

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

DE-FE0032188

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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

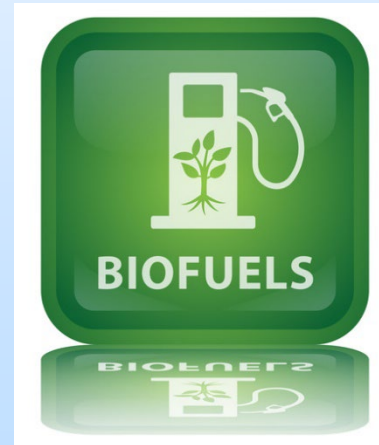
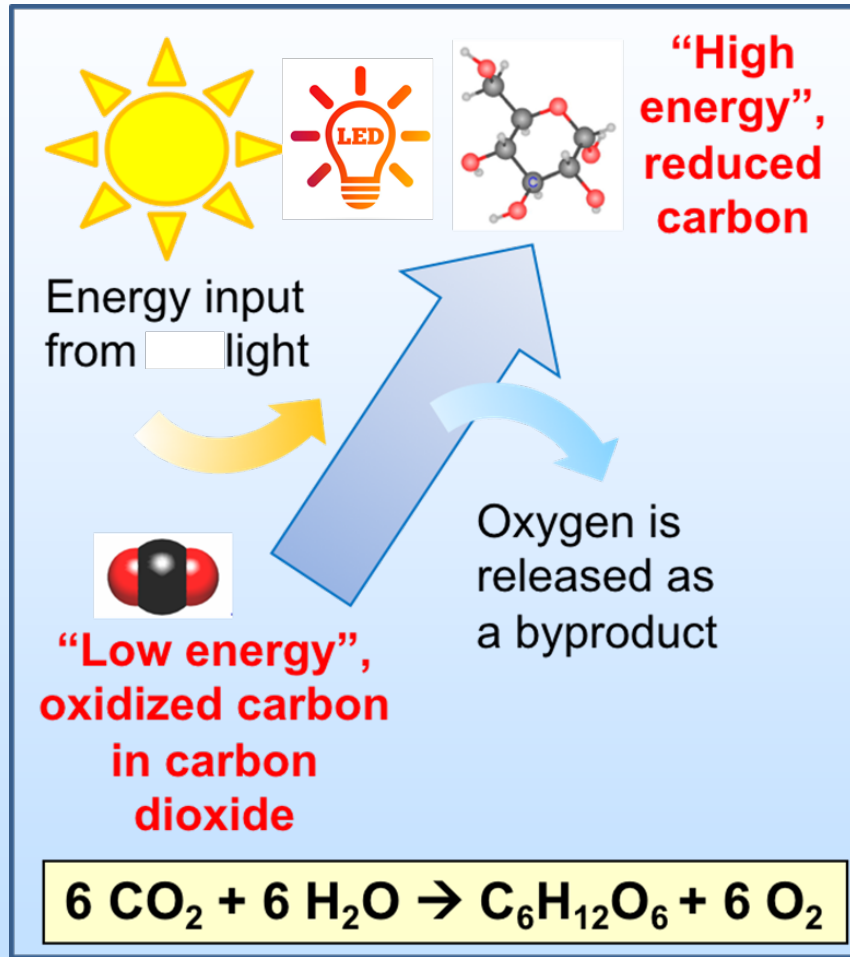
DOE NETL Program Manager: Zachary Roberts (from February 2023 to May 2024), **Richard Dunst** (from June 2024 to present)

Project Overview

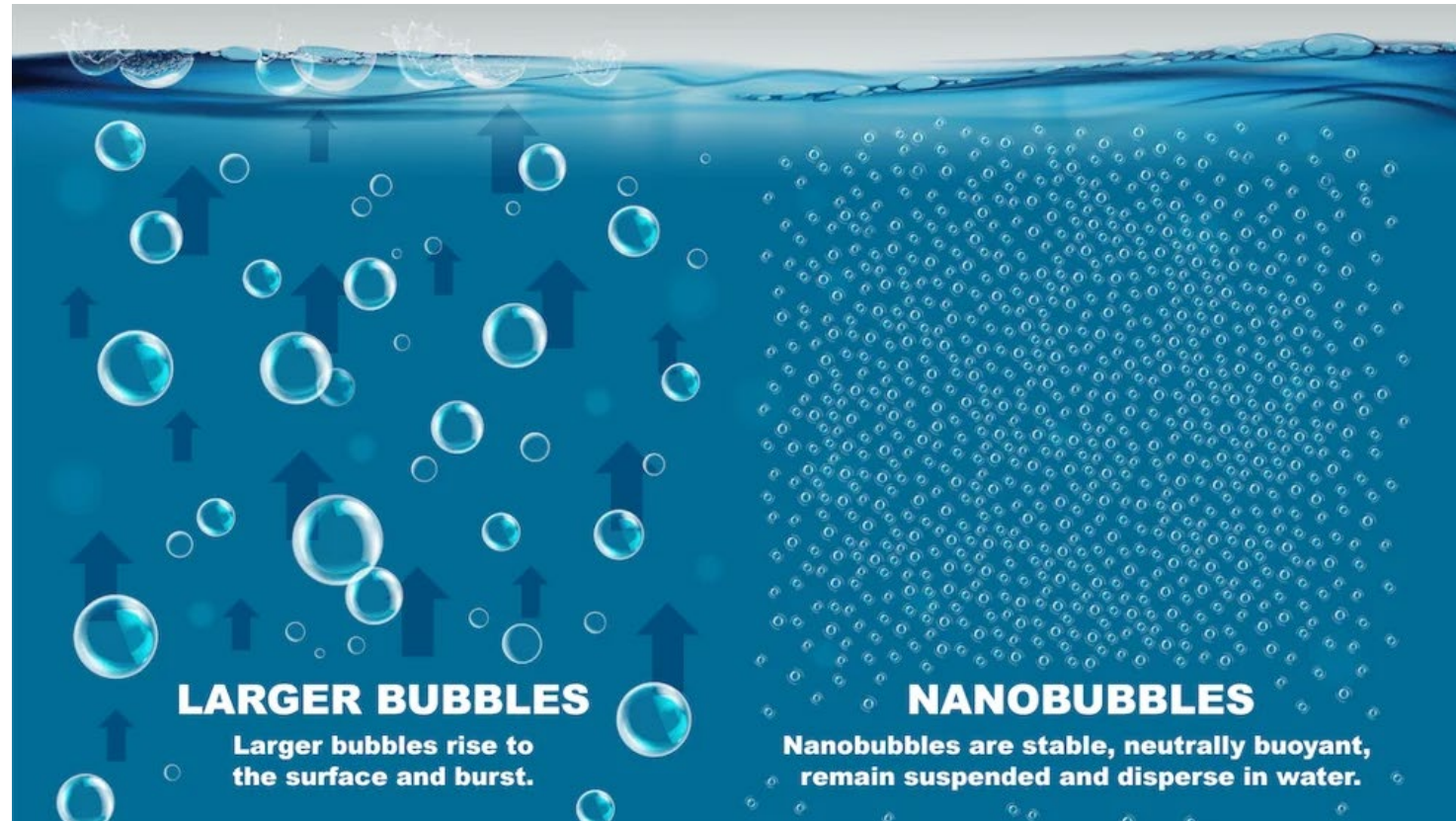
- Overall Project Objectives

The objective of this project is to engineer microalgal polycultures through a photosynthesis-driven process to capture and sequester carbon dioxide (CO₂) from power plant flue gases in the form of algae biomass and carbonate precipitates.

Technology Background



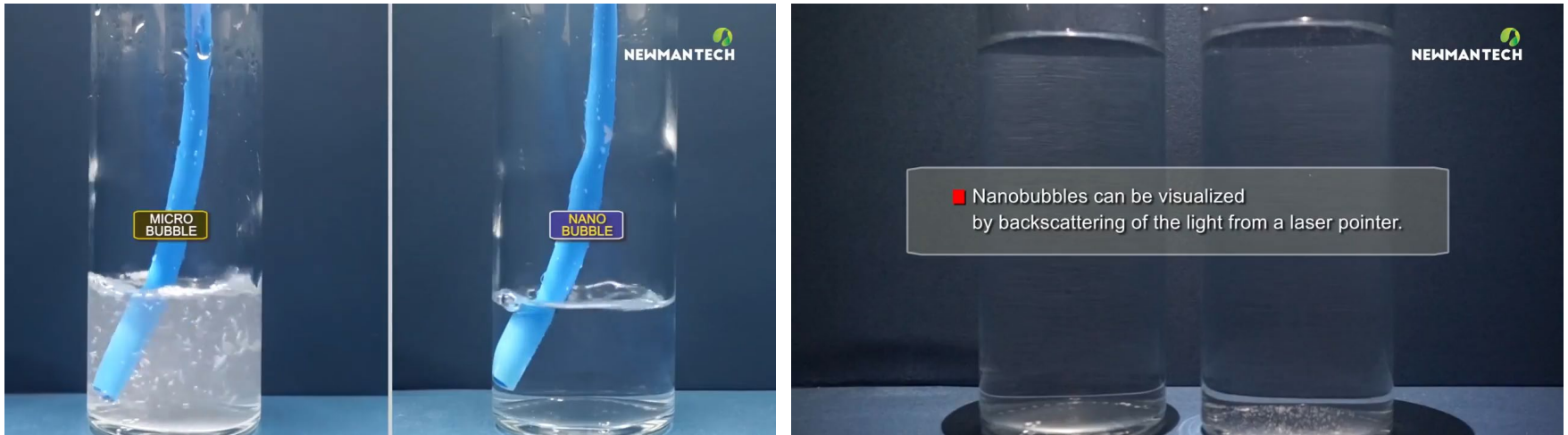
Using nanobubbles to increase carbon utilization efficiency (CUE)



Nanobubbles have the potential to enhance the CO₂ solubility and **carbon utilization efficiency** of microalgae due to their minuscule size, high gas-liquid mass transfer efficiency, and large electrostatic interactions.

