Washington University in St. Louis
James McKelvey School of Engineering

Project DE-EE0010291: Enhancing Carbon Utilization by Algal Systems via Integrated Biogas Purification, Nitrogen Reuse, and Innovative Carbon Dioxide Delivery

Zhen (Jason) He
Laura & William Jens Professor
Department of Energy, Environmental and Chemical Engineering
Washington University in St. Louis

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Project Overview

Goal: to develop an integrative system for highly efficient algal growth through effective supply of wasted CO_2 from anaerobic digestion with simultaneous biogas upgrading. The concept of circular economy is incorporated into the research approach by converting wastes into useful products.

Funding: DOE, $2,522,518; Cost Share, $648,583

Project Performance Dates:

Budget Period 1: 10/01/2022 to 08/31/2023
Budget Period 2: 09/01/2023 to 11/30/2024
Budget Period 3: 12/01/2024 to 05/31/2026

Project Team

Team Management

- Bimonthly meetings
- Annual in-person project meetings
- Sub-group communication
- Joint publications/presentations
- Student visits
- Education and outreach to underrepresented community

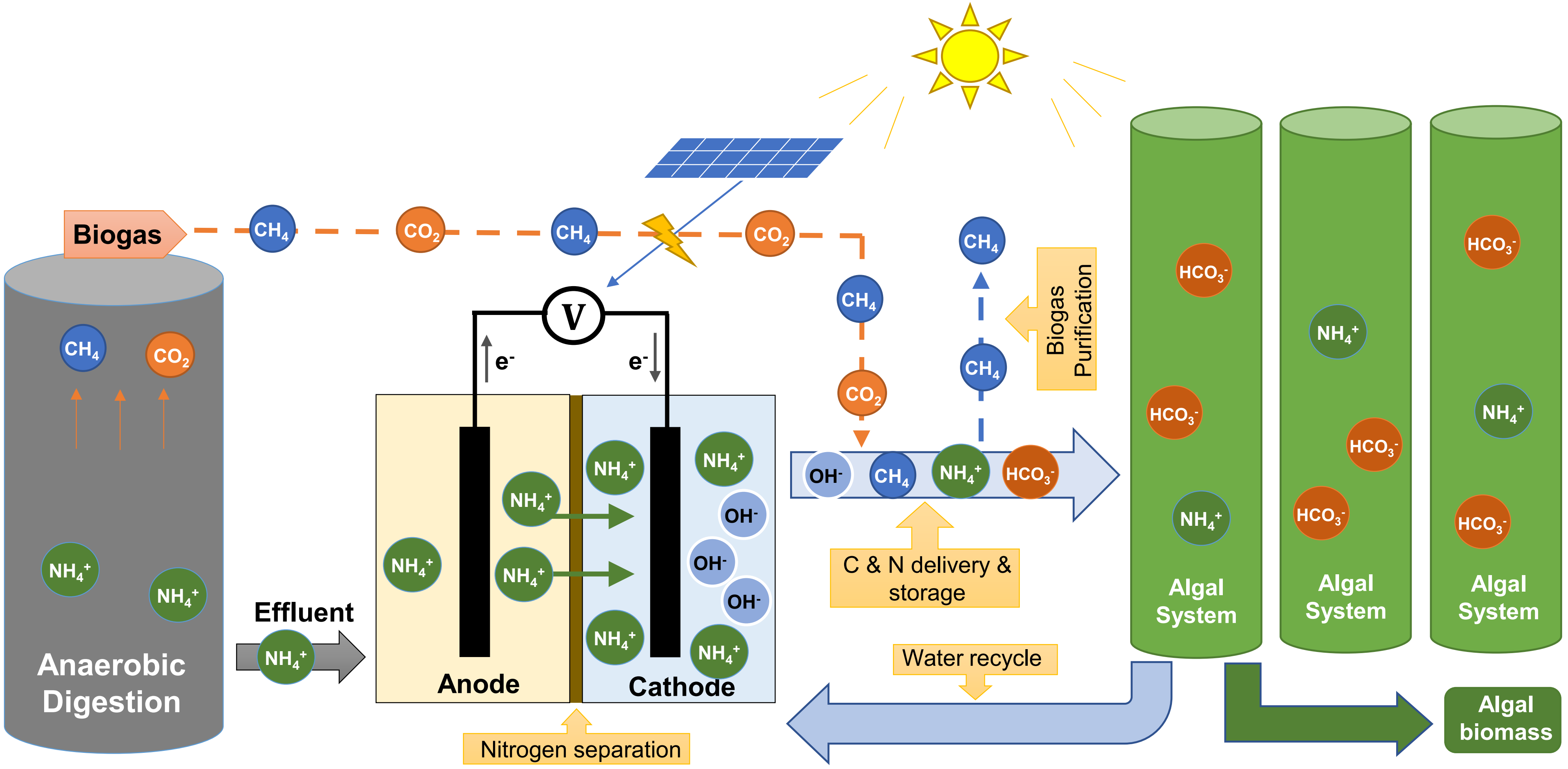
Technology Background

- The high cost of feedstock CO_2 is one of major challenges for cost-effective production of algal biomass
- Waste CO_2 such as flue gas or biogas can be a source of CO_2 for algal growth
- Simultaneous biogas upgrading to renewable natural gas (RNG), which contains >95% CH_4, provides not only CO_2 to algae, but also remove some key contaminants such as H_2S

Photosynthetic Biogas Upgrading

- Usually focus on “biogas upgrading”, not “algal production”
- Direct use of treated wastewater can introduce contamination to algal culture
- Direct supply biogas to algal reactors may have a low CO_2 capture and can introduce O_2 to the upgraded biogas
- Indirect supply biogas via adsorption columns requires regeneration of alkaline solutions

Approach - our proposed system



Technological advantages

Challenges	Solutions
CO_2 gas delivery	CO_2 is converted to bicarbonate under an alkaline condition. This bicarbonate solution will be easier to transport and better to be utilized by algae
Algae-produced O_2	Biogas purification is completed outside algal photobioreactors. Thus, O_2 will not be mixed with the purified CH_4
Biogas storage	Not needed, because CO_2 can be stored as bicarbonate in the solution when sunlight is not available to algal growth
Waste nutrients from AD	Ammonium nitrogen is separated from AD effluent by electrochemical systems and then supplied to algal growth after CO_2 capture
Process control and optimization	This system contains many variables that affect CO_2 capture and algal lipid productions. Process modeling and machine learning can be used to control PBRs.

