Continuous Algae-based Carbon Capture and Utilization (CACCU) to Transform Economics and Environmental Impacts: DE FE 0032108

Texas A&M University

Washington University in St Louis

NCCC at Southern Company

U.S. Department of Energy

National Energy Technology Laboratory
Carbon Management Project Review Meeting
August, 2023

Susie Dai
Texas A&M University

August 29, 2023

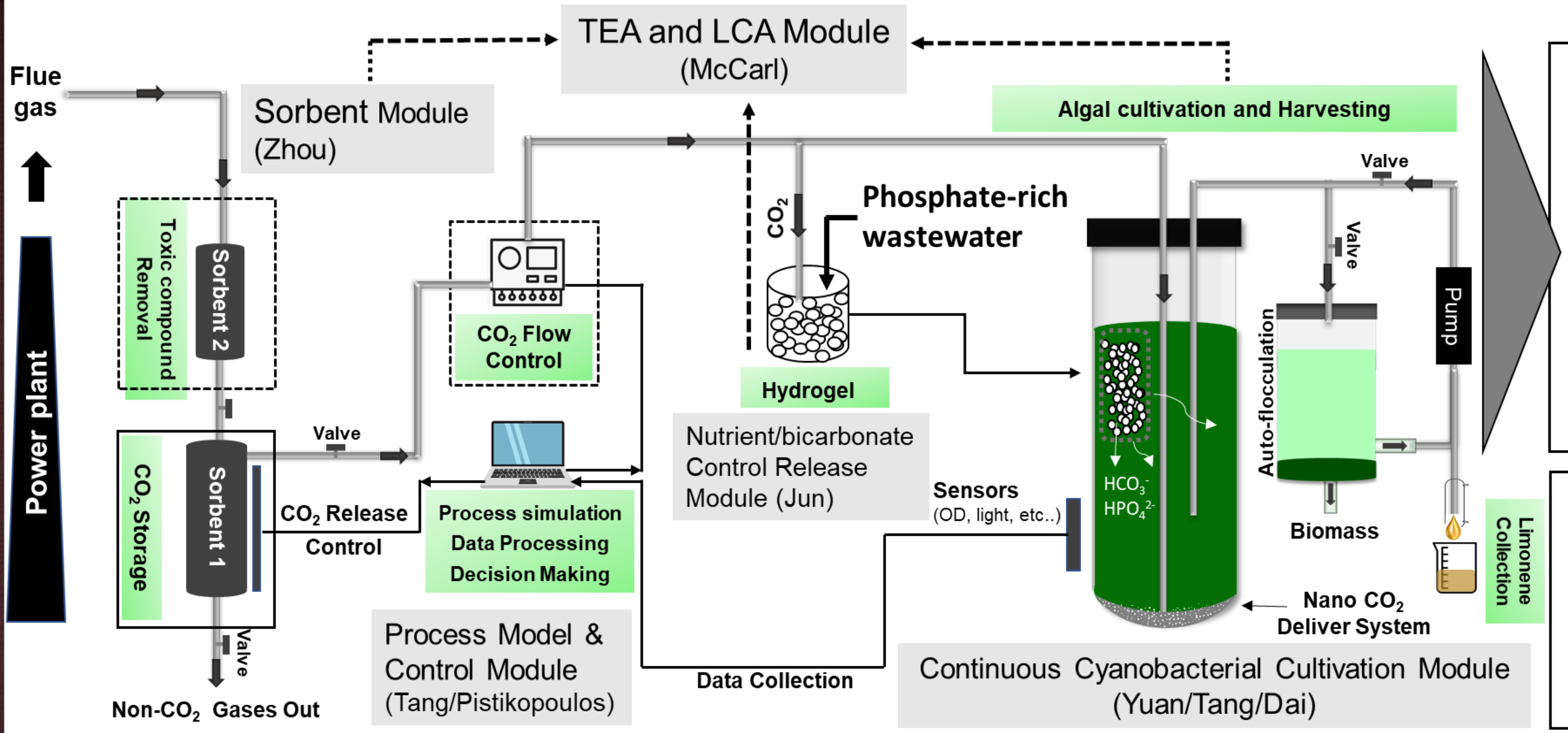
Project Overview

- Funding
  - DOE $2,000,000; Cost Share $510,583
- Overall Project Performance Dates
  - Original 10/01/2021-09/30/2024
  - Currently: with six-month extension due to late start of the entire project
- Project Participants
  - TAMU: Susie Dai, Bruce McCarl, Stratos Pistikopoulos, Chengcheng Fei
  - WUSTL: Young-shin Jun, Yinjie Tang, Joshua Yuan
  - NCCC at Southern Company: Frank Morten

Overall Project Objectives

- The project integrates novel CO_2 capture/controlled release sorbent with a breakthrough continuous algal cultivation system, assisted by hydrogel technology to reduce media cost, fertilize the algae with controlled nutrient delivery.
- Objective 1: Project management.
- Objective 2: Integrates CO_2, bicarbonate, and nutrient capture and delivery to the low-cost harvest-empowered continuous algal cultivation system with ultra-high productivity and CO_2 uptake plus valuable chemical bioproduct production. We also advance algal strain, sorbent, and hydrogel technologies to enhance carbon capture and yields of limonene, biomass, and glycogen.
- Objective 3: Scale up the sorbent technology and integrate it with algal cultivation.
- Objective 4: Test the prototype CACCU system with flue-gas coupled 100 L photobioreactors (PBRs).

Technology Background



Outcomes

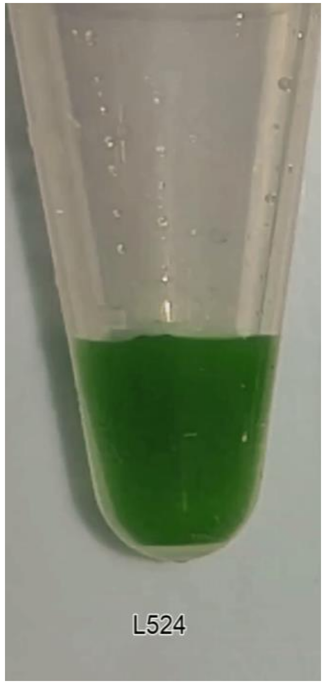
- Sorbent CO_2 capture
- Gel nutrient release
- Fast algal growth
- Easy Biomass harvest
- Process integration
- Optimal Design
- Process control
- Capital Cost
- Operating Cost
- Biomass profit
- Environmental benefits

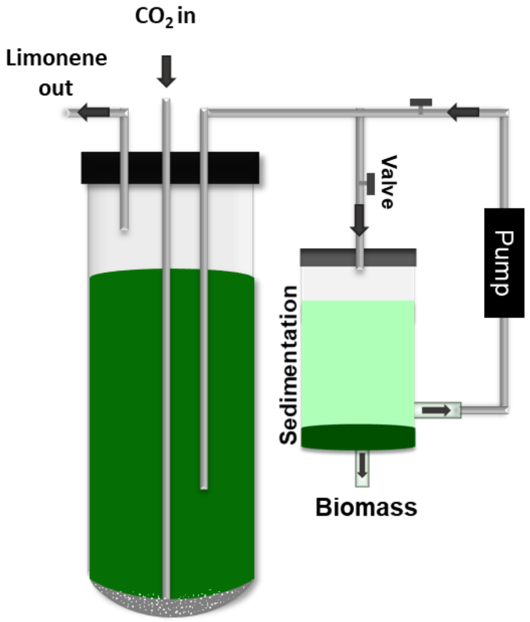
Milestones

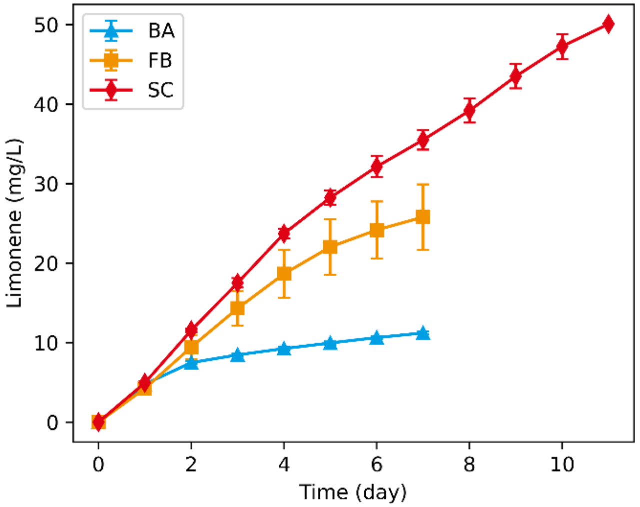
Year 1: Small scale lab tests (bio and abiotic studies)
Year 2: 20~100 L PBR test
Year 3: Outdoor tests and TEA/LCA (>100 L)