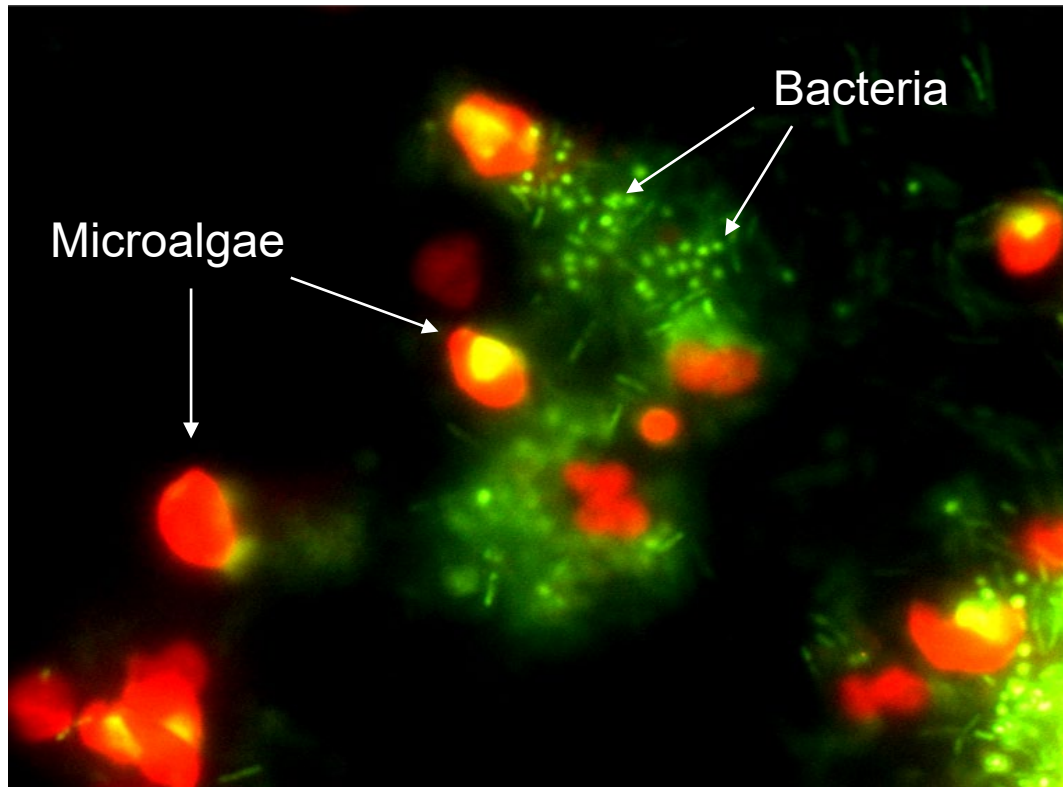
Using nanobubbles to increase carbon utilization efficiency (CUE)

Microbubble vs Nanobubble



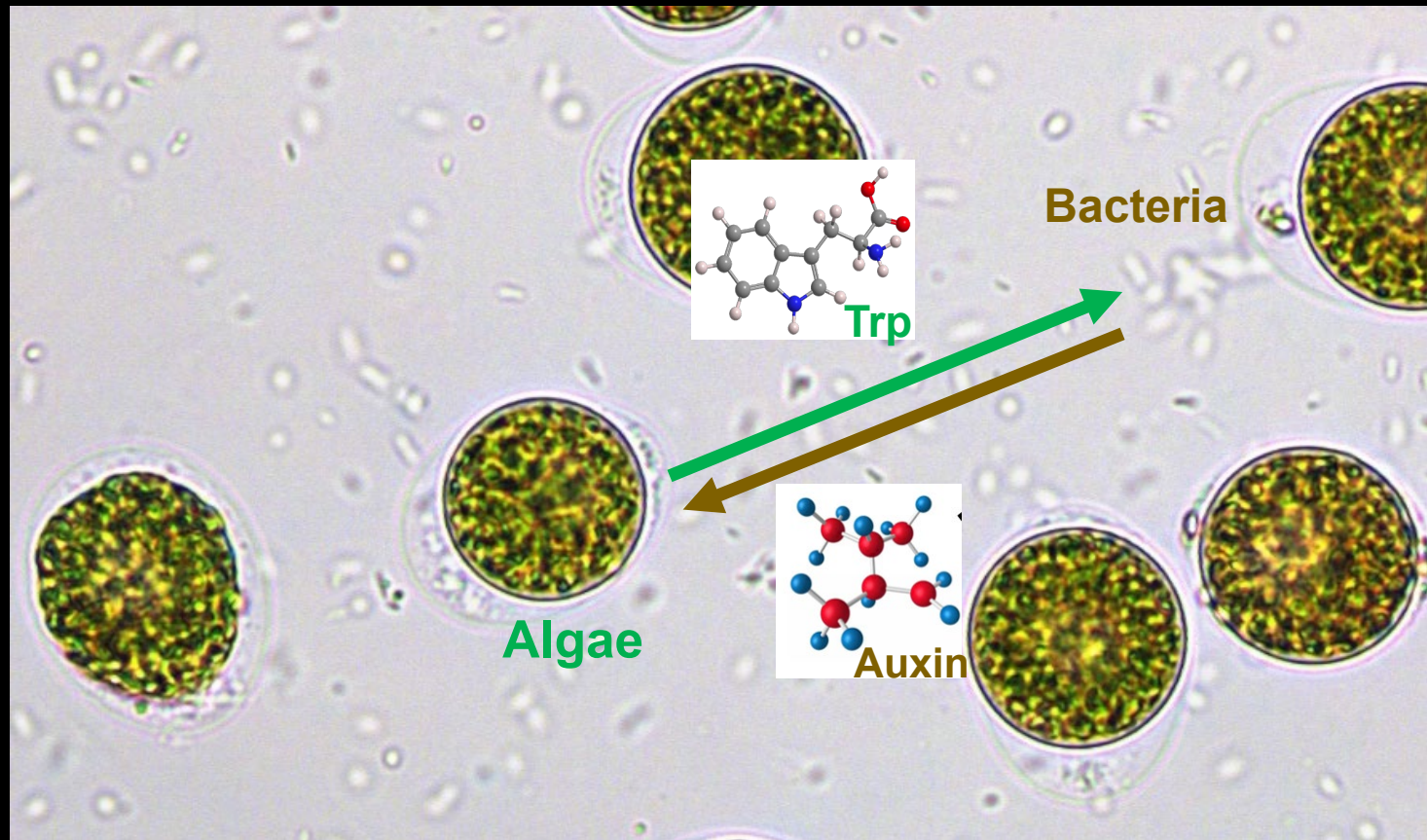
Nanobubbles have the potential to enhance the CO₂ solubility and **carbon utilization efficiency** of microalgae due to their minuscule size, high gas-liquid mass transfer efficiency, and large electrostatic interactions.