Tasks

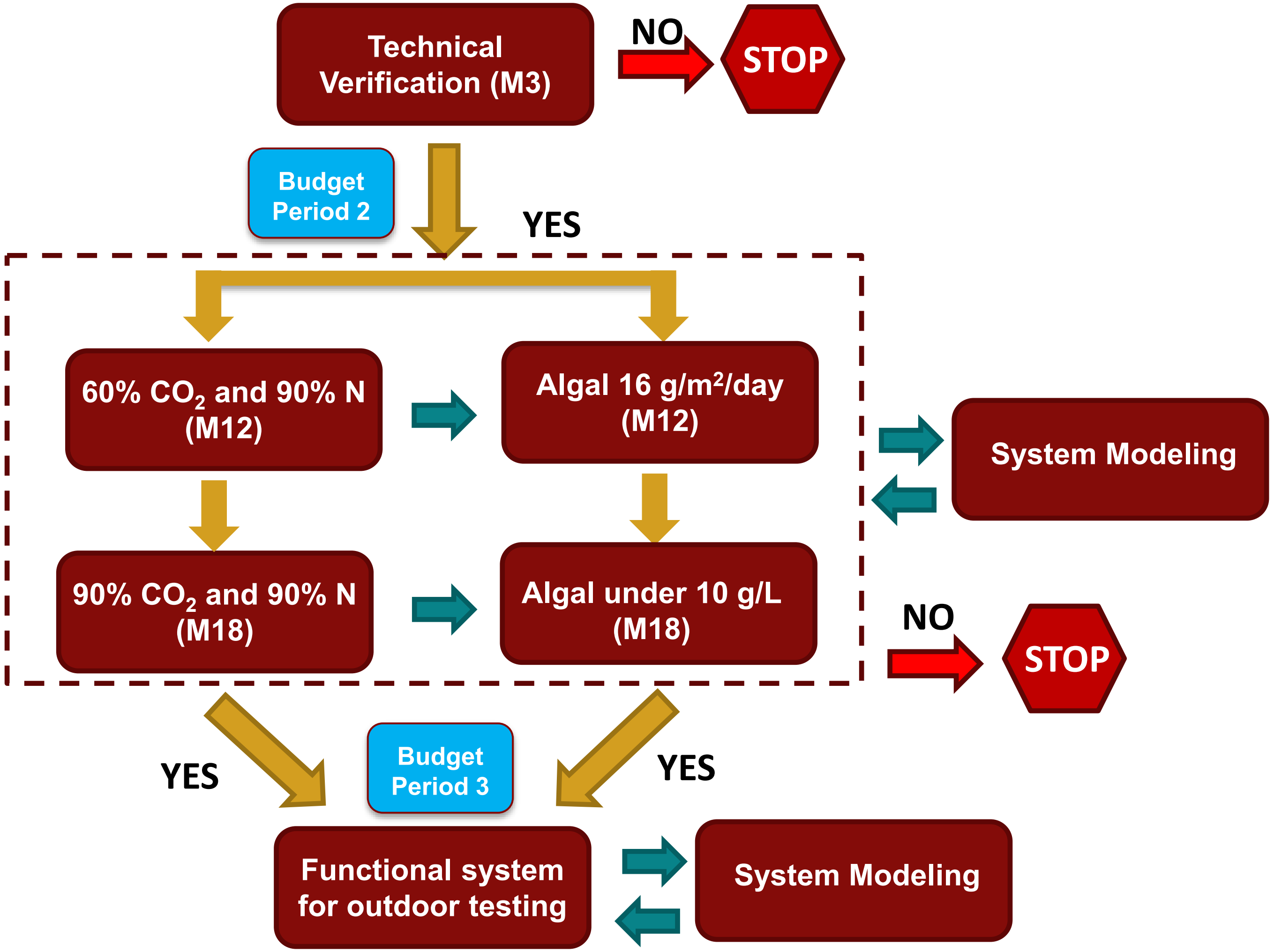
Task 1: Initial technical verification

Task 2: Capture of both CO_2 and ammonia by electrochemical effluent

Task 3: Adaptive evolution of algal strains for rapid growth and high CO_2 conversion in electrochemical effluent media

Task 4: Process modeling, life cycle, and techno-economic assessments

Task Integration



Go/No Go Decision Points

Budget Period 1 Go/No-Go Decision Point: (Literature) baseline performance metrics verified.

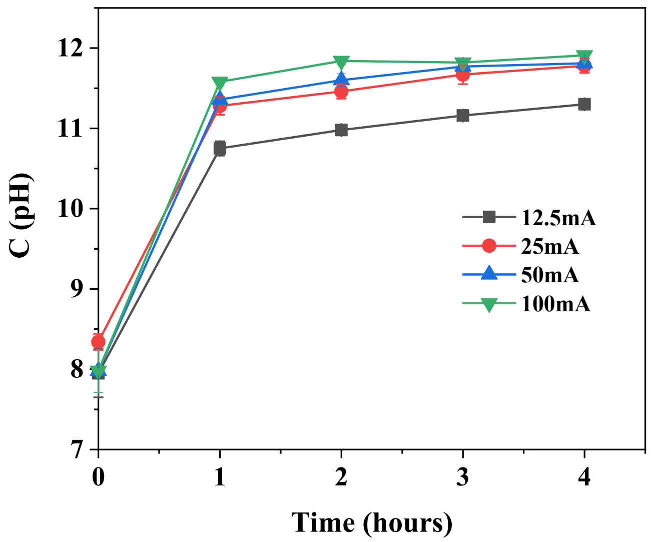
Budget Period 2 Go/No-Go Decision Point #2: Controllable electrochemical systems to generate desired C/N ratios between 5/1 and 20/1 and capture>90% of CO_2. Successful cultivation of algal strains with (overall) carbon utilization efficiency of 55% and algal biomass productivity of >16 g m^{-2} d^{-1} under a salinity of 10 g L^{-1} in the lab. Establishments of algal process and control model, initial LCA and TEA models.

