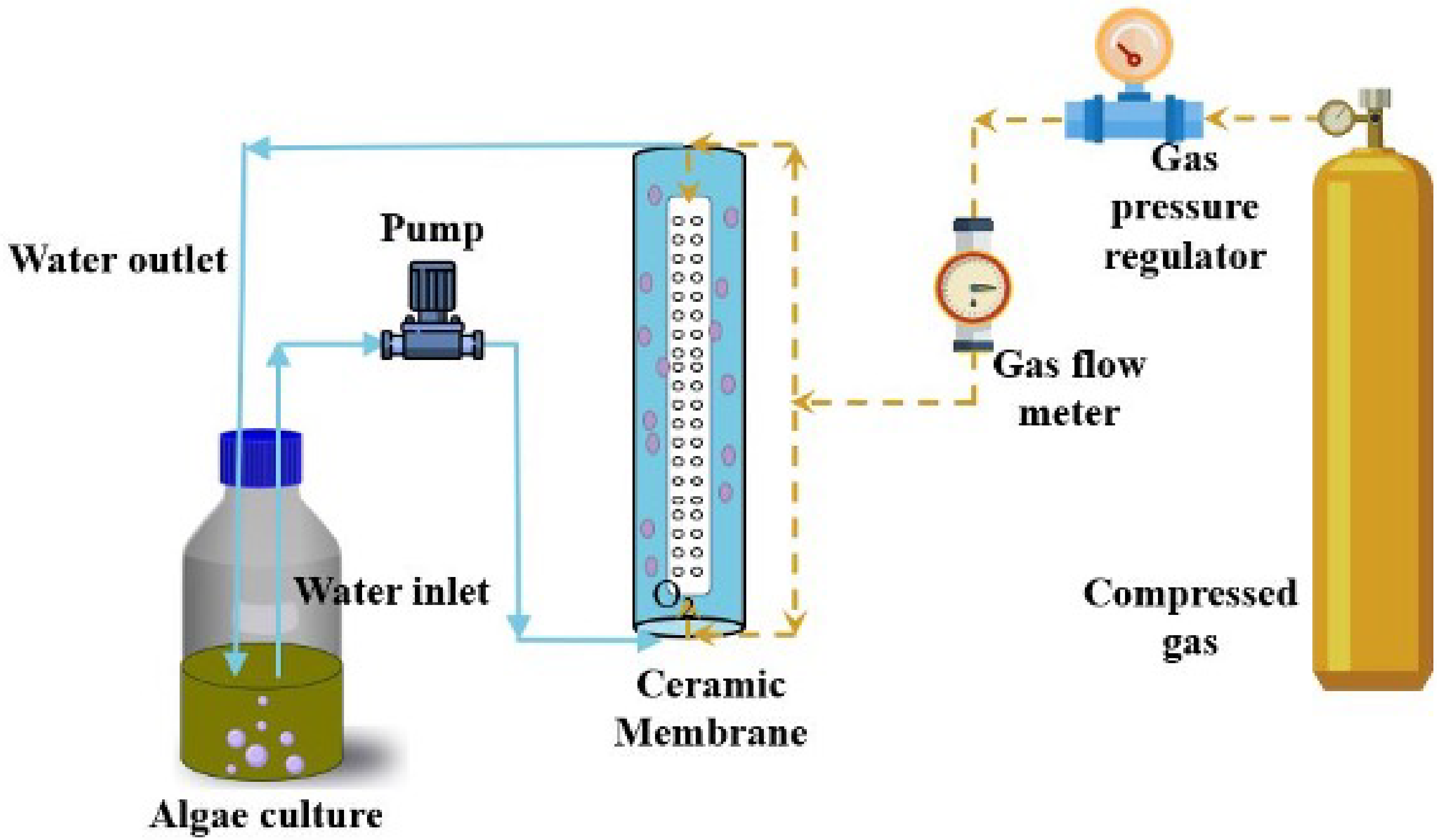
Progress: Budget Period 1 Bench-scale and 9 L scale test