The integrated CACCU system

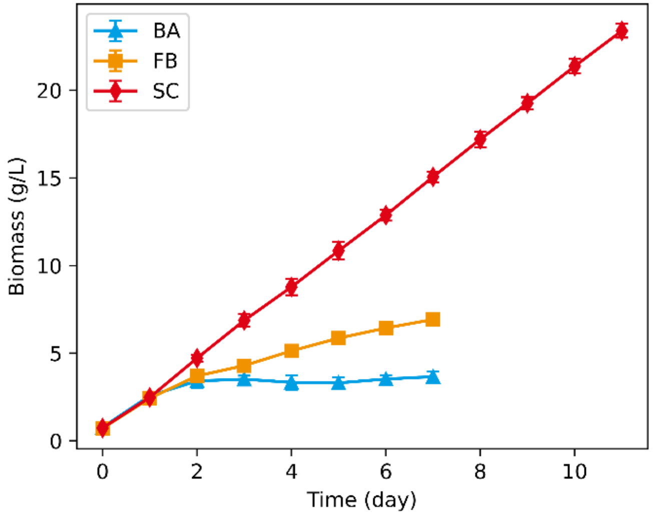
Sustainable co-production of limonene and biomass by semi-continuous cultivation







~5 mg/L/day



~2.2 g/L/day

Record productivities and yields in limonene productivity

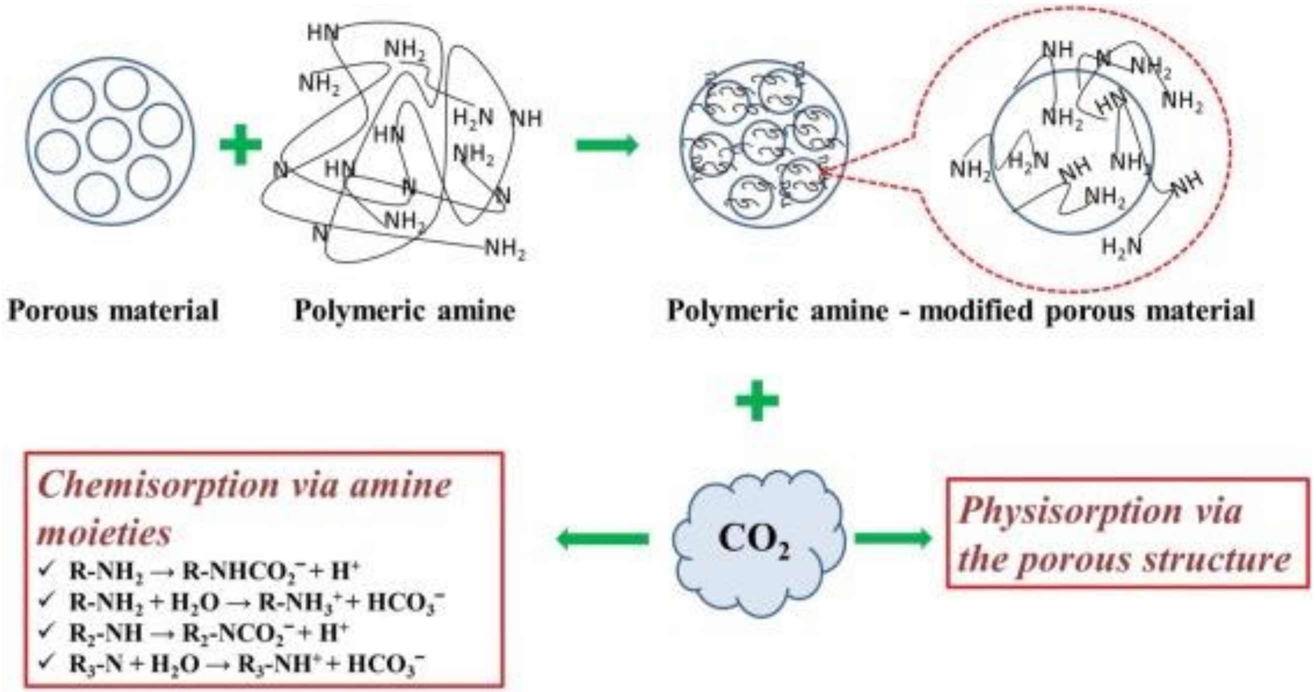
Sustainable biomass accumulation at about 1-2g/L/Day for a long period of time.

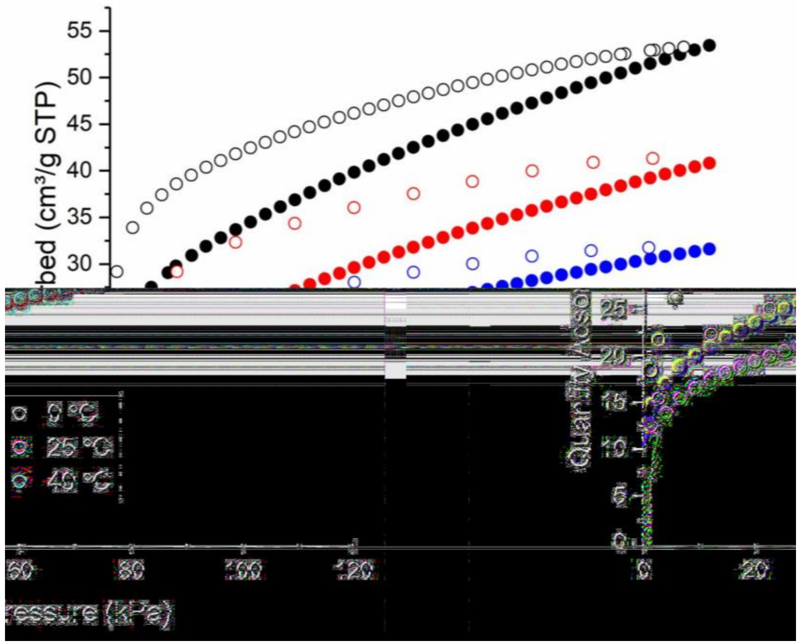
Machine learning informed semi- continuous cultivation.

Dai and Yuan's groups@TAMU

Long et al., Nature Communications, 2022, 13:541

Amine Grafted Porous Polymer Network





CO_2 adsorption of PPN-151-DETA

Zhou’s group@TAMU

Mineral-seeded mineral hydrogel composites for nutrient delivery and pH control

Adding salts or P and P-rich wastewater

Struvite ($NH_4MgPO_4 \cdot 6H_2O$)