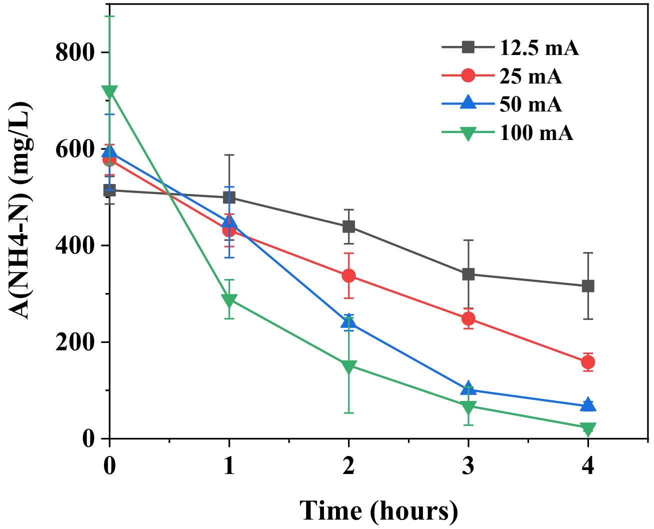
End of Project Goal: The end of project goal is to demonstrate a scalable and innovative algae growing system evolving from TRL 3 to TRL 4. At the end of the project, a demonstration-scale system will be able to convert more than 70% of the supplied CO_2 (as bicarbonate) into algal biomass with a productivity > 20 g m^{-2} d^{-1} under a maximum salinity of 15 g L^{-1}; such results will be obtained from the outdoor operation for a period of at least 30 days. A comprehensive model with predictive control will be developed for optimal algal cultivations. Both LCA and TEA models are finalized to provide information that can guide next-stage development.

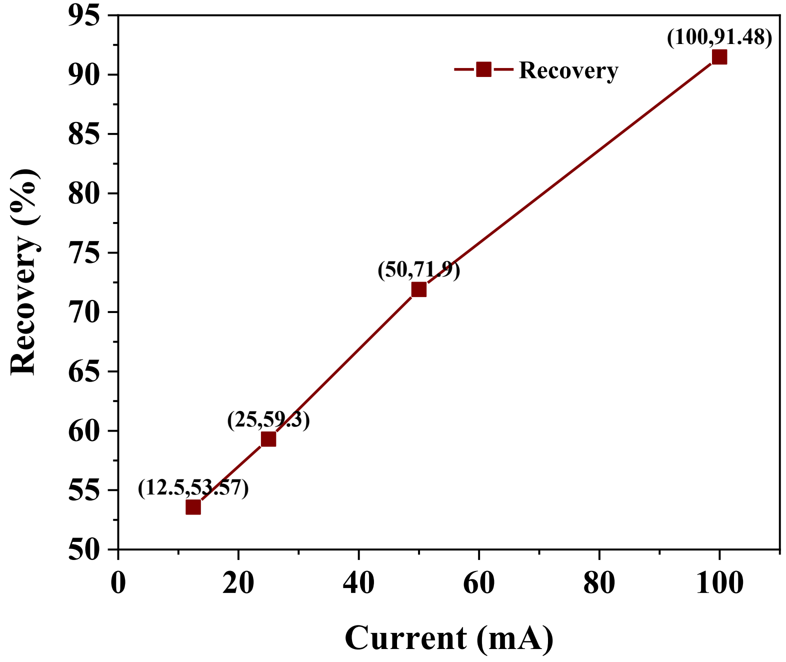
Progress and Outcome

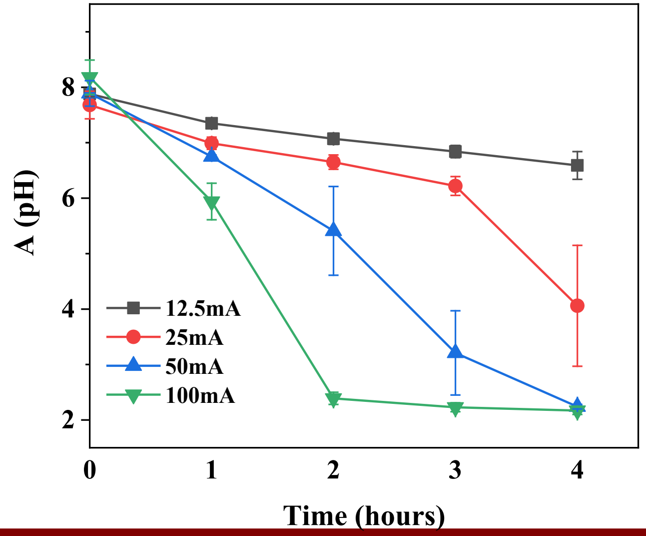
- Budget Period 1 Go/No-Go Decision Point (FY23Q4)
- [Milestone 2.1.1] Electrochemical systems driven by power supply can recover >90% of ammonium from AD centrate and generate an alkaline solution with a pH >11(FY24Q1)
- [Milestone 3.1.1] Either Scenedesmus or Chlorella strain can grow in medium containing at least 30 mM ammonium/ammonia and 168 mM bicarbonate/carbonate (FY24Q3)
- [Milestone 4.1.1] Development of multiple-substrate algal growth model coupled with lighting and temperature functions via MATLAB Simulink platform (FY24Q3)
- [Milestone 4.2.1] Draft version of GREET with pathway for the proposed system (FY24Q2)
- [Milestone 4.3.1] Establish a process model for the proposed system based on the experimental data (FY24Q1)

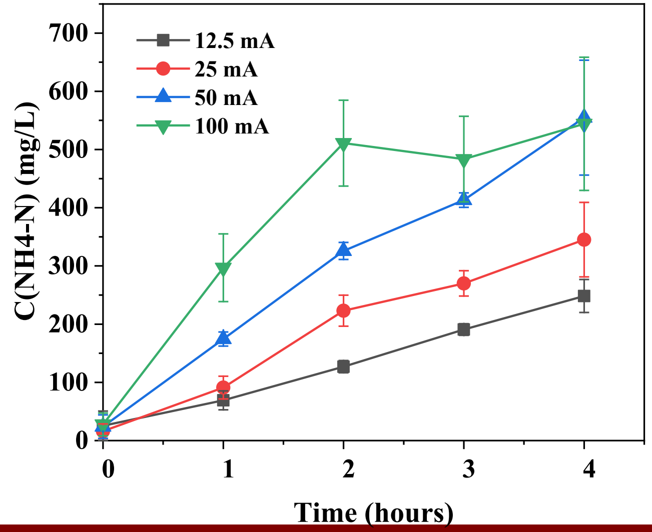
Task 2: CO_2 capture and ammonia recovery