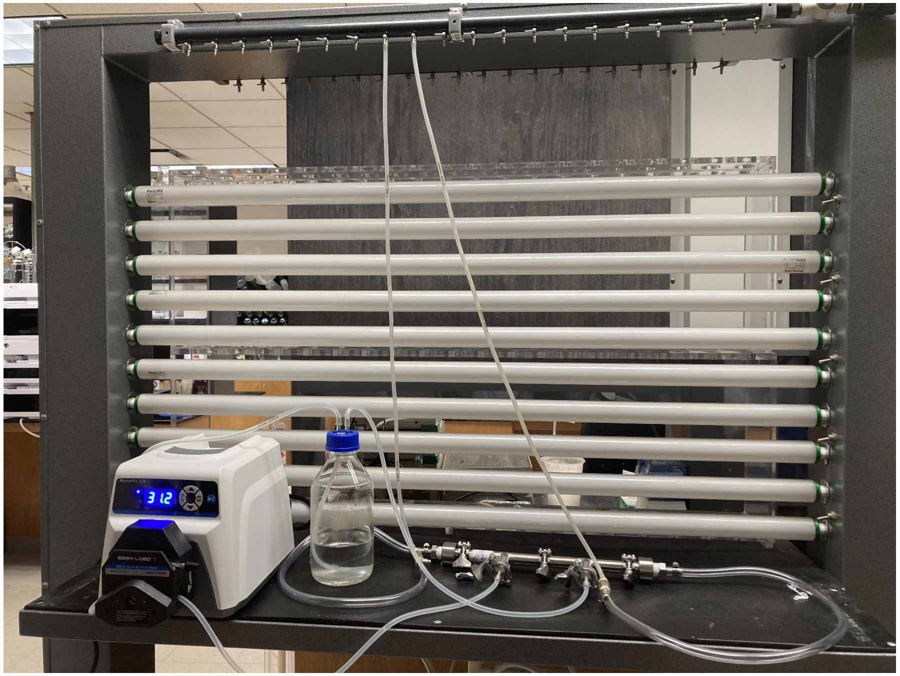
Wen Zhang and NJIT team

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

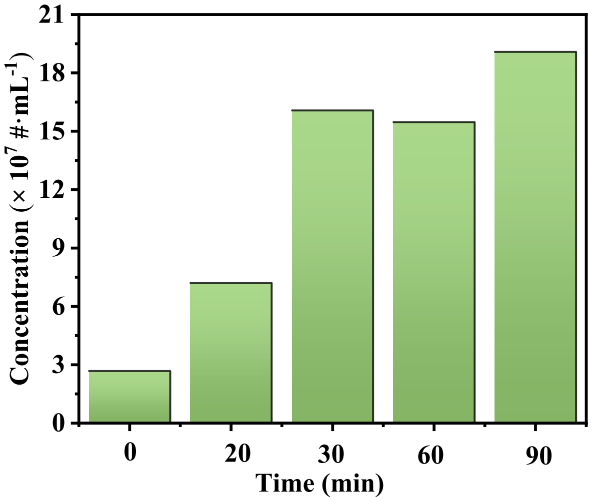


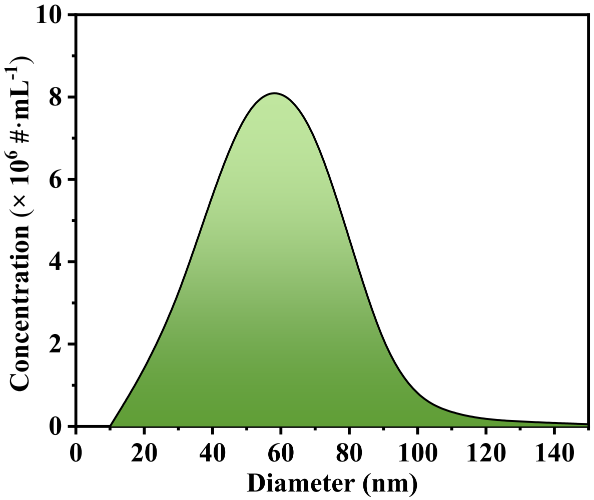
Wen Zhang and NJIT team

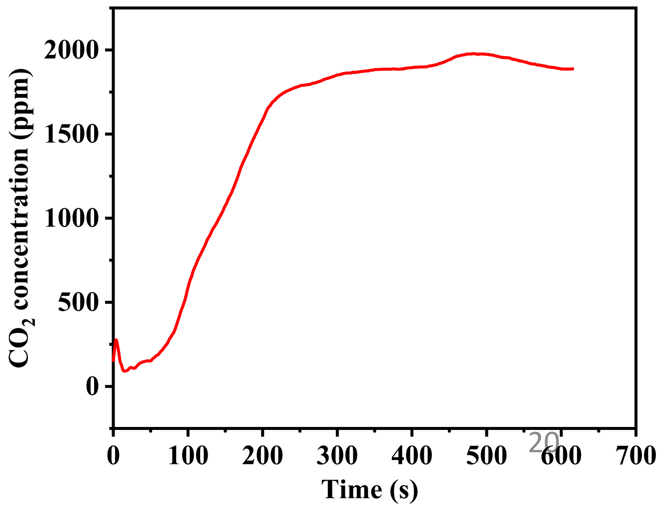
Progress: Budget Period 1 Bench-scale and 9 L scale test



1. Using pure CO_2, the observed dissolved CO_2 in the nanobubble water suspension is near 2,000 ppm, which corresponds to a partial pressure of **1.18 atm** (the injection pressure is 145 kPa or 1.43 atm).