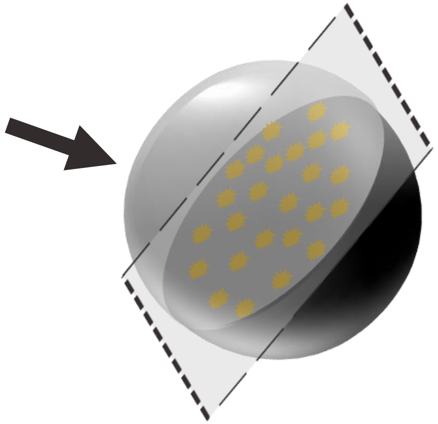
CO_2 capture/dissolution

Ca^{2+}

HPO_4^{2-}

NH_4^+

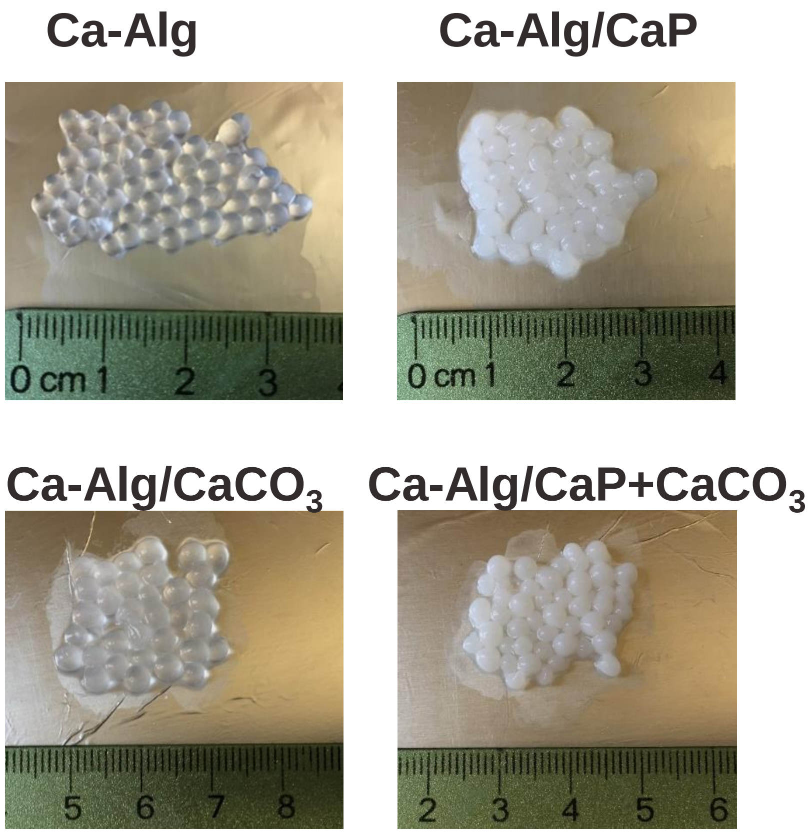
HCO_3^-



Calcium-Alginate Hydrogel (Ca-Alg)

Mineral seed

Jun and Tang's groups@WUSTL



Kim, D and Jun, Y.-S., *Green Chemistry* **2018,** *20* (2), 534-543.

- Calcium phosphate, calcium carbonate, or ammonia-containing mineral seeds formed during alginate crosslinking.
- When placed into calcium phosphate/carbonate supersaturated solution, mineral seeds grow, collecting and incorporating phosphate, bicarbonate, and ammonia-containing minerals.

Translating process models into a process systems engineering framework at scale involves some critical steps

1) Accurate modeling of process dynamics

2) Reduced order approximation of nonlinear dynamics

Surrogate linear models can tame computational complexity

Linear programs can provide *certificates of optimality*

3) Design of control scheme

4) Formulation of a network design as a mixed integer program (MIP)

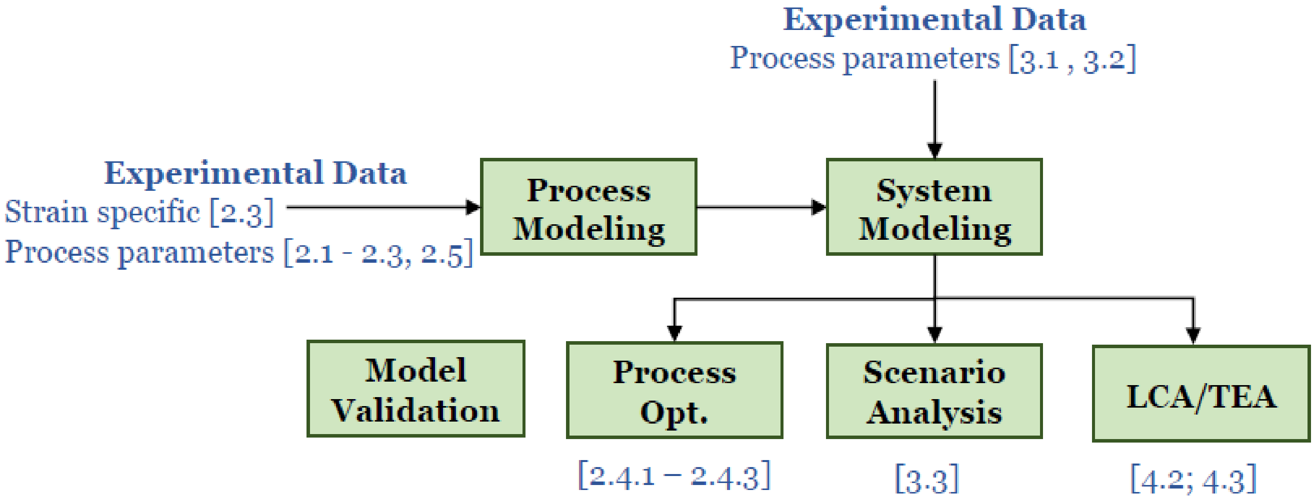
MIPs can be optimized to multiple objectives

Network decisions can be modeled as binary variables

Scheduling can be integrated (multiscale approach)

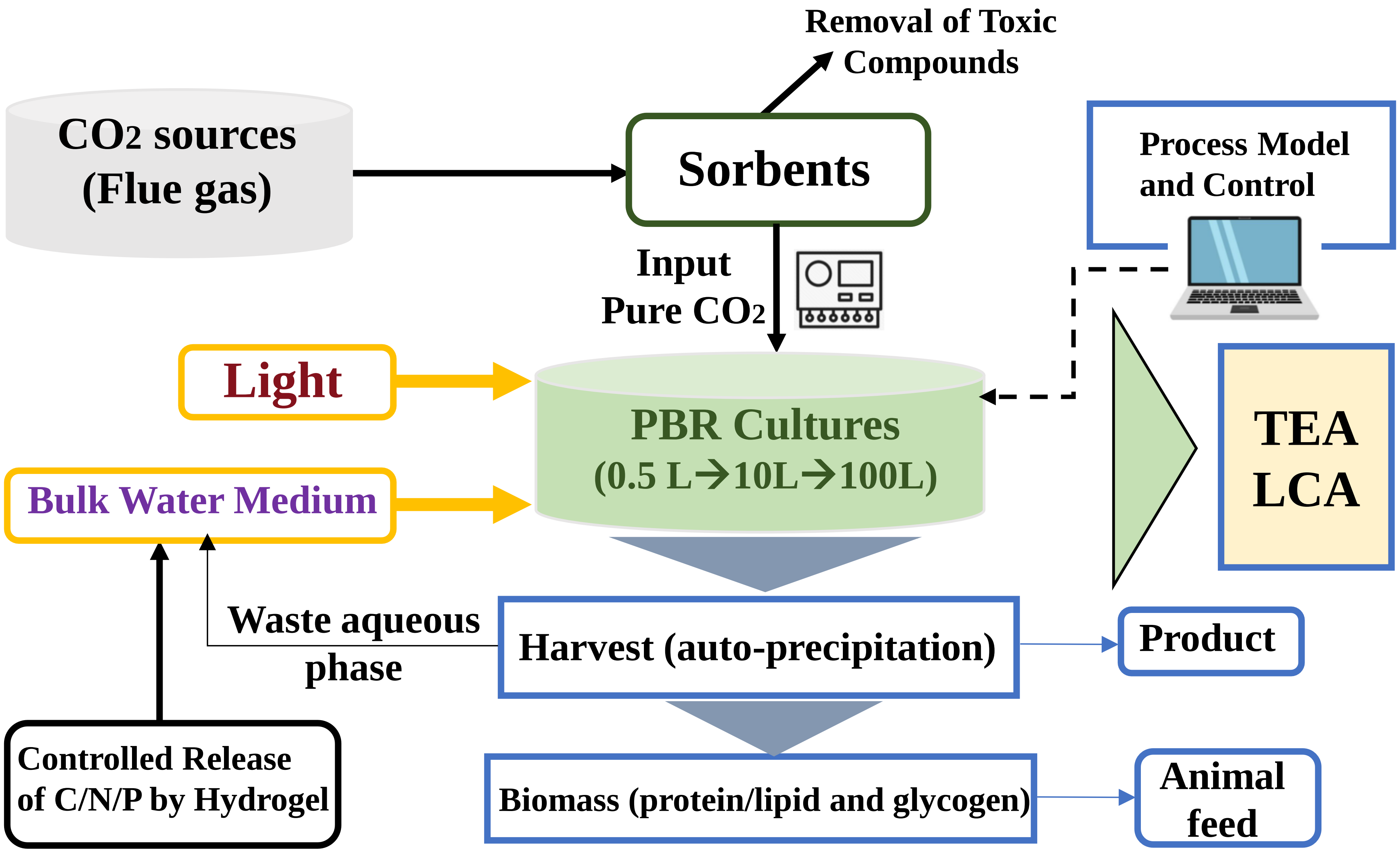
5) Integration of lifecycle tools

OpenLCA data integration with MIP framework (MIP)