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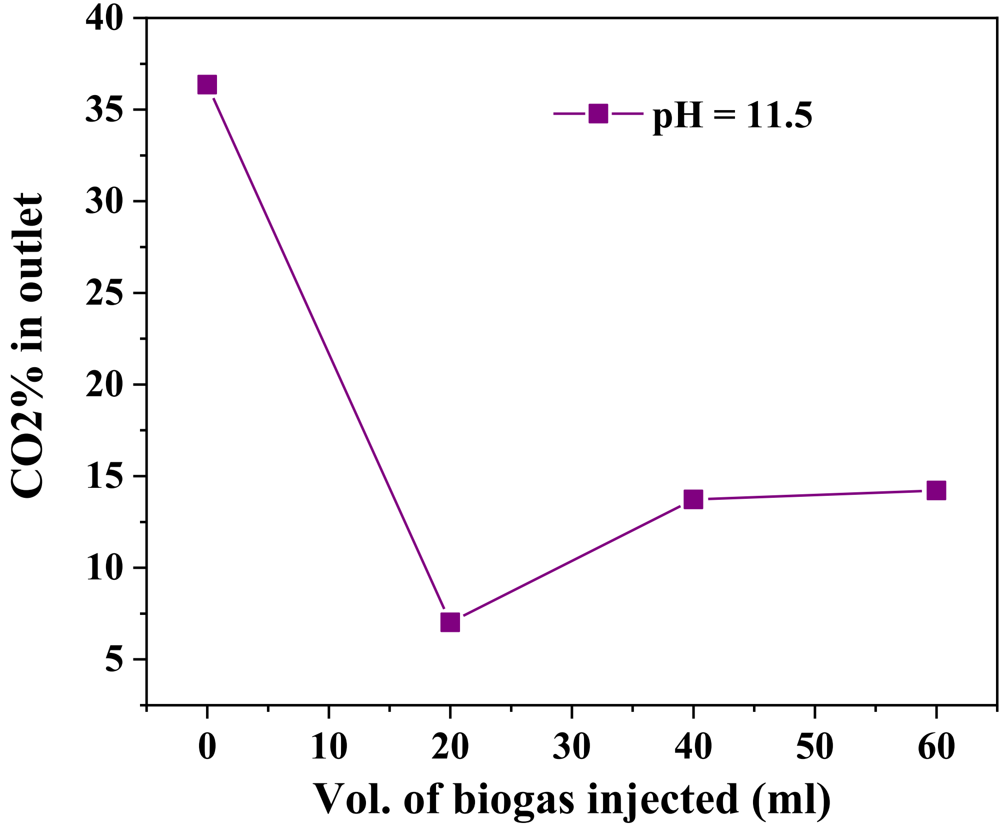
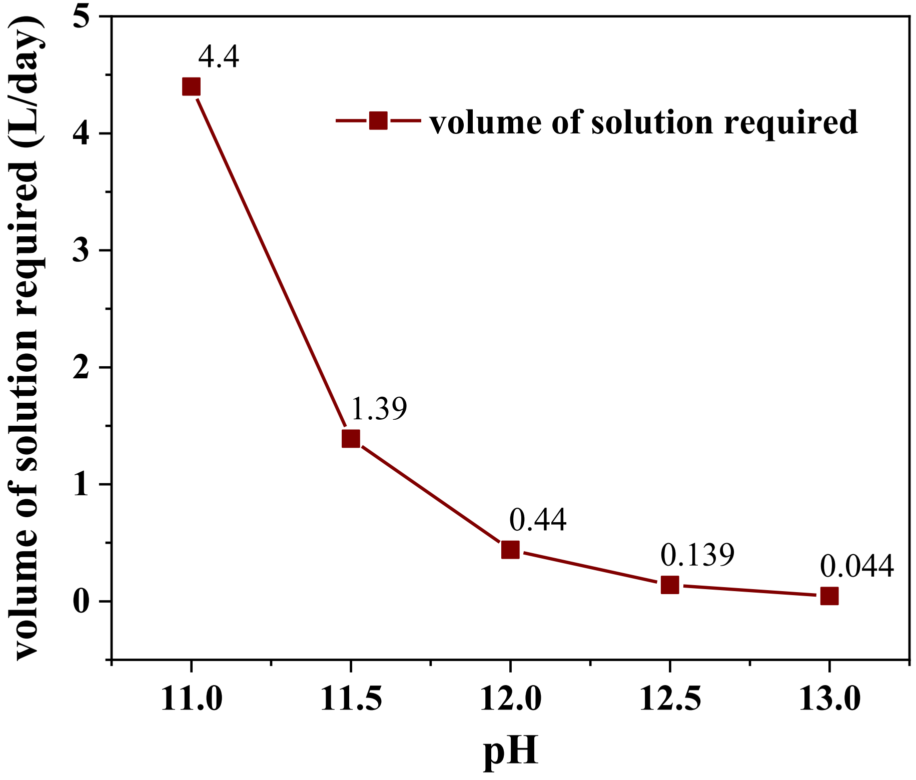
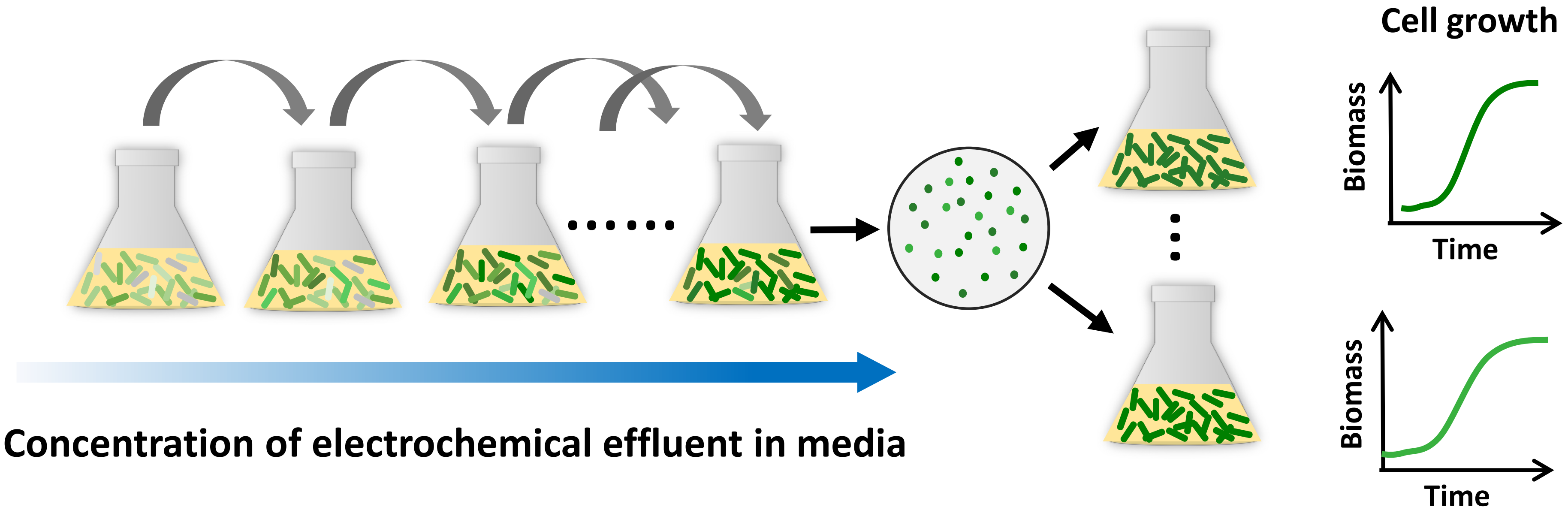