2. The ambient air solubility under one atm can provide only **0.0004 atm** of the partial pressure of CO_2. Thus, the nanobubbles of CO_2 increases the partial pressure up to 1.18 atm and resulted in nearly **3,000 times** of the CO_2 solubility under ambient air.







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

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

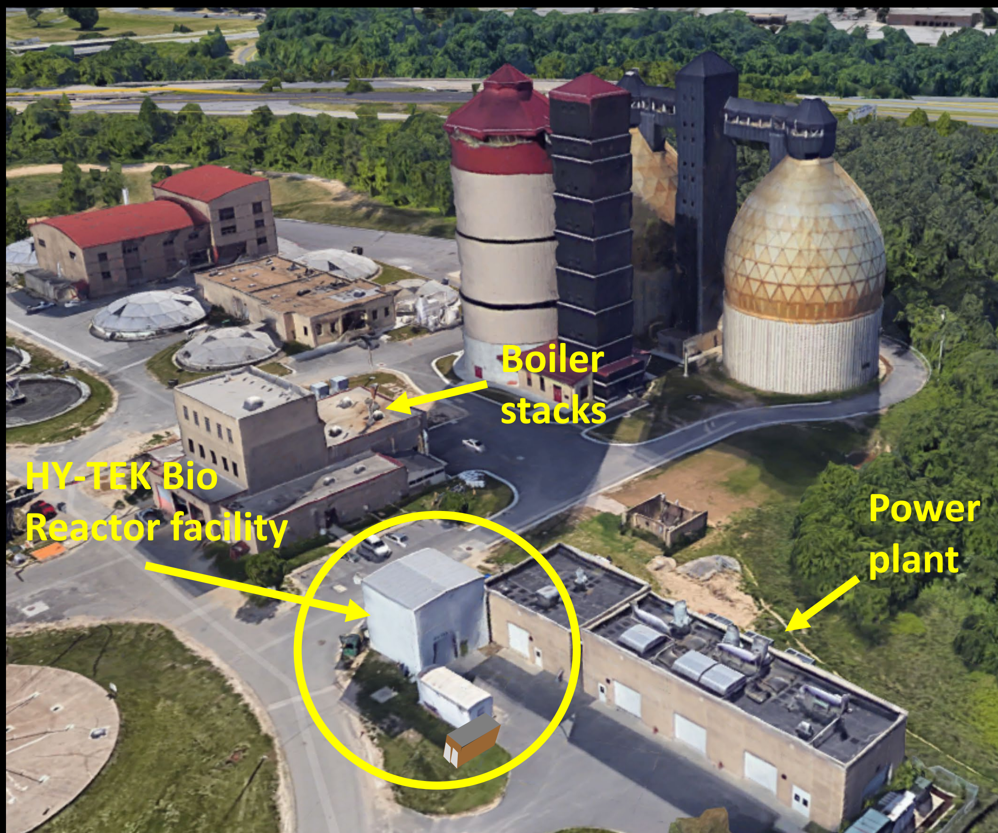
- Use 9-L bioreactor systems to clean flue gas with algae culture.