Microbiomes in algal culture systems



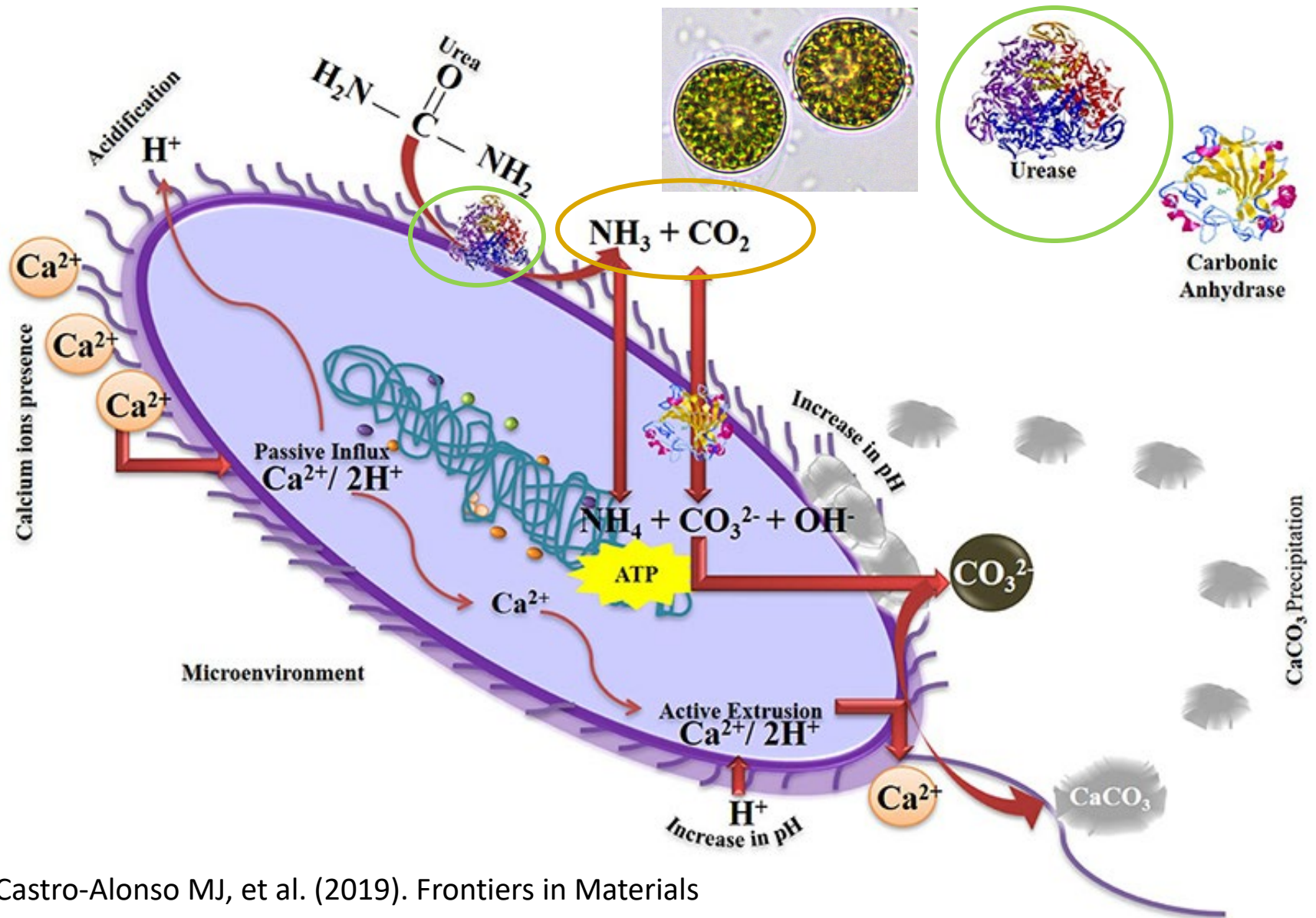
Complex bacteria co-exist in algal cultures and some can have beneficial effects: 1) Promote algal growth; 2) Induce calcium carbonate precipitation.

Microbial interactions in non-axenic microalgal cultures



Microbially Induced Calcium Carbonate Precipitation

Microbially Induced Calcium Carbonate Precipitation (MICP) and Urease

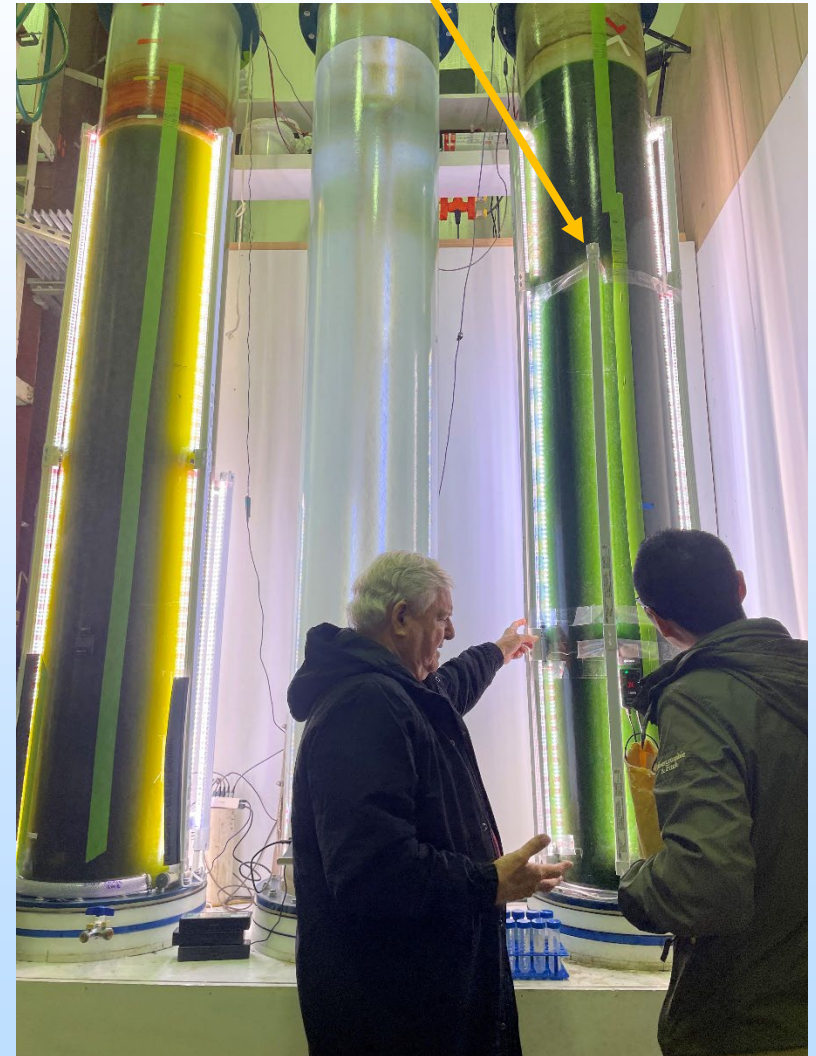


We focused on two major microalgal species

Nannochloropsis oceanica IMET1

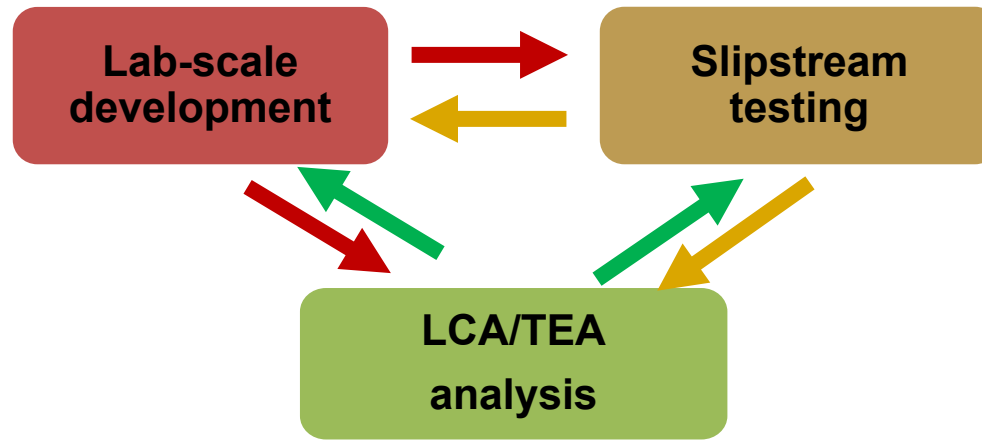


Scenedesmus obliquus HTB1



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

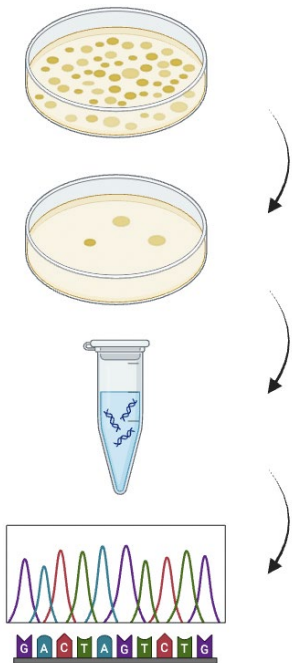
Subtask 2.2 - Laboratory development of freshwater *Scenedesmus* system

- 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.

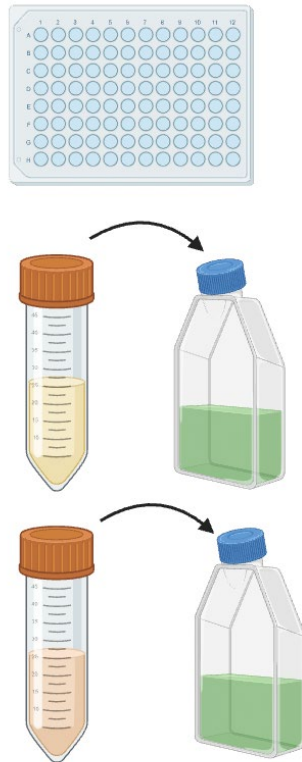
Milestone 2.2 Isolate and confirm the identity of >5 urease-producing bacteria and >5 probiotic bacterial strains for *Scenedesmus* HTB1; Date: M15

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

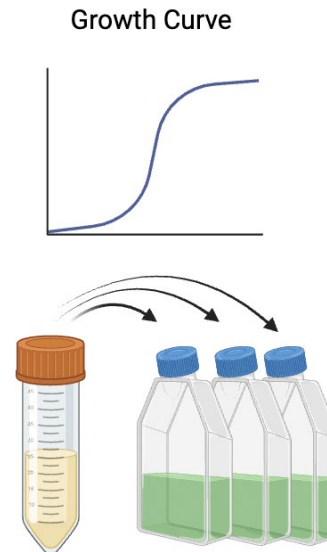
Phase 1 - Isolation and identification of bacteria