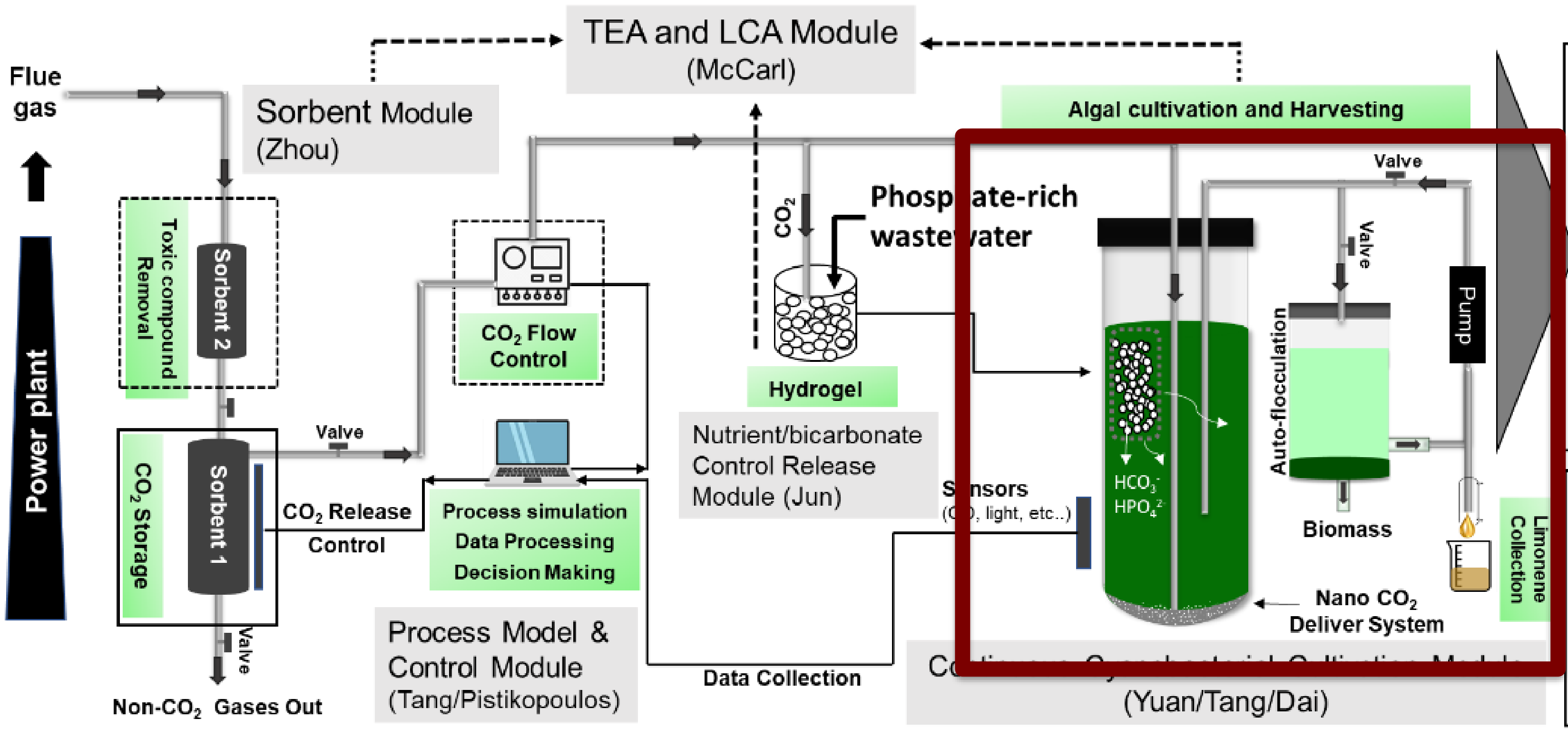
Tang, Pistikopoulos and McCarl’s groups@TAMU&WUSTL

Technical Approach/Project Scope



Progress

Task	Milestone Title	Baseline	Complete Date	Status
2.1.1	**Achieve average algae biomass yield 1.2g/L/D using sorbent-released CO_2, with optimized release rate and composition, along with nutrient optimization, at 0.5 Liter scale**	1g/L/Day with 5% of CO_2 from commercial source	Q6(03/31/2023) (previous version: Q4)	**Completed** **1.94 g/L/D at 0.5L scale, using CO_2 released from PPN-151-DETA**
2.1.2	**Obtain 2 alternative pathways**	Report the pathways and mechanisms	Q7(06/30/2023) (previously Q5)	**Completed** **Acquired alternative strains in Q4**
2.2.1	**Achieve average dry weight percent of carbonate/P/N-containing minerals -- mineral 40 wt.% at 50g scale**		Q7(06/30/2023) (previously Q5)	**Completed** **Hydrogel-based nutrient release technology (P, N and bicarbonate) has been tested**
2.3	**Achieve average algae biomass yield >1.5 g/L/D using engineered strains and sorbent-released CO_2, with optimized release rate and composition, along with nutrient optimization, at 0.5 Liter scale**	1g/L/Day with 5% of CO_2 from commercial source	Q8(09/30/2023) (previous version Q6)	**Completed** **1.94 g/L at 0.5L scale, using CO_2 released** **from PPN-151-DETA**



Outcomes

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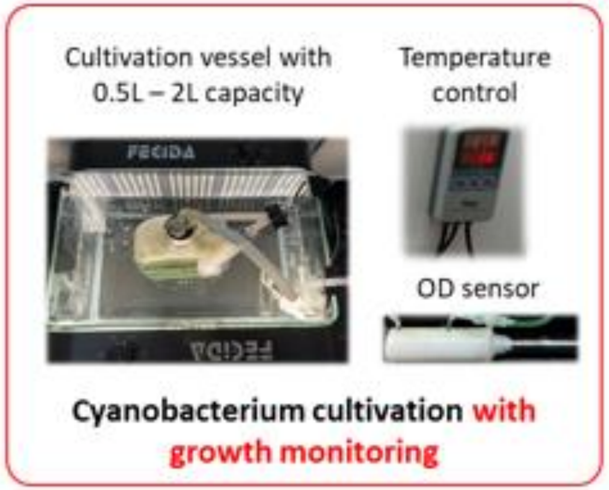
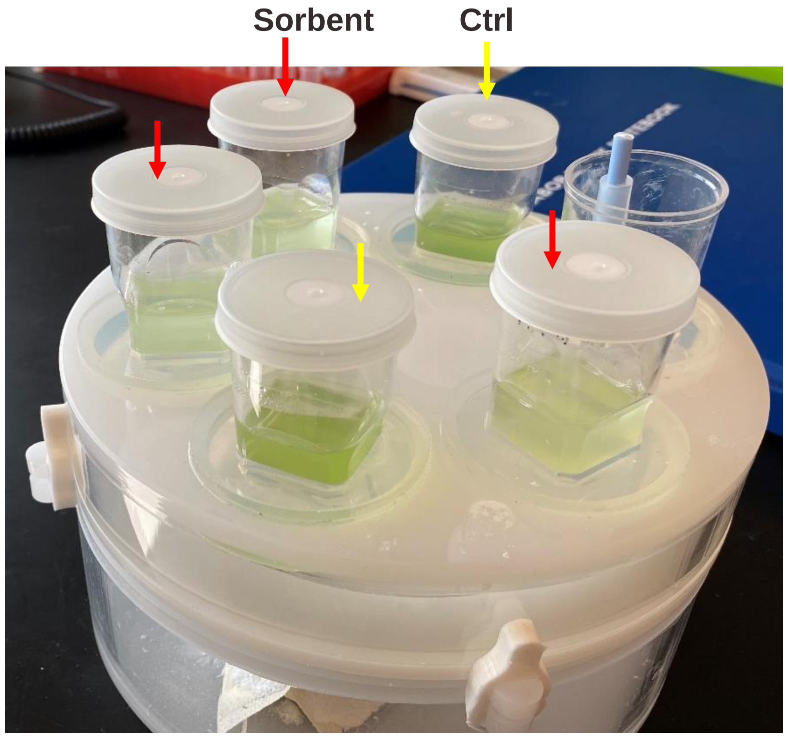
Year 2: 20~100 L PBR test
Year 3: Outdoor tests and TEA/LCA (>100 L)