***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.

BP1 Success Criteria: Determine the best combinations of urease and probiotic bacterial strains and bubbling mechanisms for *S. obliquus* HTB1 and *N. oceanica* IMET1 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. Date: M18

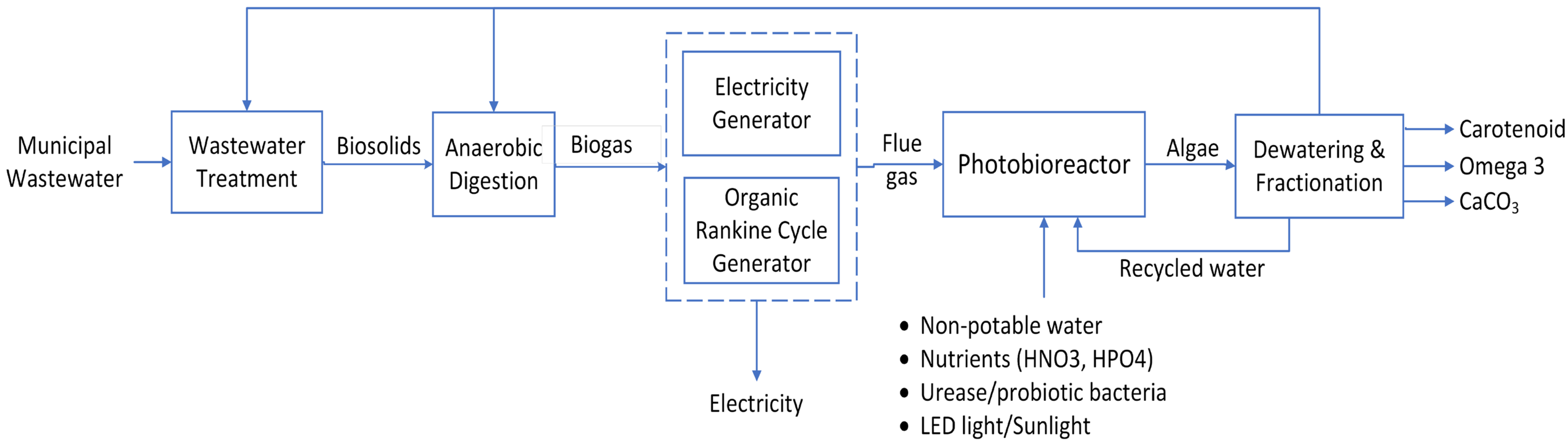
HY-TEK Bio's Facility at the Back River Waste Water Treatment Plant



Current HTB site in operation for more than 8yrs

Robert Mroz and HY-TEK Bio Team

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



LCA and TEA hotspots: to identify environmental and cost hotspots and provide feedback to the team members to improve the process design

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

Troy Hawkins, Ed Weinberg, Udayan Singh, and Farah Naaz

Plans for future work- BP1

Milestone Title	Planned Completion date	Actual Completion date	Verification Method
<u>*Milestone 2.1:*</u> Isolate and confirm the identity of >5 urease-producing bacteria and >5 probiotic bacterial strains for *Nannochloropsis oceanica* IMET1	Month 15	N/A	Via Quarterly Reports submitted to DOE Project Officer
<u>*Milestone 3.2:*</u> Isolate and confirm the identity of >5 urease-producing bacteria and >5 probiotic bacterial strains for *Scenedesmus obliquus* HTB1	Month 15	N/A	Same as above
<u>*Milestone 3.3:*</u> Generate CO_2 nanobubbles with concentrations of up to 3×10^{14} bubbles·L^{-1} and sizes ranging from 300 nm to 1 μm in diameter and microbubbles with concentrations of up to 1×10^{8} bubbles·L^{-1} and sizes ranging from 10 to 100 μm	Month 12	N/A	Same as above

No change in the scope of work, and no extra fund requested.