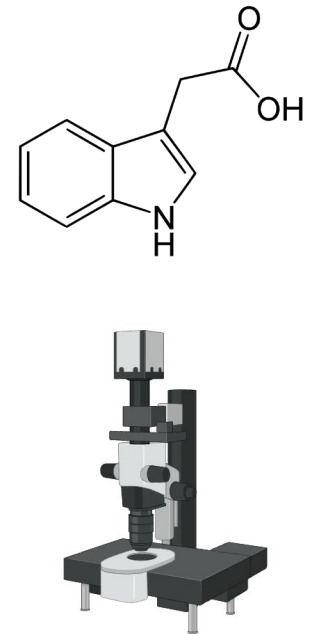
Phase 2 - Screening of multiple bacterial isolates



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

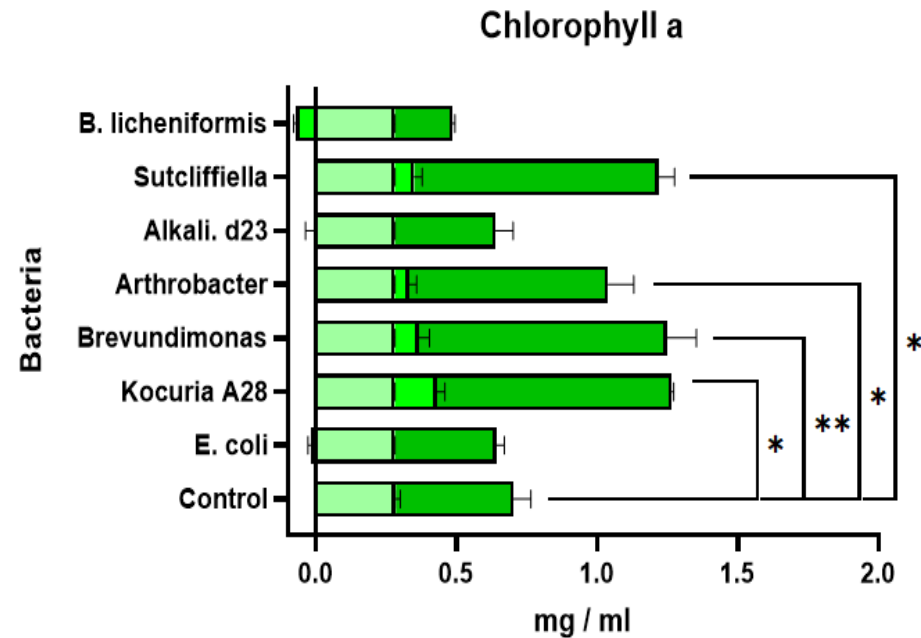
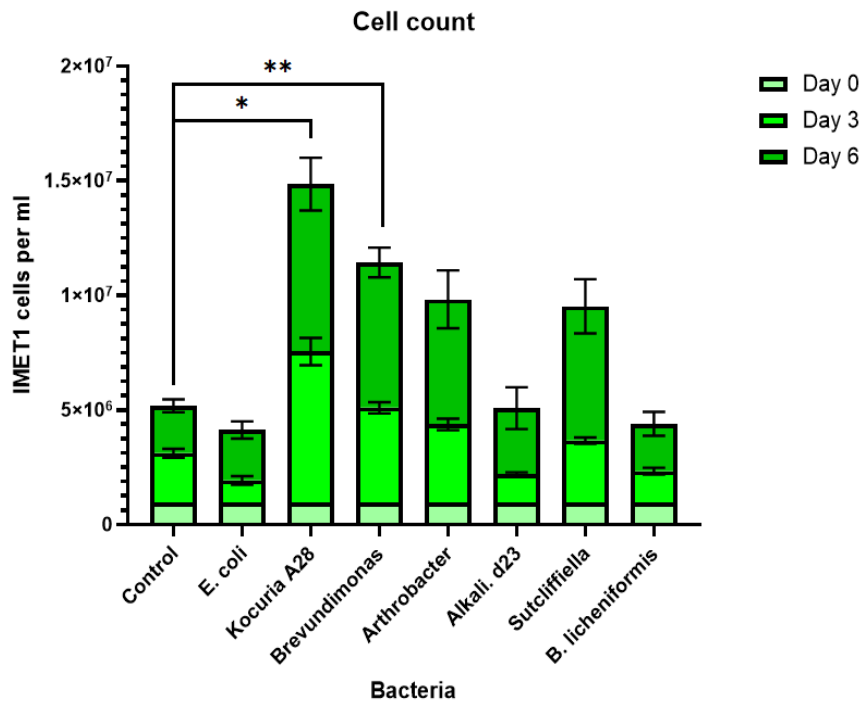


Phase 4 - Understanding the mechanism of growth promotion



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

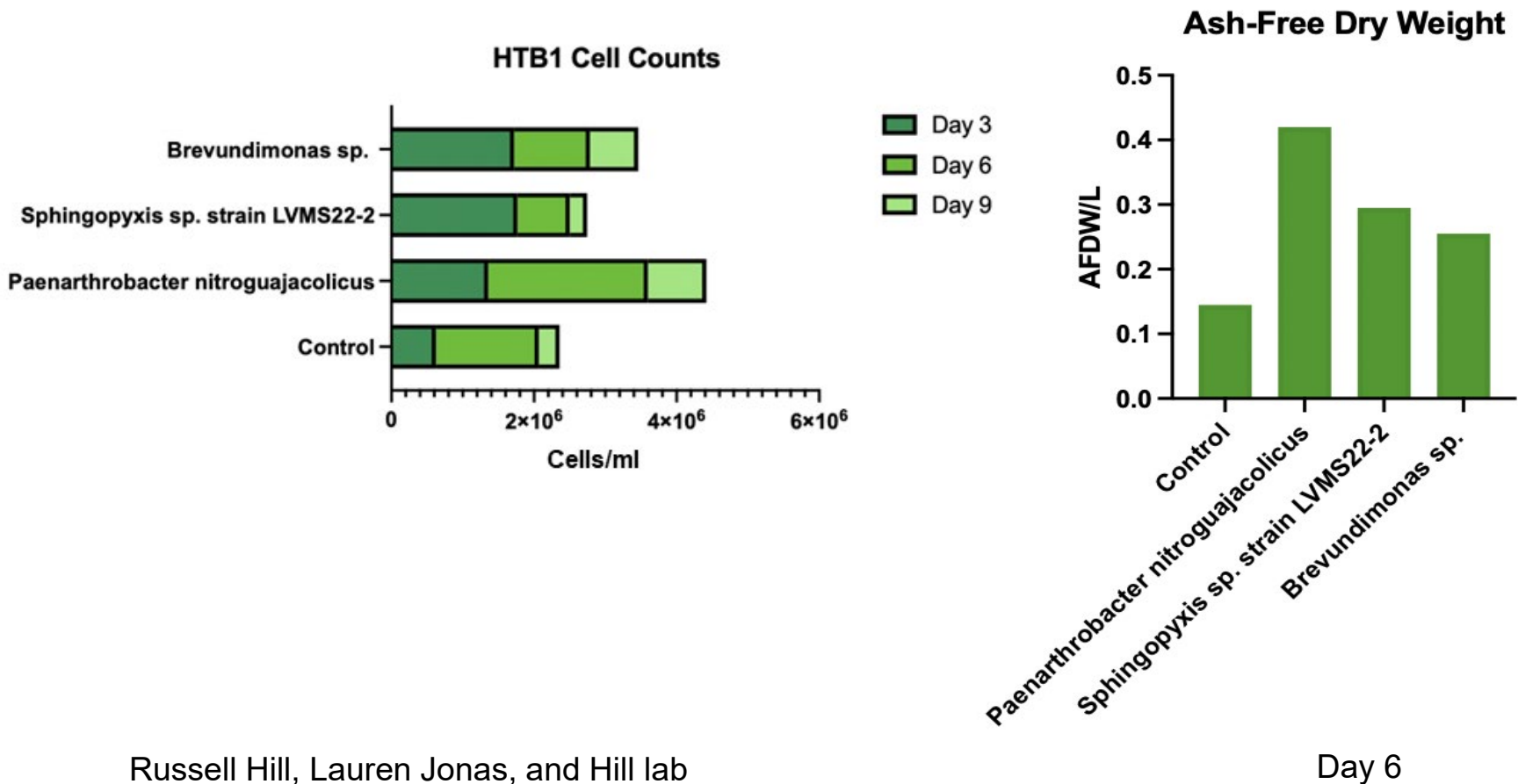
Nannochloropsis IMET1 Growth Promoting Isolates



Several bacterial strains help promote the growth of IMET1

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

Scenedesmus HTB1 Growth Promoting Isolates



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

Growth Promoting Bacteria Isolates

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

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
<i>Paenarthrobacter nitroguajacolicus</i>	99.42	Both
<i>Staphylococcus saprophyticus</i>	99.28	Both
<i>Agrobacterium tumefaciens</i>	99.53	Both
<i>Bosea vestrisii</i>	99.27	HTB1
<i>Bosea</i> sp.	99.77	HTB1
<i>Pseudomonas knackmussi/stutzeri</i>	100.00	IMET1
<i>Bacillus amyloliquefaciens</i>	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