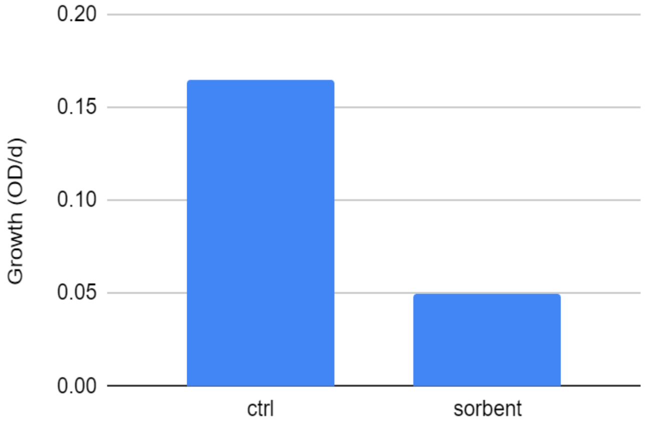


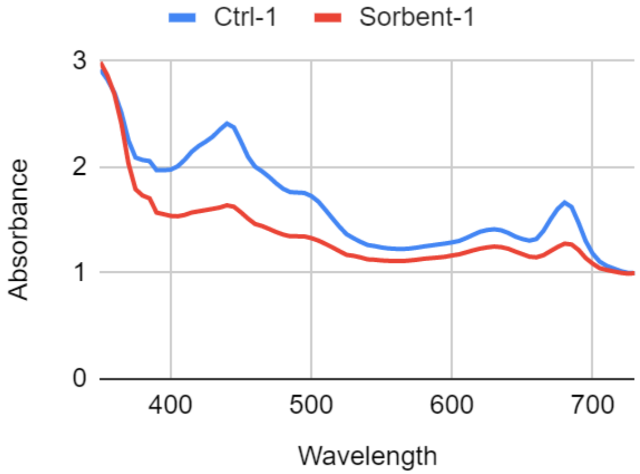
Dai's group @TAMU
Yuan's group @WashU

Sorbent-Algae integration system–Version 1



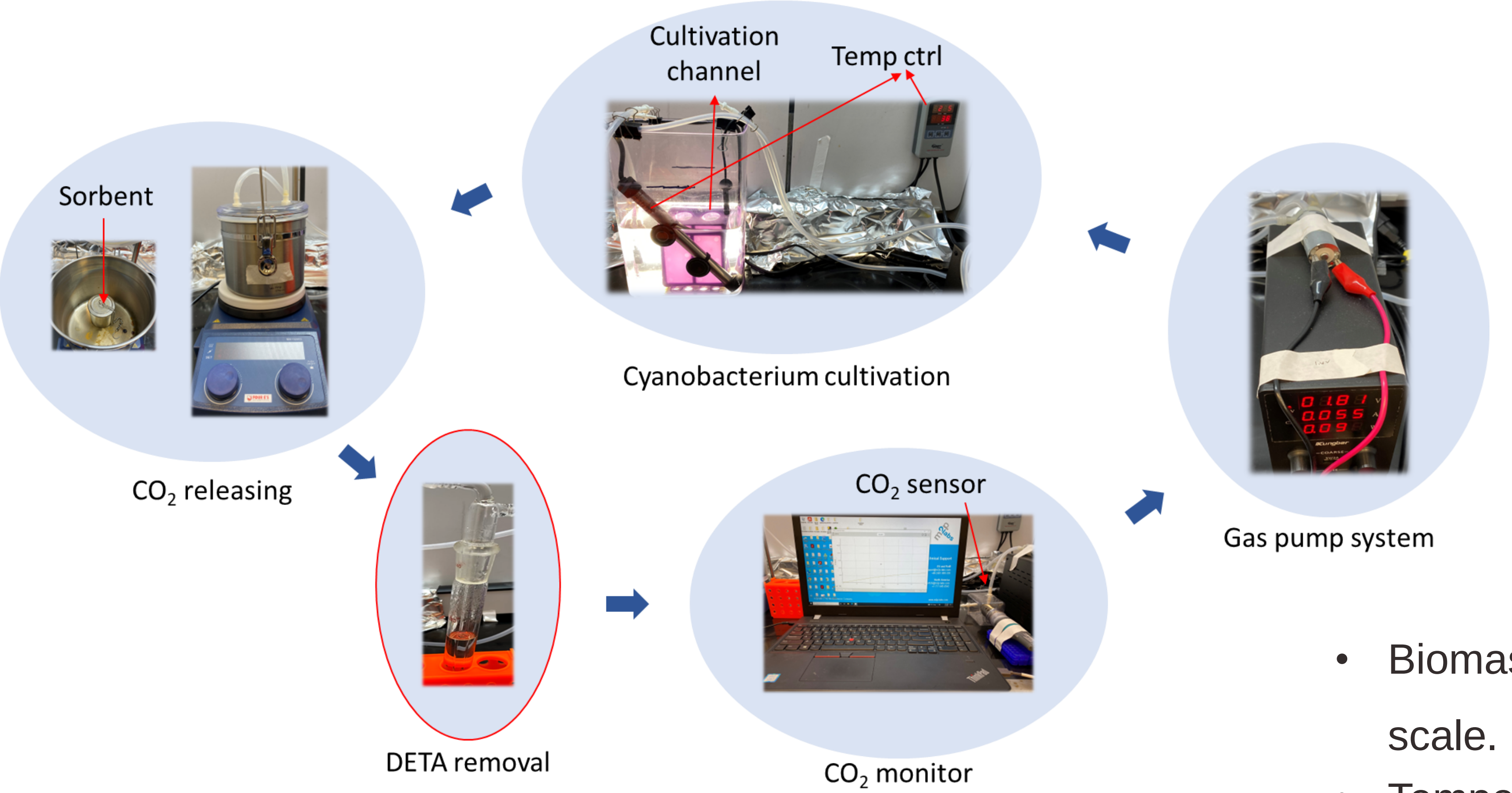
33 °C for 24h

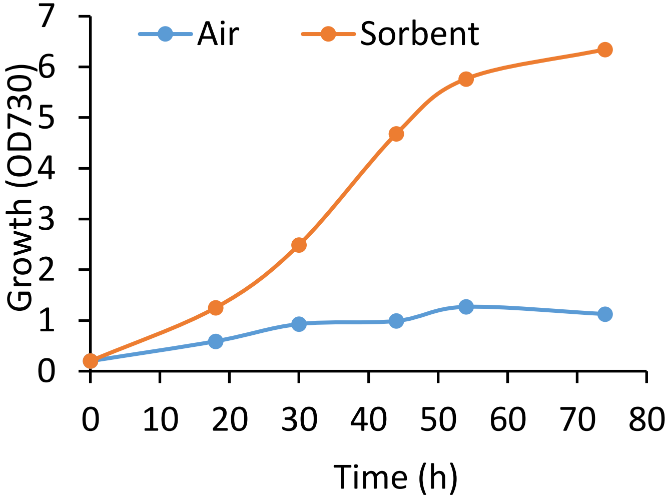




- **Significant inhibition** was observed in the sorbent group
- Cell toxicity from leached amine (DETA)

Evolution of The Integration System –Version 2





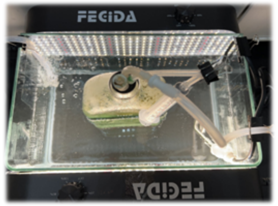
- Biomass productivity: 0.9 g/L/d at 50 ml scale.
- Temperature, light, CO_2 are not optimal.

To be improved: ❑ Scale to 0.5L ❑ Cultivation setups ❑ Sorbent heating

Evolution of The Integration System –Version 3

- ❑ Water/oil bath for sorbent heating
- ❑ Temperature sensor

Cultivation vessel with 0.5L – 2L capacity



Temperature control

Cyanobacterium cultivation

- ❑ Improved water bath to control growth temperature
- ❑ 0.5L to 2L capacity
- ❑ Improved light system