Summary

- Urease effect on carbonate precipitation confirmed; further tests in progress.
- Micro-/Nano-bubble generation tests in progress; we will proceed with lab tests of seawater and freshwater cultures.
- Bioreactor parts ordered and in preparation for bioreactor tests with flue gas.

Appendix

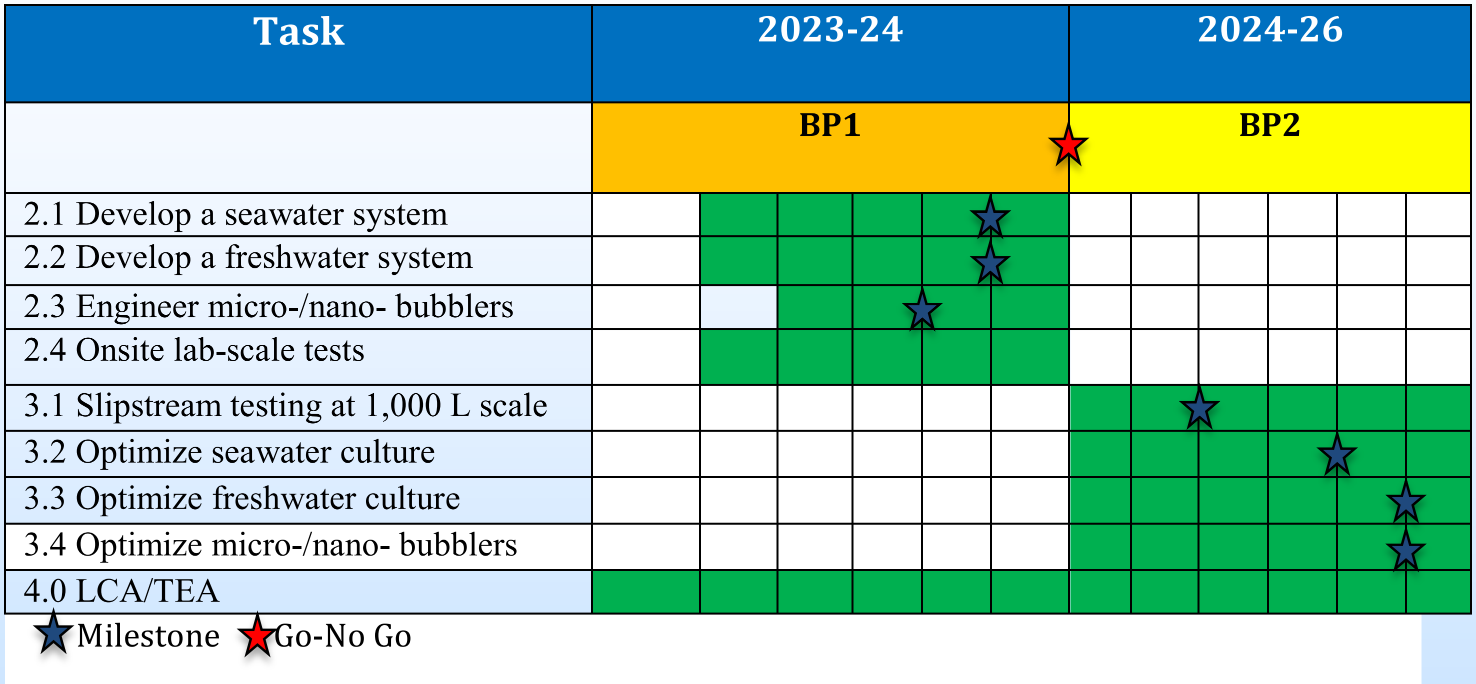
– These slides will not be discussed during the presentation but are mandatory.

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.