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

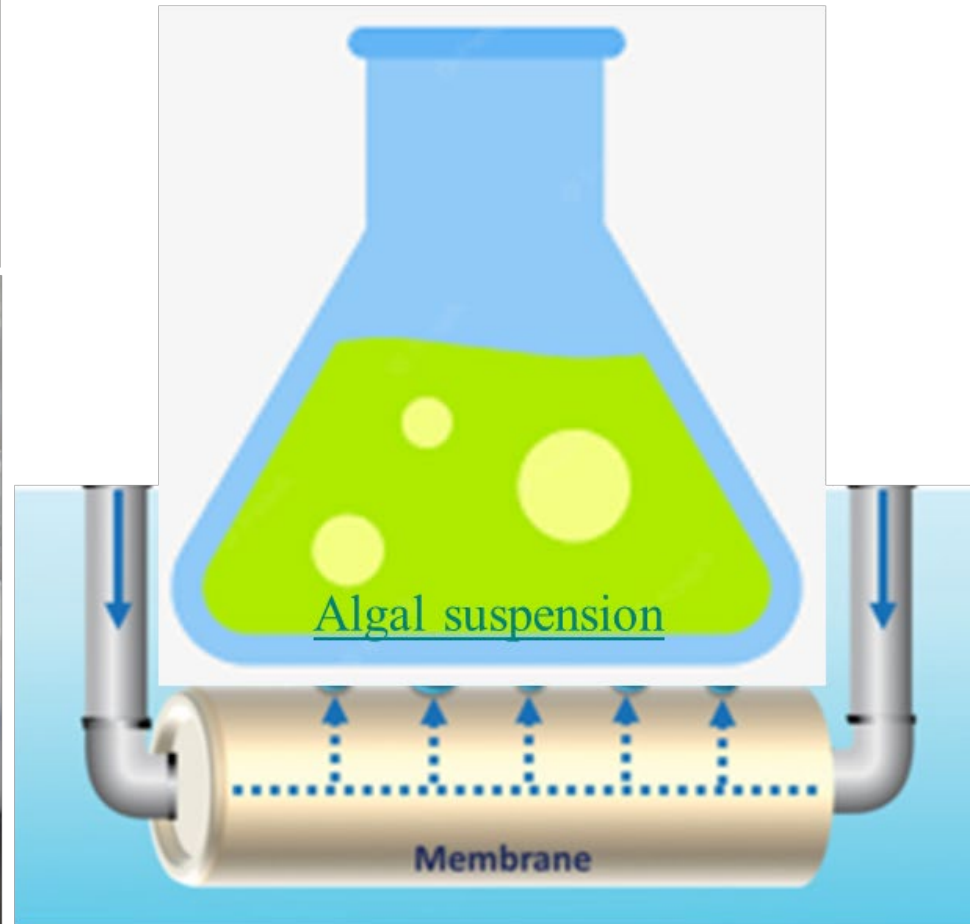
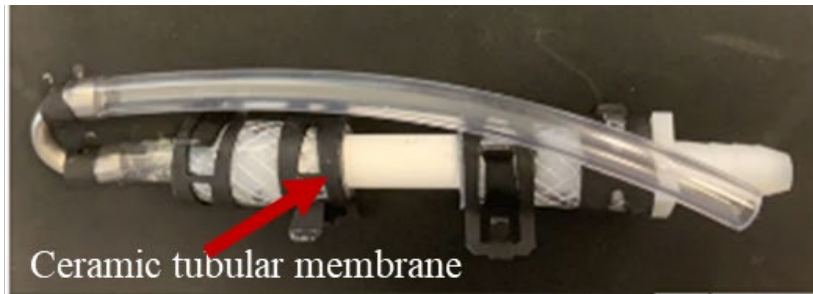
Subtask 2.3 - Development and testing of bubblers

- Generate and optimize micro- and nano-bubbles of CO₂ dispersion;
- Determine key parameters such as bubble sizes and CO₂ flow or flux

Milestone 2.3 Generate CO₂ nanobubbles with concentrations of up to 1×10^8 bubbles·L⁻¹;

Date: M12

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

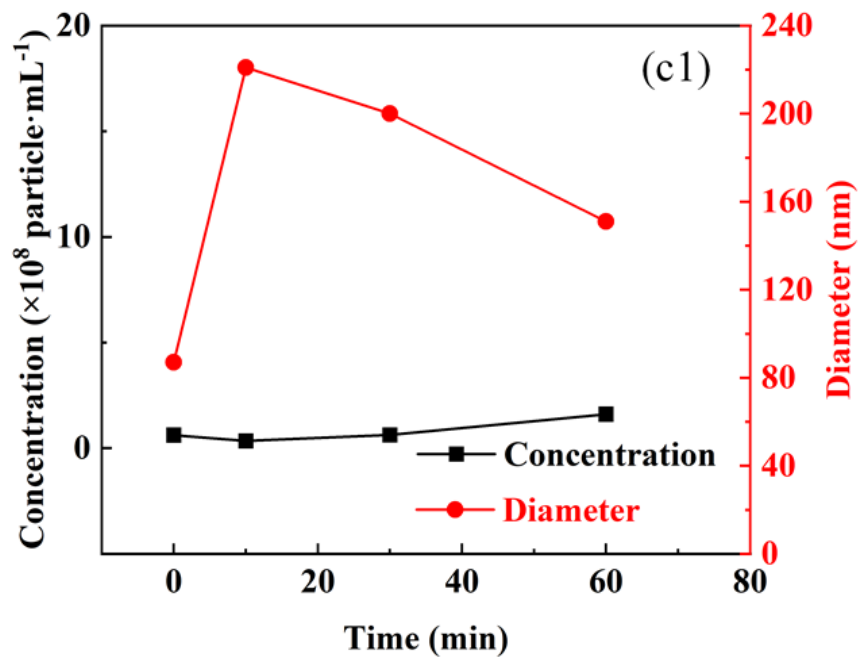


Wen Zhang's group at NJIT

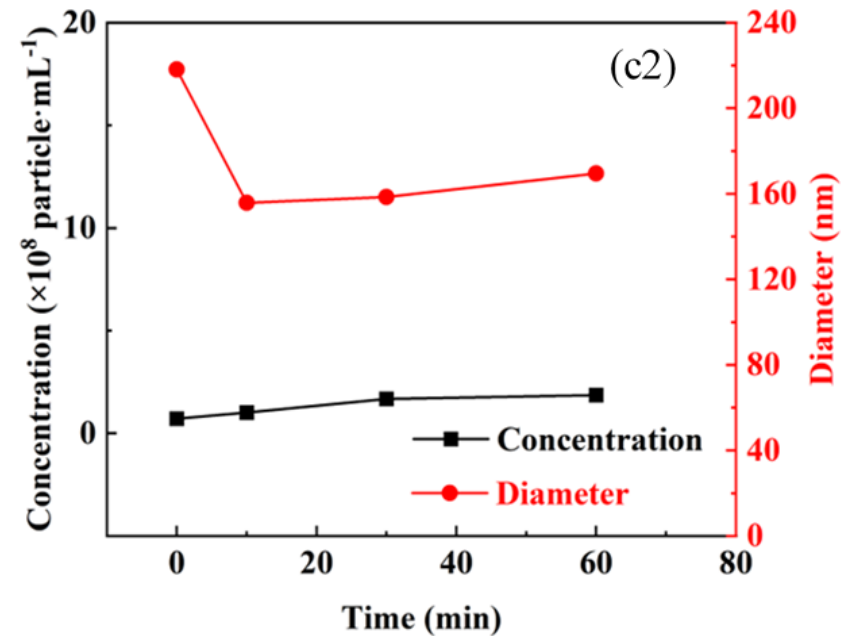
Progress: Budget Period 1 Bench-scale and 9 L scale test

Characterization of CO₂ nanobubbles in the **direct injection mode** with 10% CO₂

f/2 medium (for *Nannochloropsis*)



BG-11 medium (for *Scenedesmus*)