Task 3: Algal strain adaptation

Adaptive evolution to evolve *Chlorella Sorokiniana* strains

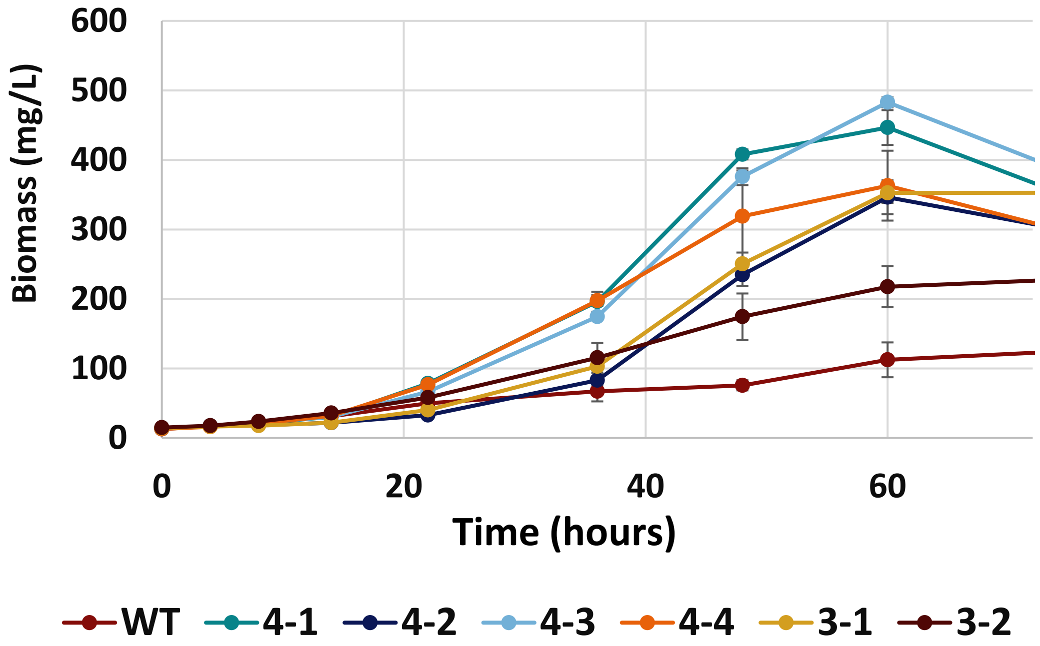


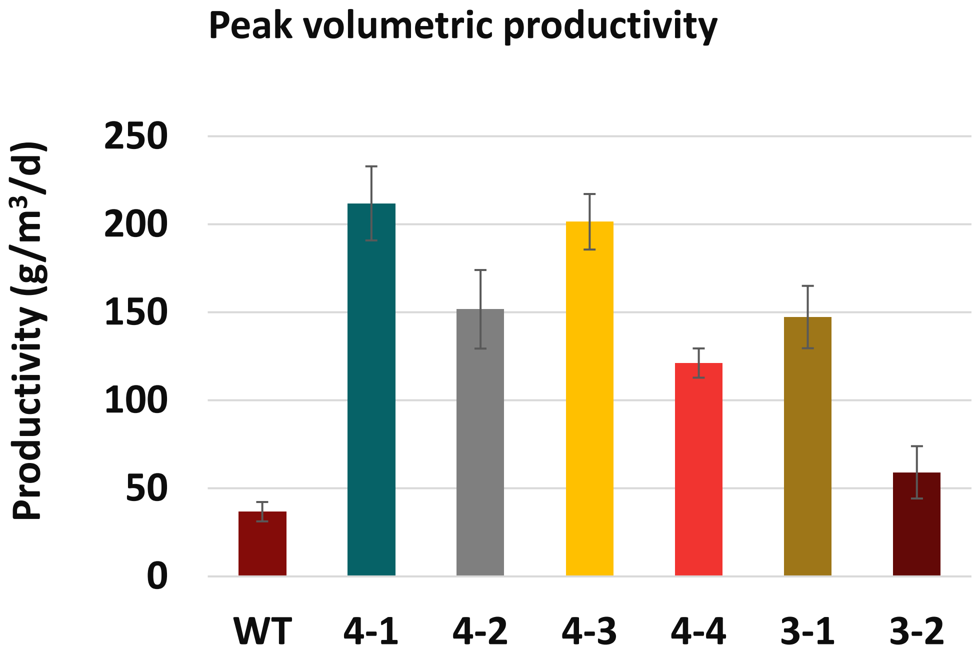
Wt C. Sorokiniana —*EMS*→ Mutated cells —*Wash and Incubate*→ Recovered cells —*stress*→ Cells with stress tolerance