CO_2 controller

Sorbent

Water bath

Heating pad

Automatic CO_2 releasing

Gas pump

Variable power supply

Gas pump system

1M MES to remove while minimizing CO_2 dissolving

Amine removal

CO_2 data logging

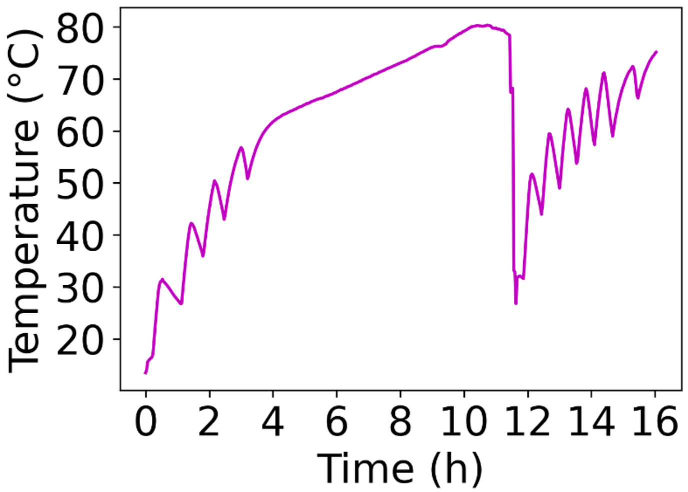
CO_2 sensor

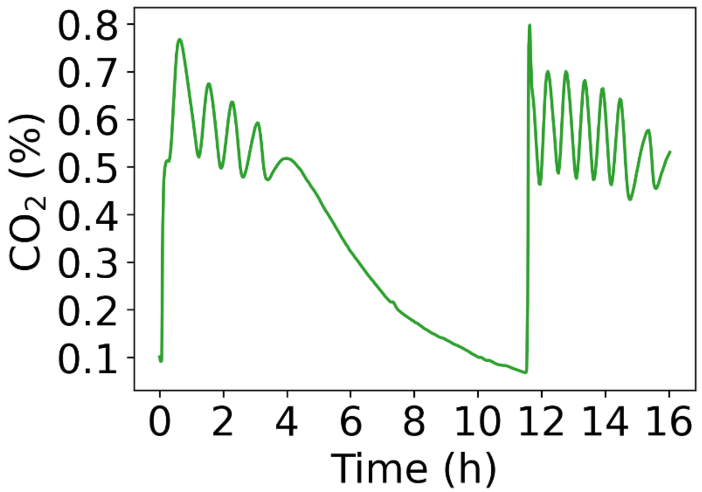
CO_2 monitor

Logged data:

- CO_2 concentration
- Sorbent temperature

Evolution of The Integration System –Version 3

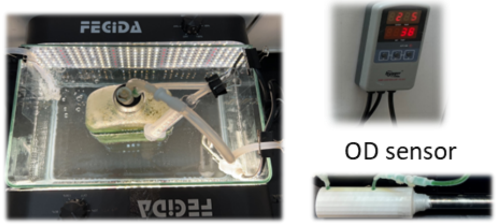




- Biomass productivity: **1.56 g/L/d** (in 16h) at 0.5L scale. **→ surpassed Q6 and Q8 milestones**
- Light is close to optimal
- CO_2 is not optimal
- No growth monitoring system

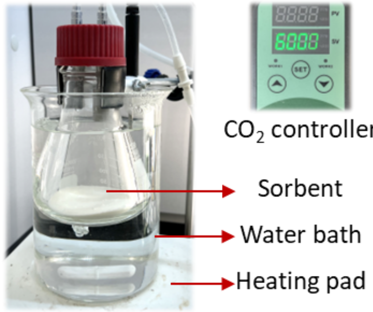
Evolution of The Integration System –Version 4

- ❑ Turbidity sensor with a 3D-printed sensor house
- ❑ Continuously collecting samples from the PBR
- ❑ Samples will be pumped back to PBR



Cyanobacterium cultivation with growth monitoring

Gas pump system



Automatic CO_2 releasing

- ❑ Replace MES with H_2SO_4 to increase its life cycle

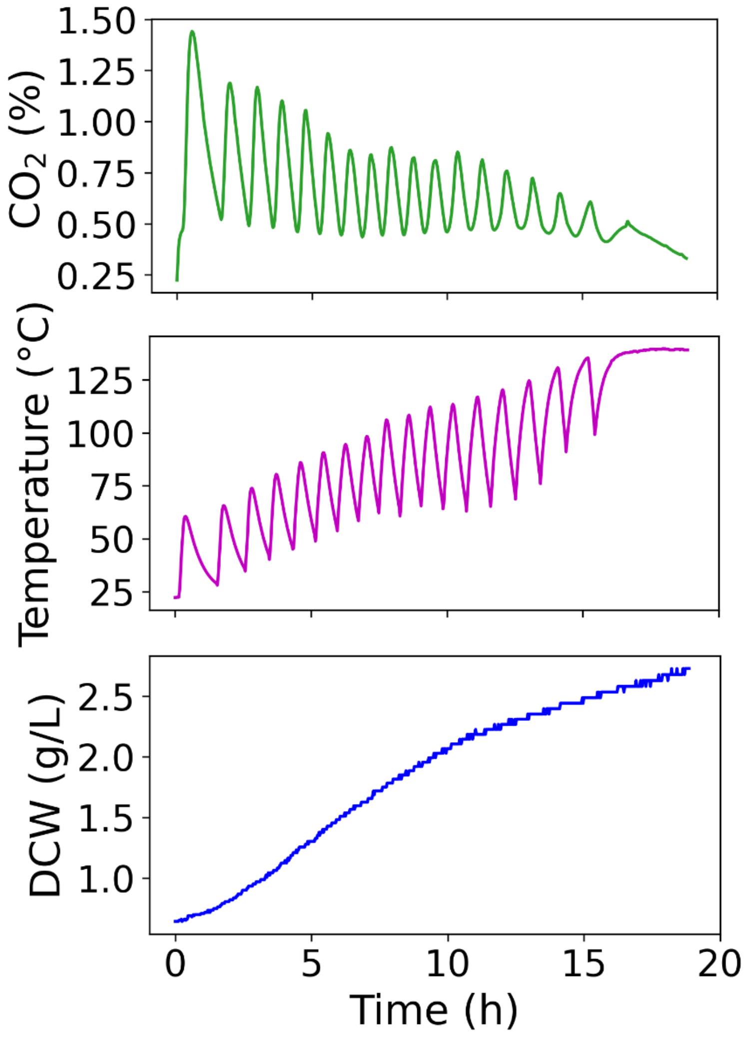
Amine removal

CO_2 monitor

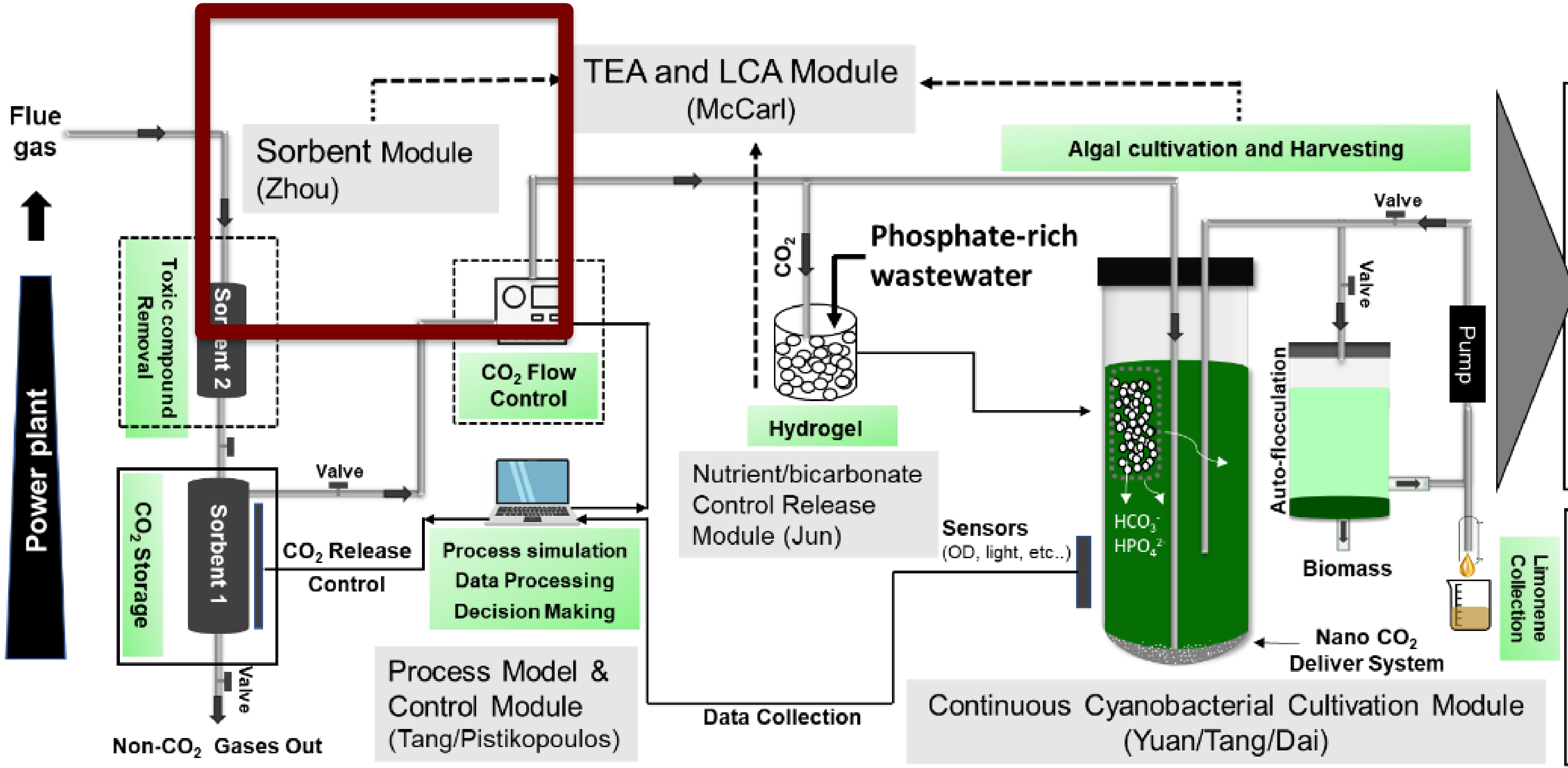
Logged data:

- CO_2 concentration
- Sorbent temperature
- Growth curve

Evolution of The Integration System –Version 4



- Achieved real-time monitoring & data logging of CO_2, sorbent temperature, and algae growth.
- Biomass productivity: 1.94 g/L/d.
- Milestones: Q6—1.2g/L/d; Q8—1.5g/L/d; Q10—1.8g/L/d (2L).



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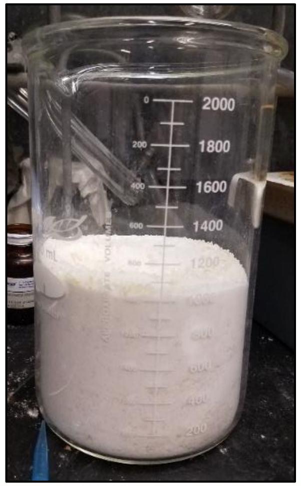
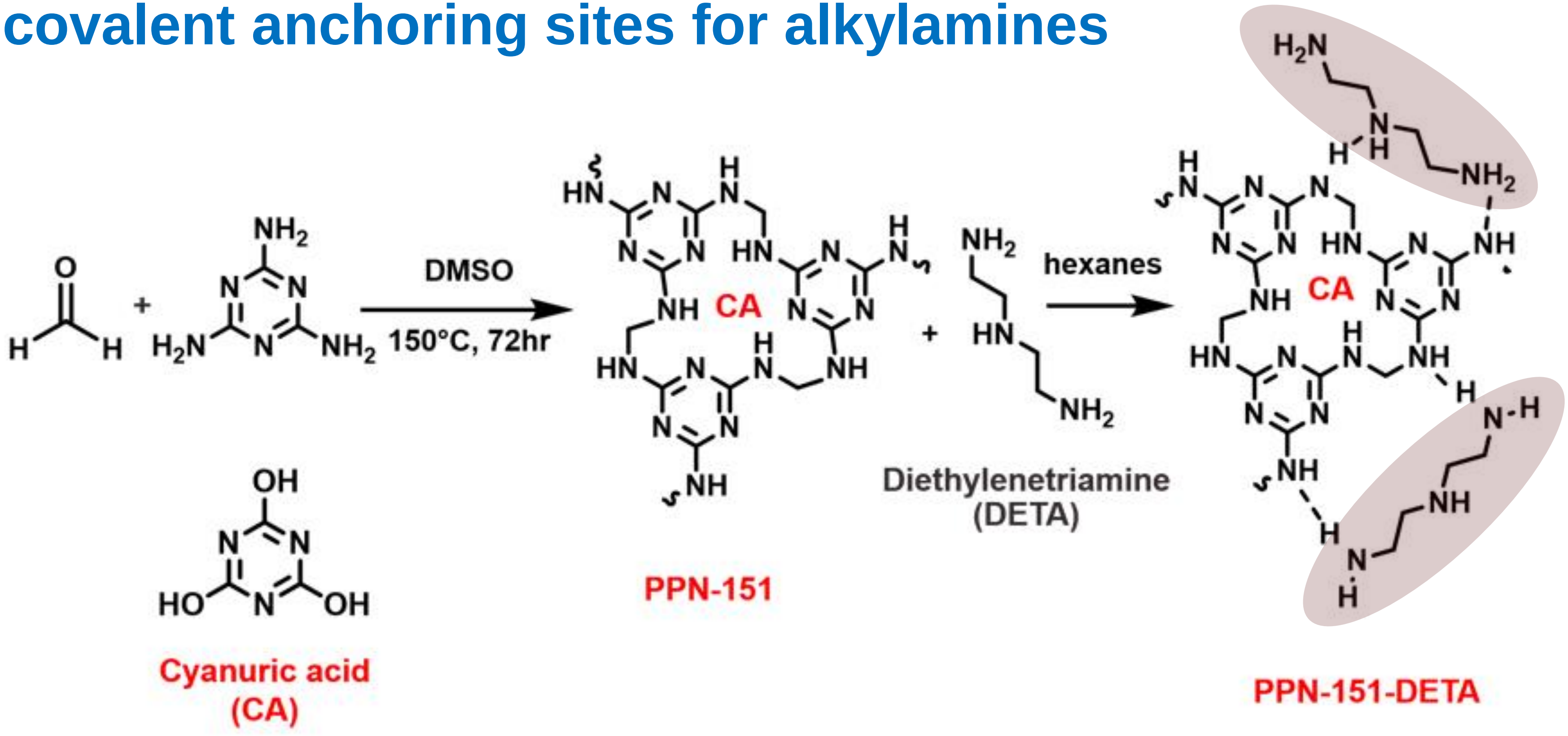


Zhou's group@TAMU

Physically Attached Amines in PPN-151-DETA

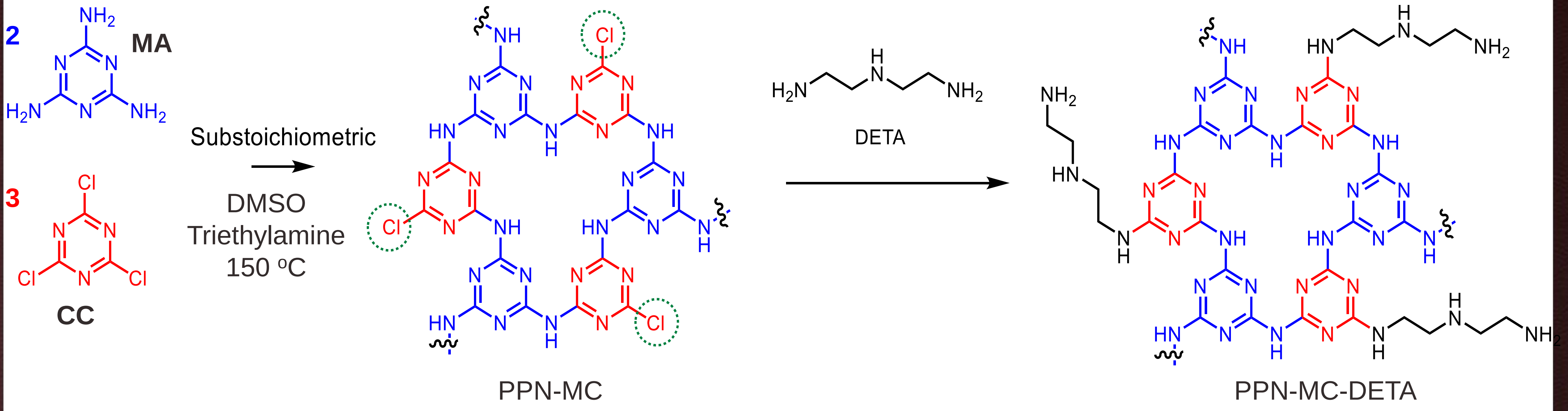
- Physically impregnated amines
- CA - noncovalent anchoring sites for alkylamines



Advantage: Easy recycle of PPN-151 backbone;
Disadvantage: Potential amine loss during application.