Wen Zhang's group at NJIT

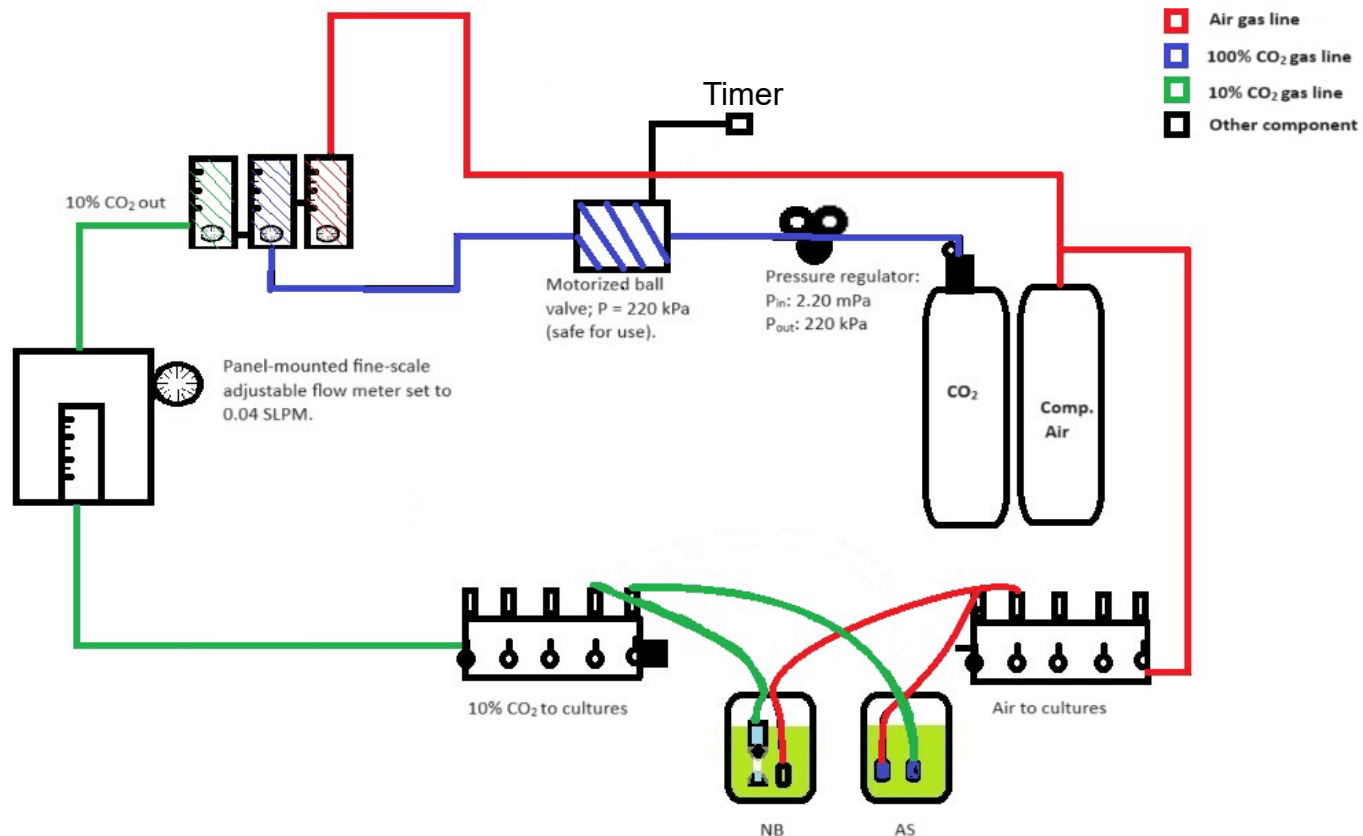
Milestone 2.3 Generate CO₂ nanobubbles with concentrations of up to 1×10^8 bubbles·L⁻¹

BP1 Success Criteria

Determine the best combinations of urease and probiotic bacterial strains and bubbling mechanisms that facilitate an average productivity of 30 g/m²/day and a CUE >50% (algae biomass) or >60% (algae and CaCO₃ precipitates) in lab culture and 9-L bioreactors.

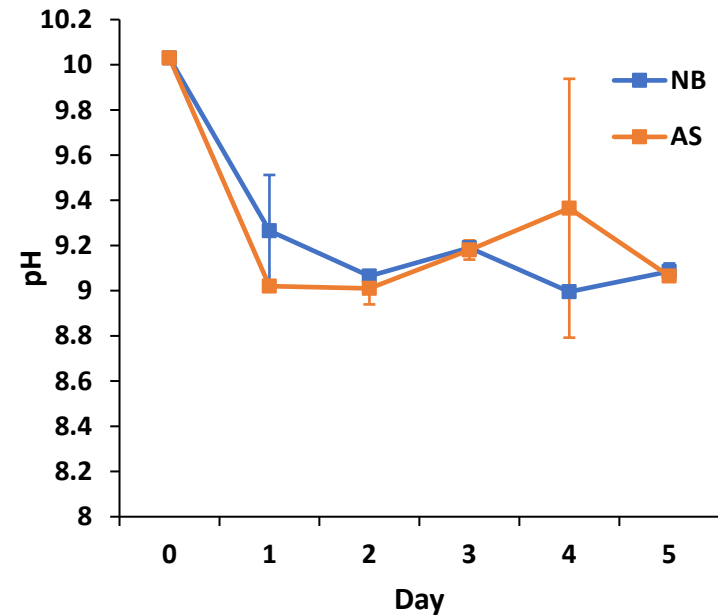
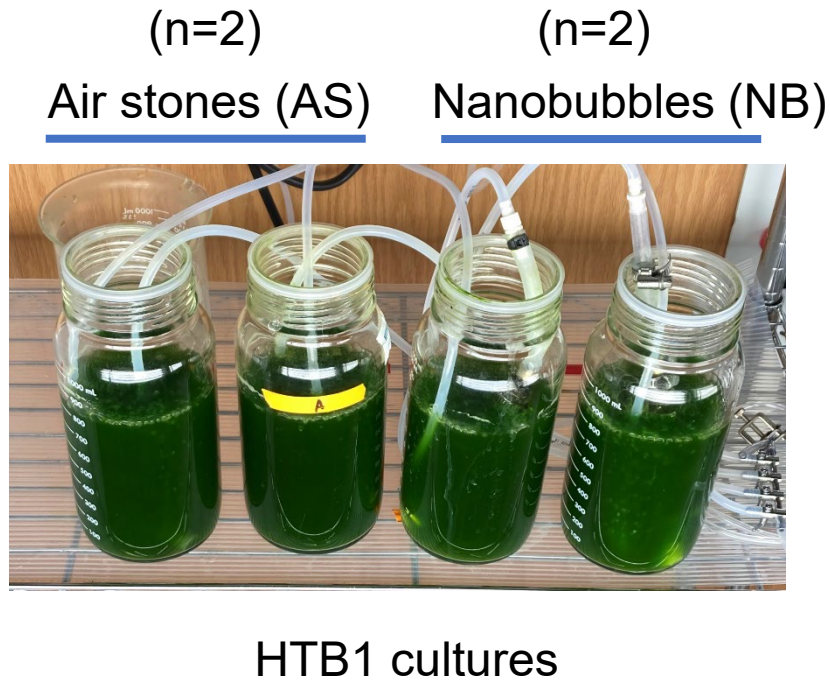
Progress: Budget Period 1 Bench-scale and 9 L scale test

The design of the automated CO₂ sparging system



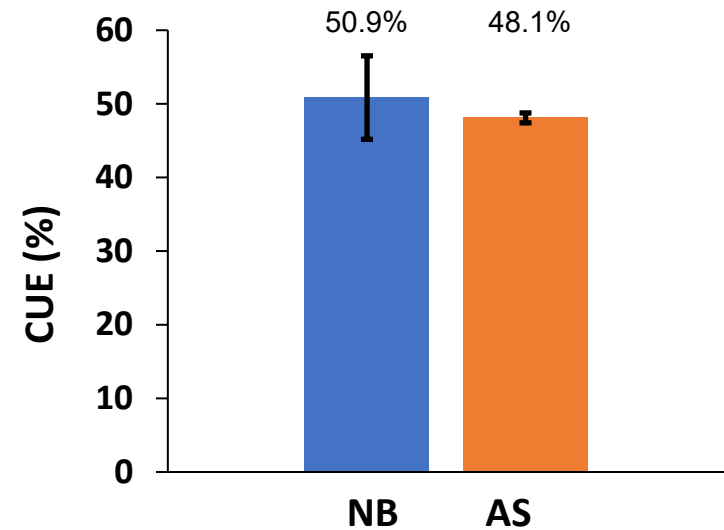
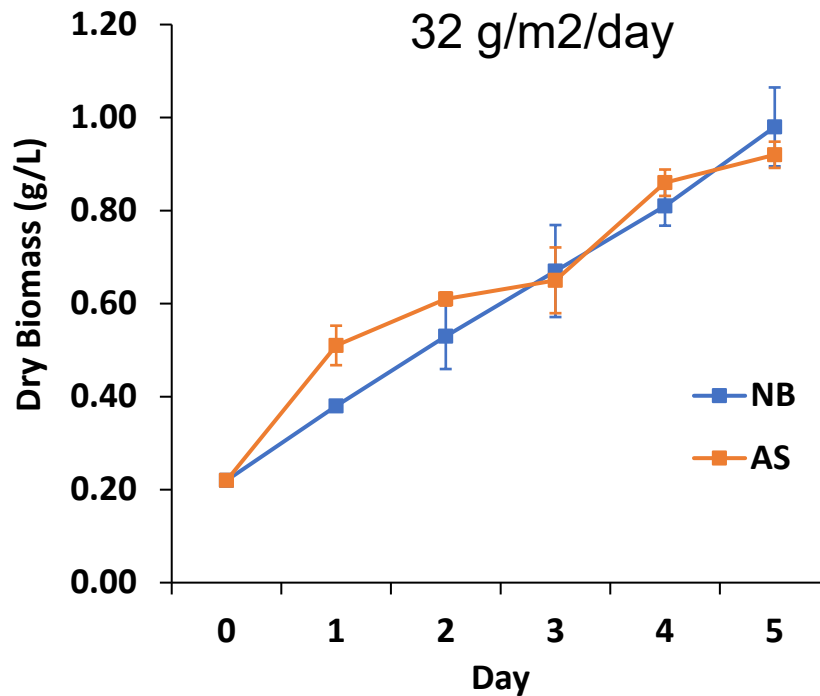
This system allows us to charge 10% CO₂ using a timer at set times. In this experiment, we set the system to charge 10% CO₂ for 5 minutes 8 times per day. Charging cultures with CO₂ multiple times per day manually can be very **labor-intensive and difficult** to manage for the long incubation experiments.