Increasing $(NH_4)HCO_3$ concentrations

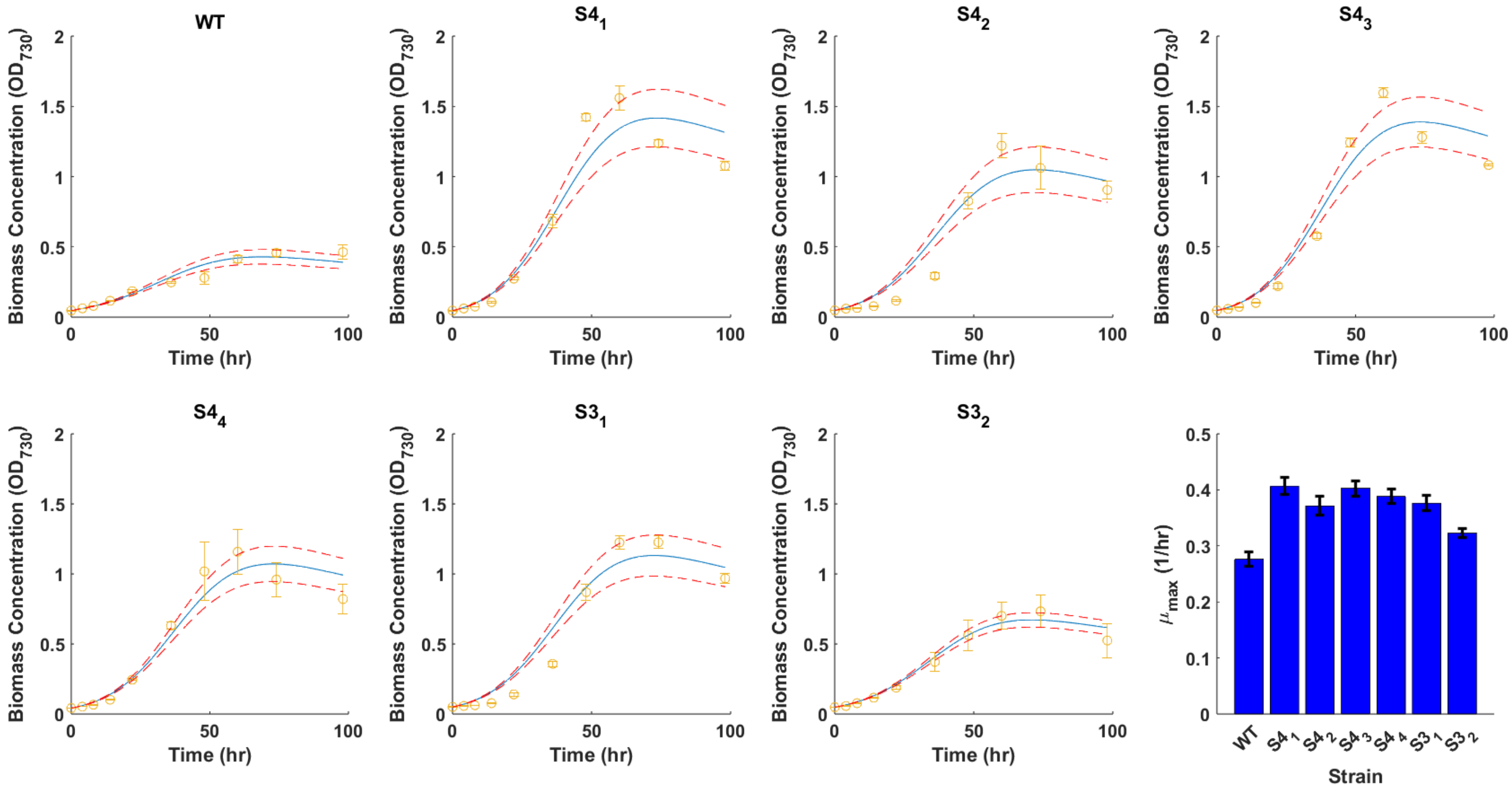
Task 3: Algal strain adaptation

Growth Curve in concentrated NH_4HCO_3 medium
168 mM HCO_3^- & 30 mM NH_4^+





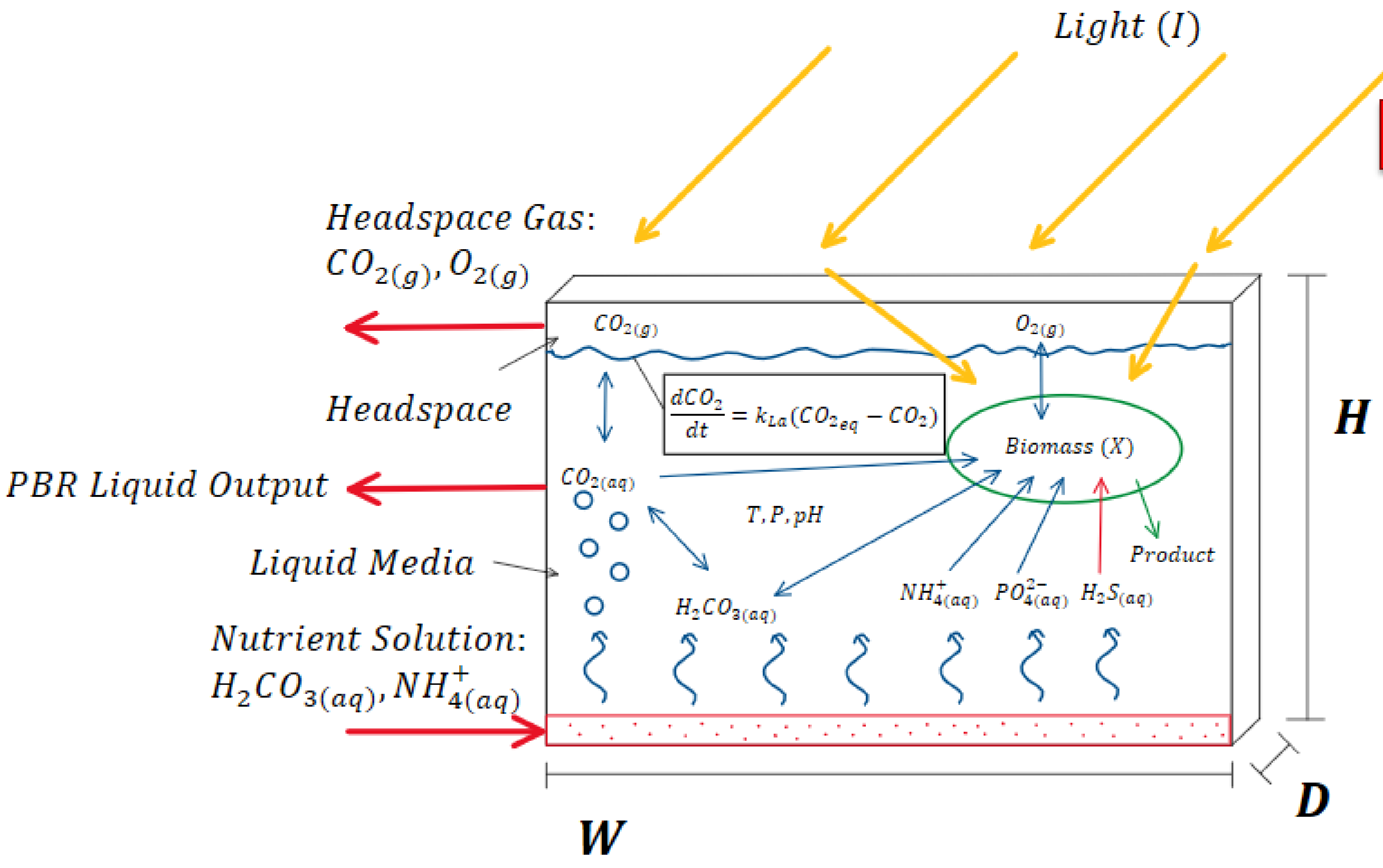
Task 4: Process modeling

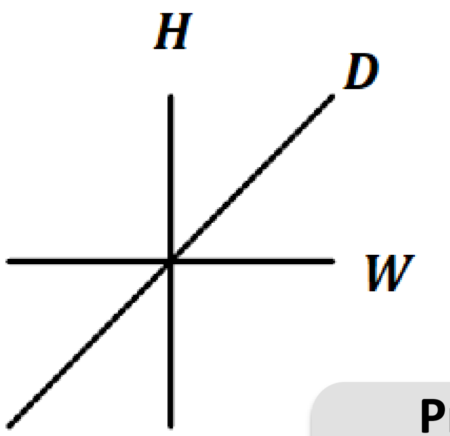


O: experimental data
---: model prediction
---: 95% confidence intervals for model prediction

: fitted values for μ_{max} parameter from nonlinear regression

Task 4: Process modeling



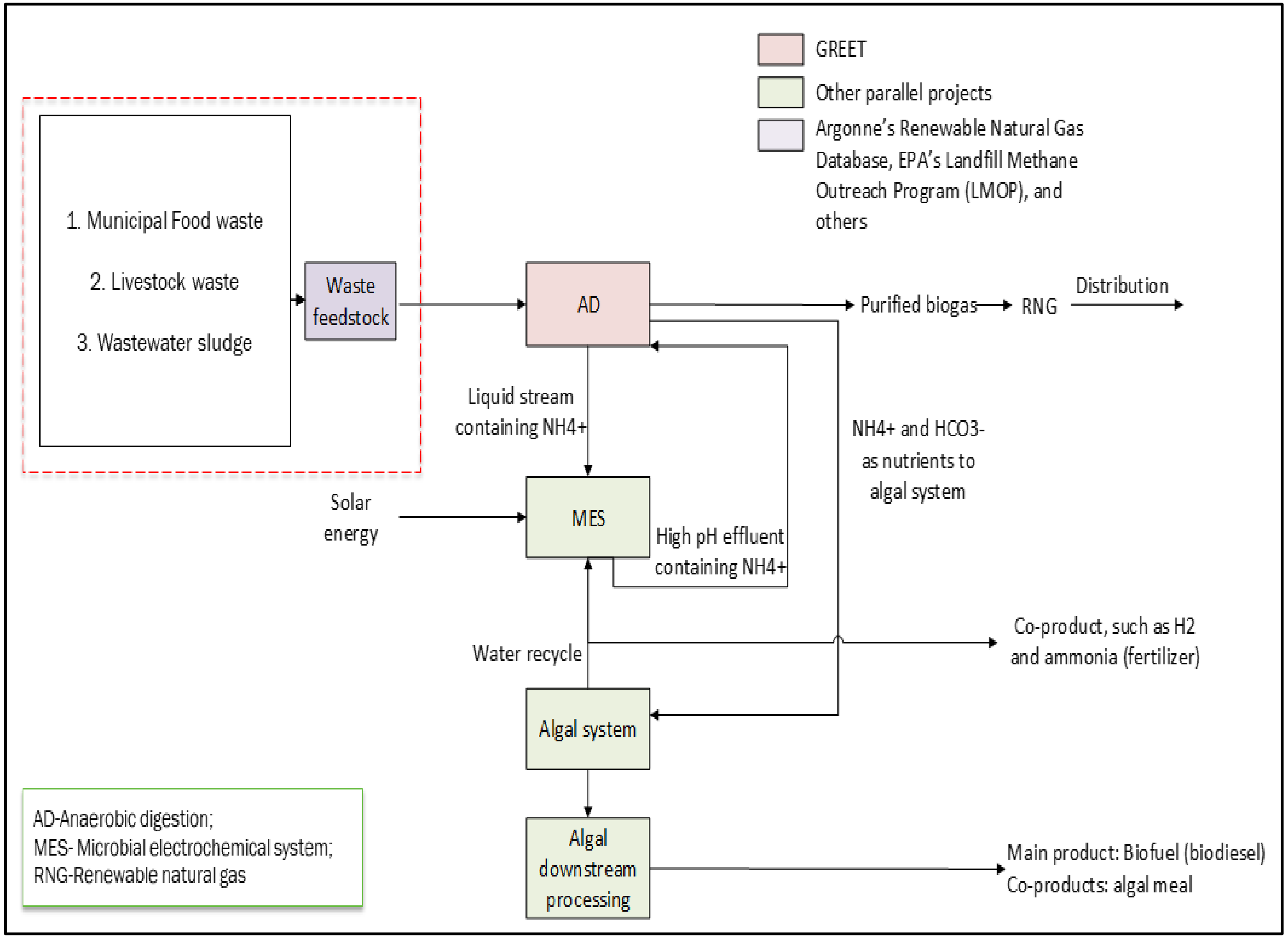


Kinetic Model:

$$\frac{dy_i}{dt} = f(t, y_1, y_2, \ldots, y_n)$$

Predictive Model Control, Bioprocess Optimization

Task 4: Life cycle assessment

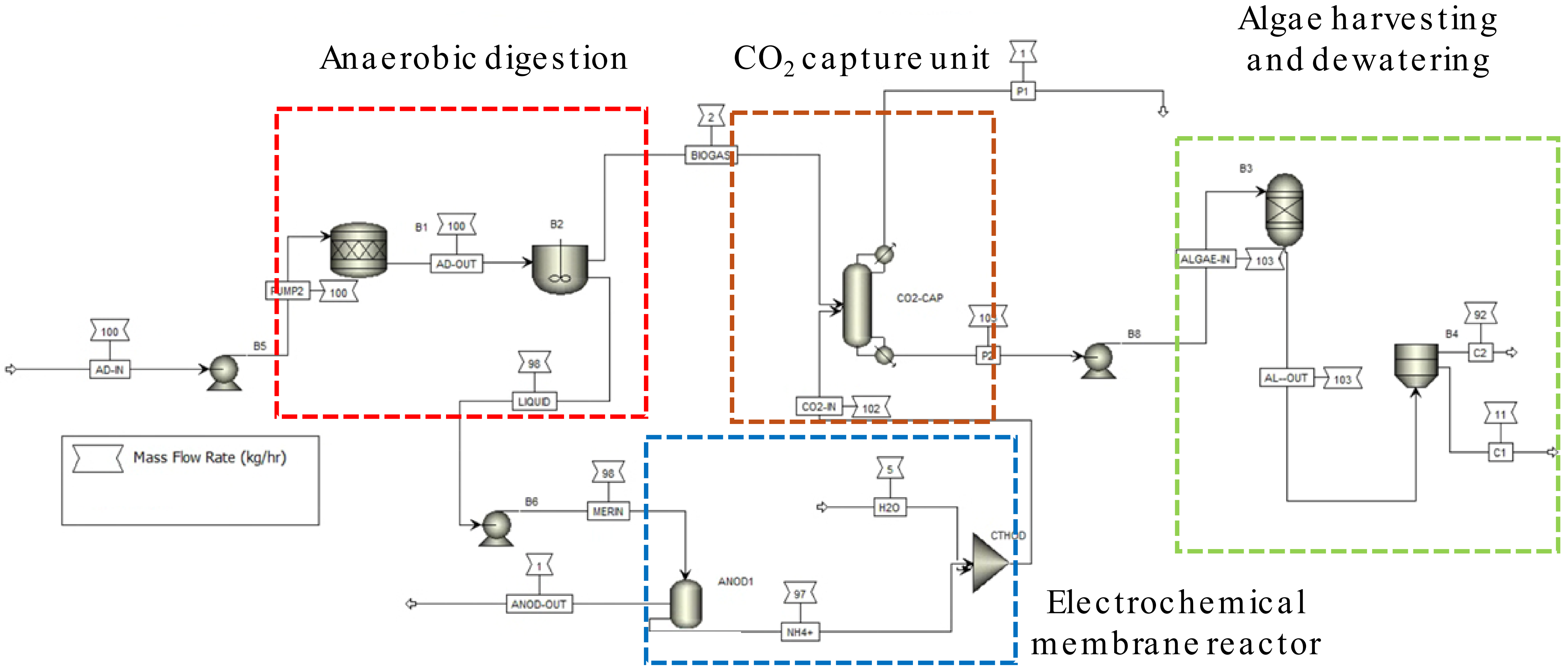


Building LCA model framework:

Existing data resources:

- AD: existing GREET model
- MES: leverage the model framework for MEC from another parallel project
- Photobioreactor: leverage the model framework for PBR from another project

Task 4: Techno-Economic Analysis



Community Benefit Activities

- >50% trainees (undergraduates, graduate students, and postdocs) are from the minority/underrepresented groups
- We showcased our cyanobacteria culture system to kids who visited Saint Louis Science Center for the SciFest (July 13).
- Two undergraduate students from Lincoln University of Missouri are currently conducting summer research on algal growth at WashU.

Challenges and Lessons

- pH 11.5 is not sufficient for CO_2 absorption

  Mitigation: increase the target pH to 12.5 by the electrochemical cell

- N_2 gas occurs in the upgraded biogas

  Mitigation: examine sampling methods to minimize N_2 gas

- Algal species could not grow well under a high pH condition

  Mitigation: a new electrochemical cell to generate acidic solution for pH buffering

- Industrial partner

  Mitigation: purchase a commercial PBR system with the similar design

Plans for future testing/development/commercialization

- Continue the proposed work with a target BP2 verification in February/March of 2025
- Identify new industrial partners with a focus on technology development beyond this DOE project (instead of replacing Clearas in the proposed work)
- Explore the interest of Wastewater Treatment Facilities and livestock AD facilities in the proposed technology
- Formulate a strategy for system scaling up (to 50 L in total) for BP3 work, especially electrochemical cells

Summary

- This project has successfully passed the Initial Verification.
- The initial results have demonstrated that the proposed system can capture more than 60% of CO_2 in the simulated biogas
- Algal species was adapted to the target concentrations of both bicarbonate and ammonium
- Initial process/LCA/TEA models are being developed.
- The project is moving forward as scheduled in the Budget Period 2