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



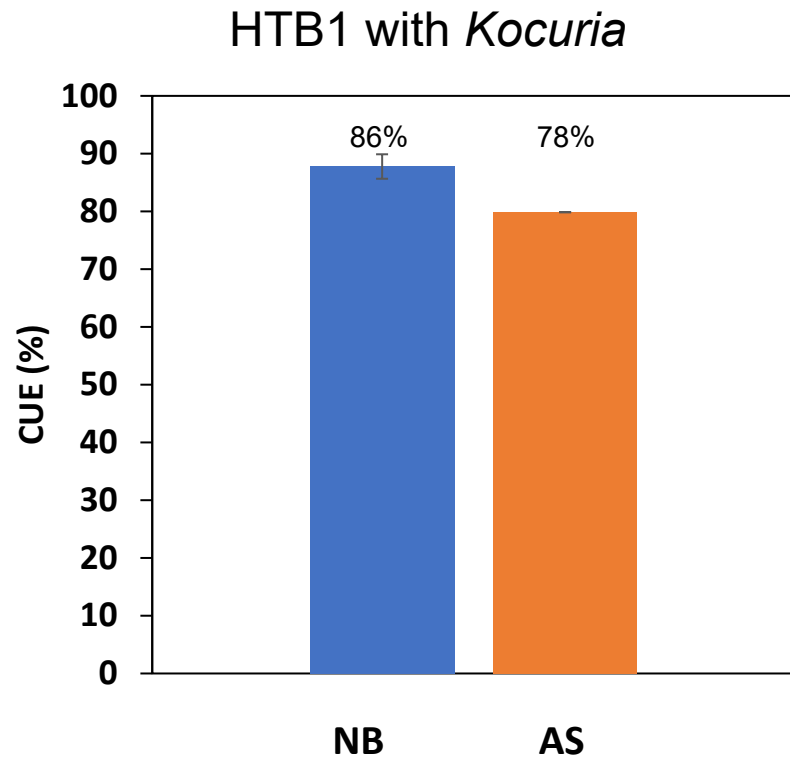
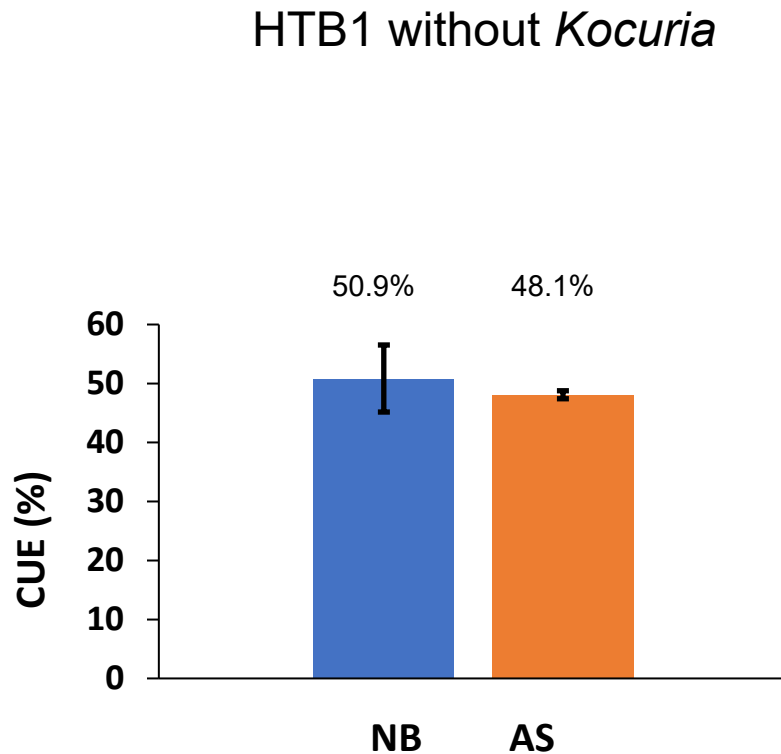
The pH remained relatively stable in both nanobubble and air stone cultures over five days of growth.

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



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

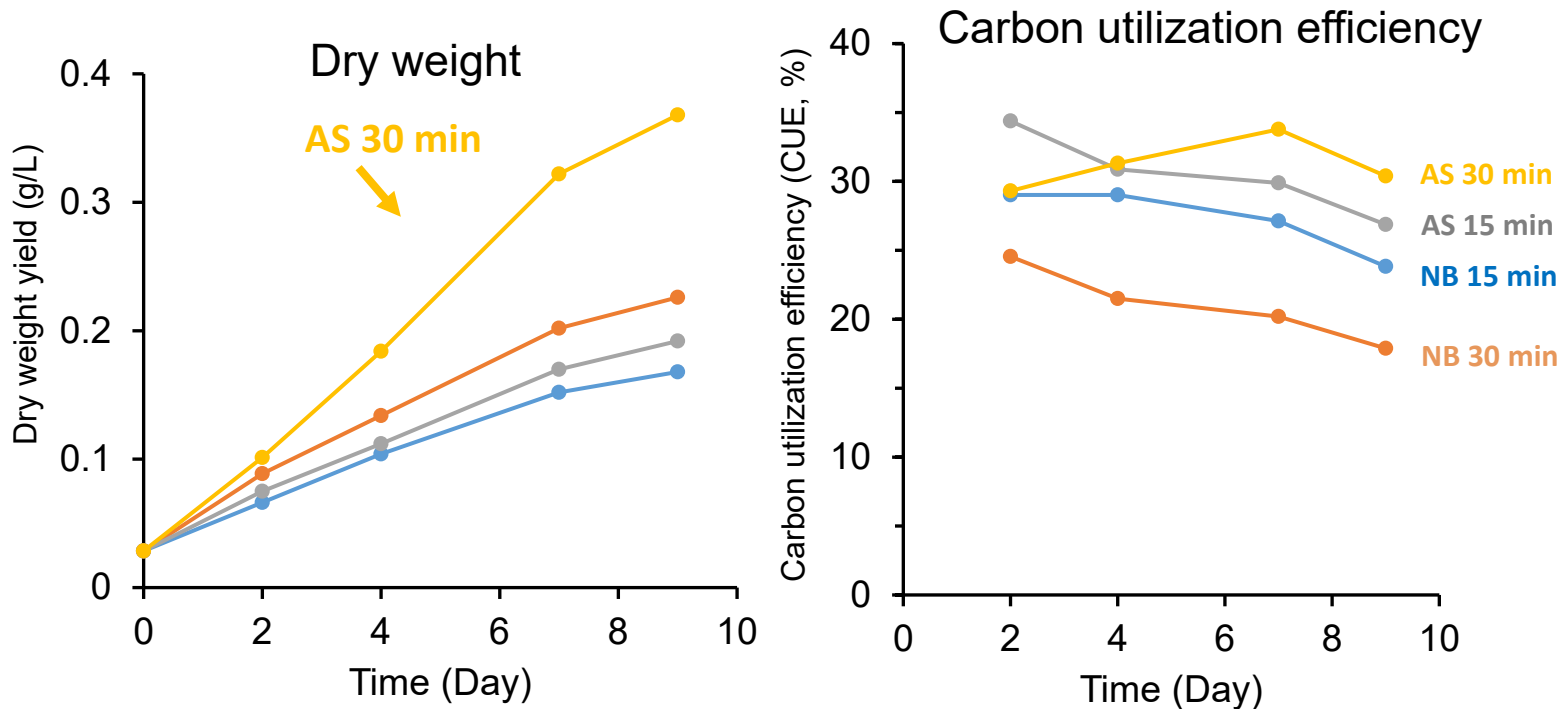
Progress: Budget Period 1 Bench-scale and 9 L scale test



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

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%.

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

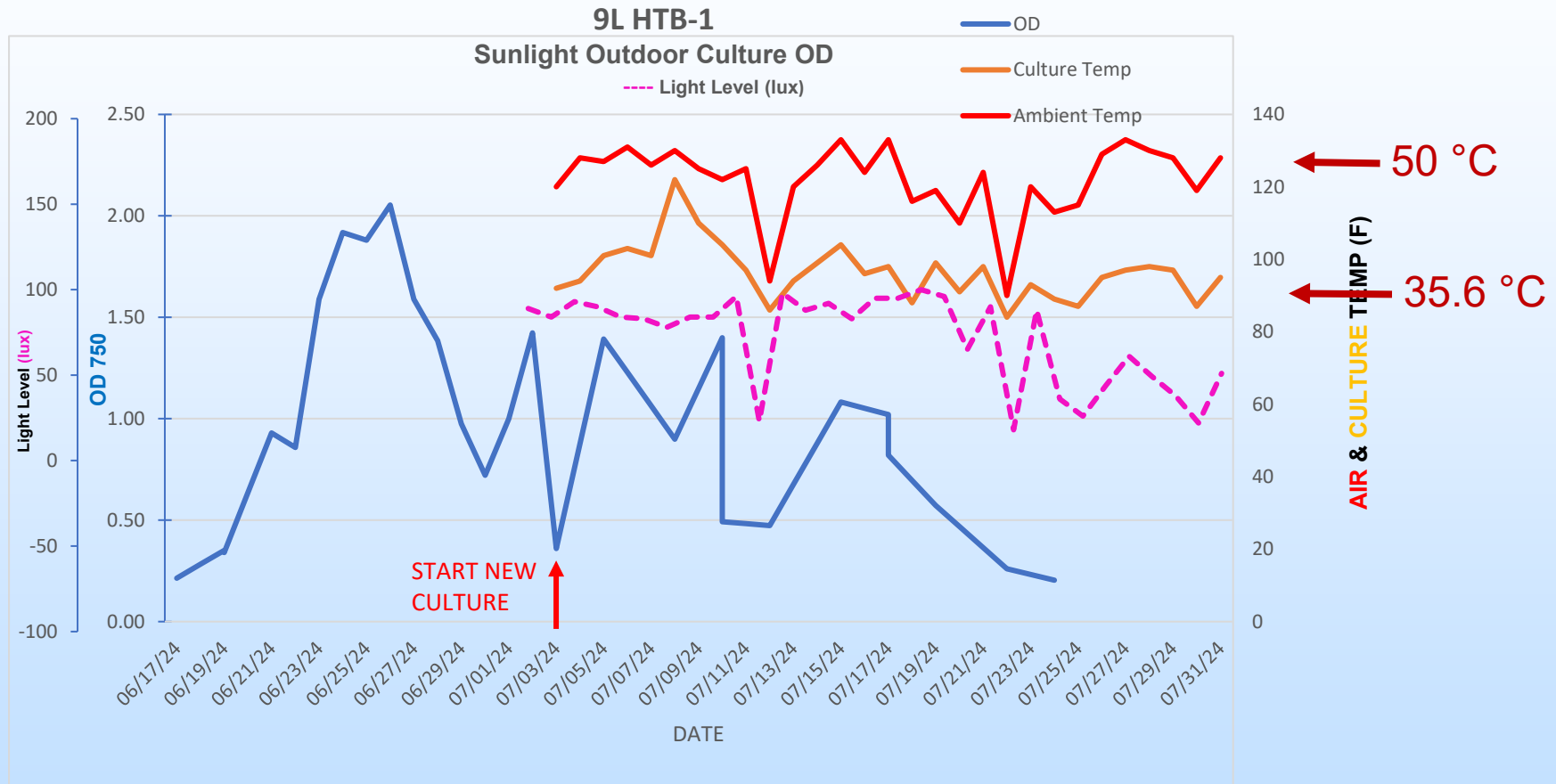
HY-TEK Bio's Facility at the Back River Waste Water Treatment Plant



9-L Bioreactor tests

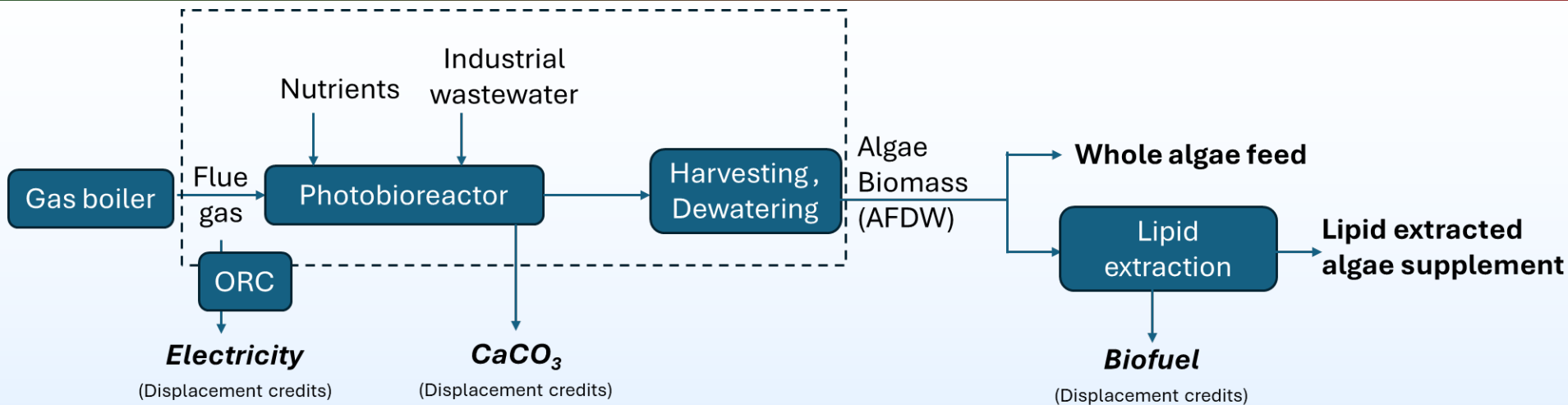
Robert Mroz's group at HY-TEK Bio₃₀

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



Growth of HTB1 in the 9L outdoor bioreactor

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:

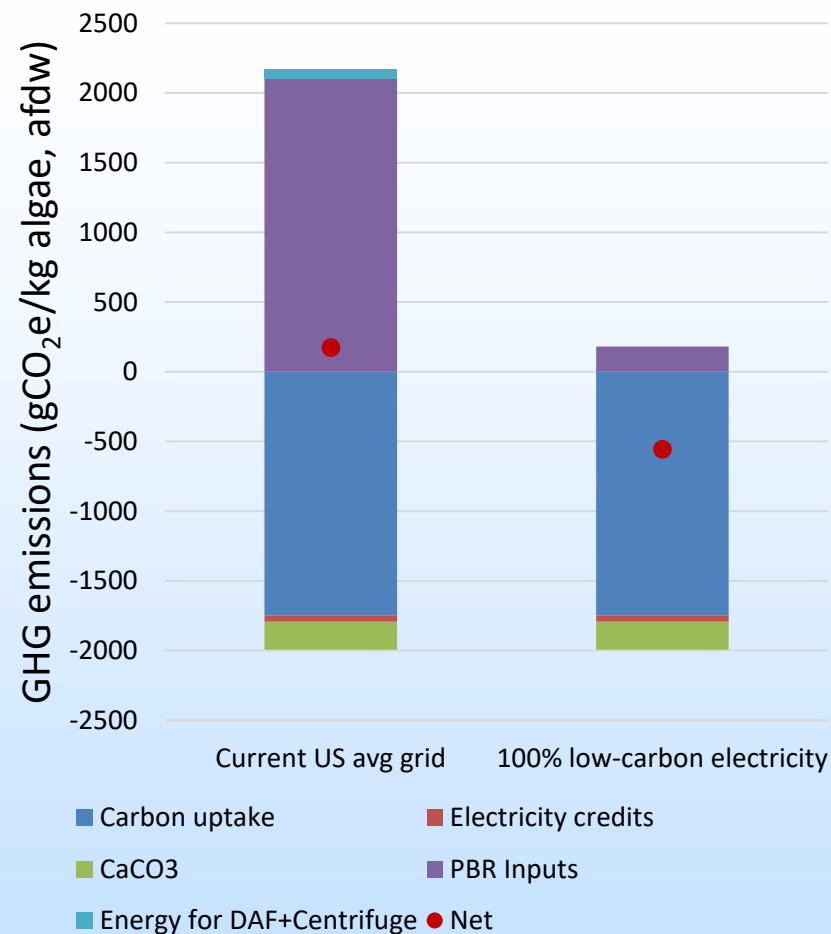
- Greenhouse gas (GHG) emissions (CO₂, CH₄, N₂O)
- Criteria air pollutant emissions (VOC, CO, NO_x, PM₁₀, PM_{2.5}, and SO_x)
- Fossil energy use
- Water consumption

TEA metrics:

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

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 (afdwt); 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-HNO₃ per kg-algae (dry) and P-nutrients equivalent to 0.041 kg-H₃PO₄ 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 gCO₂e/kg algae when assuming current U.S. average emission factor but decarbonizing grid may bring down emissions to -557 gCO₂e/kg algae

Plans for future work- BP1

Milestone Title	Planned Completion date	Actual Completion date	Verification Method	Comments
<u>Milestone 2.1:</u> Isolate and confirm the identity of >5 urease-producing bacteria and >5 probiotic bacterial strains for <i>Nannochloropsis oceanica</i>	Month 15	N/A	Via Quarterly Reports submitted to DOE Project Officer	100% completion
<u>Milestone 2.2:</u> Isolate and confirm the identity of >5 urease-producing bacteria and >5 probiotic bacterial strains for <i>Scenedesmus obliquus</i>	Month 15	N/A	Same as above	100% completion
<u>Milestone 2.3:</u> Generate CO ₂ nano-/micro-bubbles with concentrations of up to 1×10^8 bubbles·L ⁻¹	Month 12	2/14/2024	Same as above	100% completion
<u>BP1 success criteria:</u> 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 (<i>Li working with all PIs</i>) - Project Reporting (<i>All PIs</i>)	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 (<i>Li and Hill</i>) - Freshwater algal carbon sequestration (<i>Chen and Hill</i>)	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 (<i>Zhang</i>) - Bubbler optimization at 1,000 L scale (<i>Zhang</i>)	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 (<i>Mroz</i>) - Slipstream test at 1,000 L scale (<i>Mroz</i>)	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 (<i>Hawkins</i>) - Perform contribution analysis, benchmarked against other conventional algae processes (<i>Hawkins</i>)	Argonne National Lab is the lead on this task.

Gantt Chart

Project Schedule (Gantt chart)*

Task	2023-24						2024-26					
	BP1						BP2					
2.1 Develop a seawater system						★						
2.2 Develop a freshwater system						★						
2.3 Engineer micro-/nano- bubblers				★								
2.4 Onsite lab-scale tests												
3.1 Slipstream testing at 1,000 L scale								★				
3.2 Optimize seawater culture									★			
3.3 Optimize freshwater culture											★	
3.4 Optimize micro-/nano- bubblers											★	
4.0 LCA/TEA												

★ Milestone ★ Go-No Go

* 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.