PPN Design – Substoichiometric Strategy

Condensation Reaction

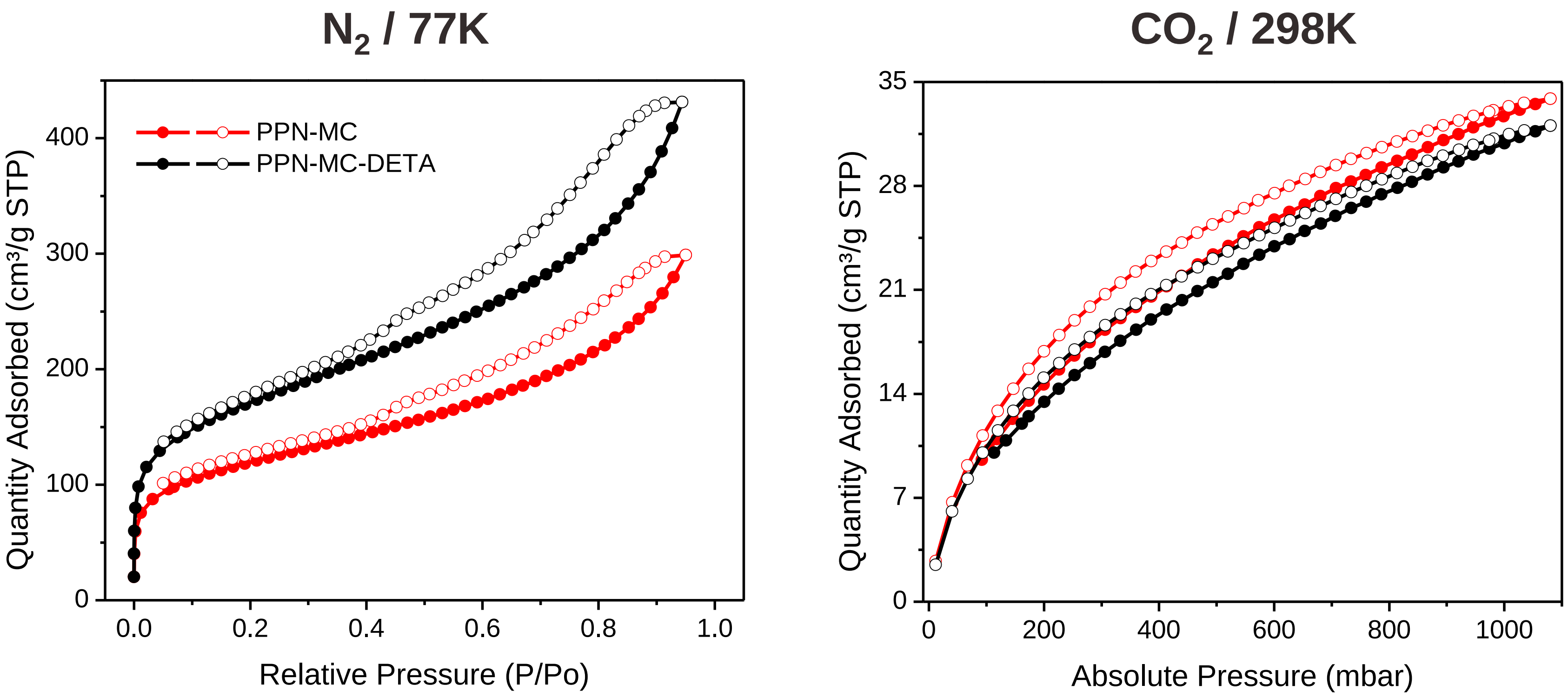


Advantages: 1. Commercially available starting materials;

2. Easy functionalization.

Porosity and CO_2 Uptake Study

PPN-MC

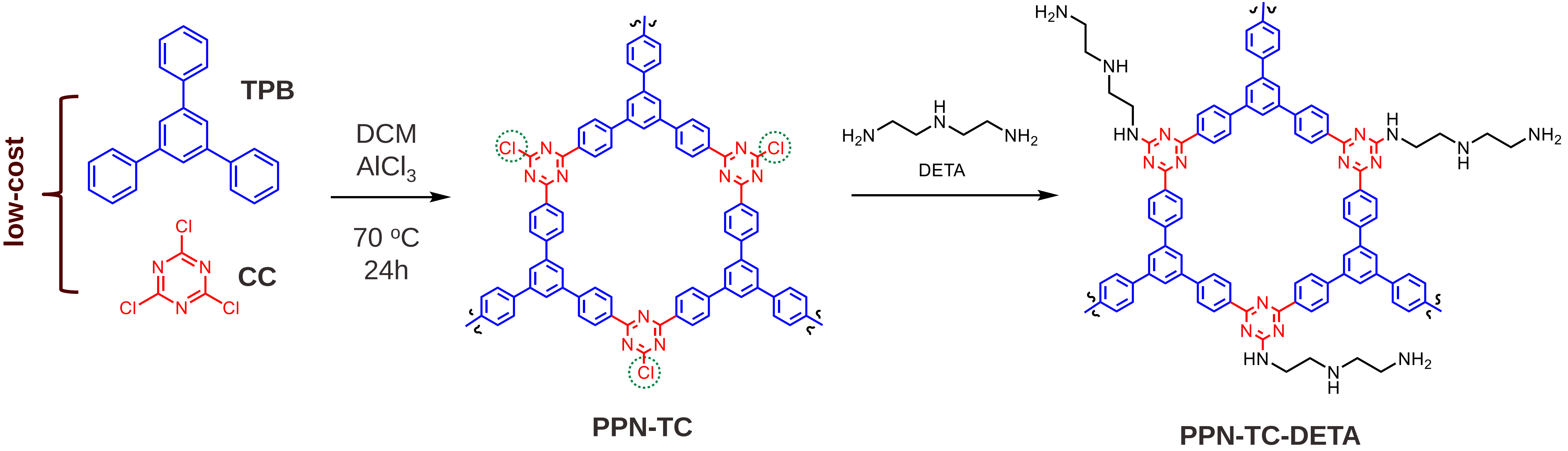


After DETA tethering:

1. BET surface area decrease from 580 to 409 m^2/g
2. CO_2 adsorption increased slightly.

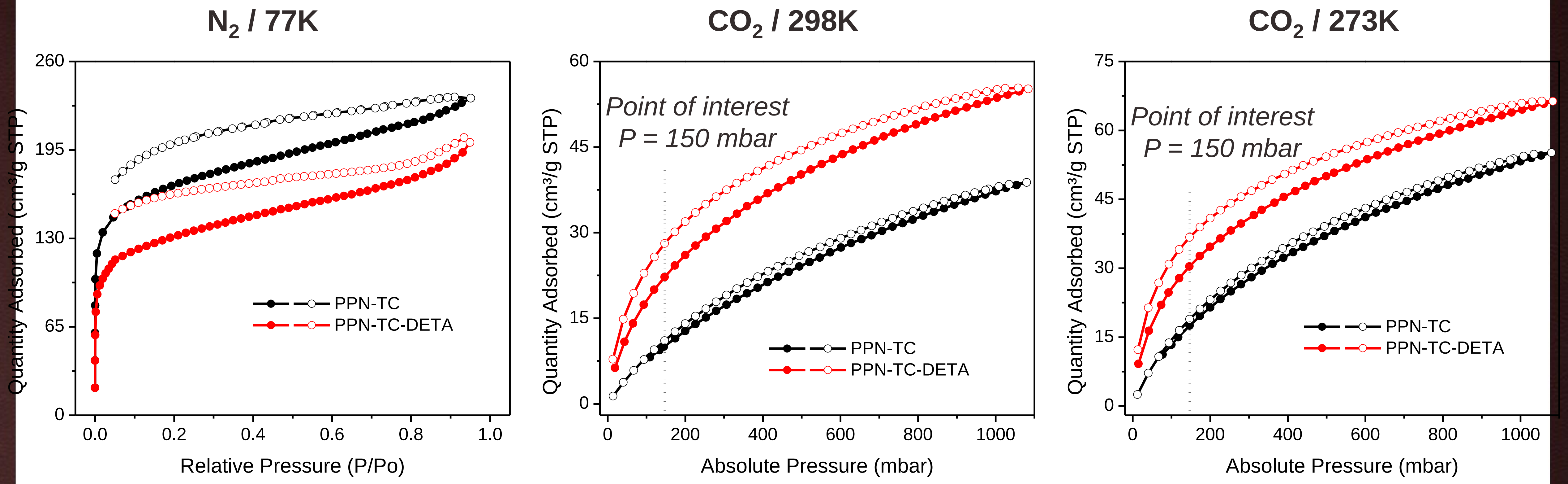
Substoichiometric Strategy – New Scaffold

Friedel-Crafts Acylation Reaction



Unpublished results

Porosity and CO_2 Uptake Study



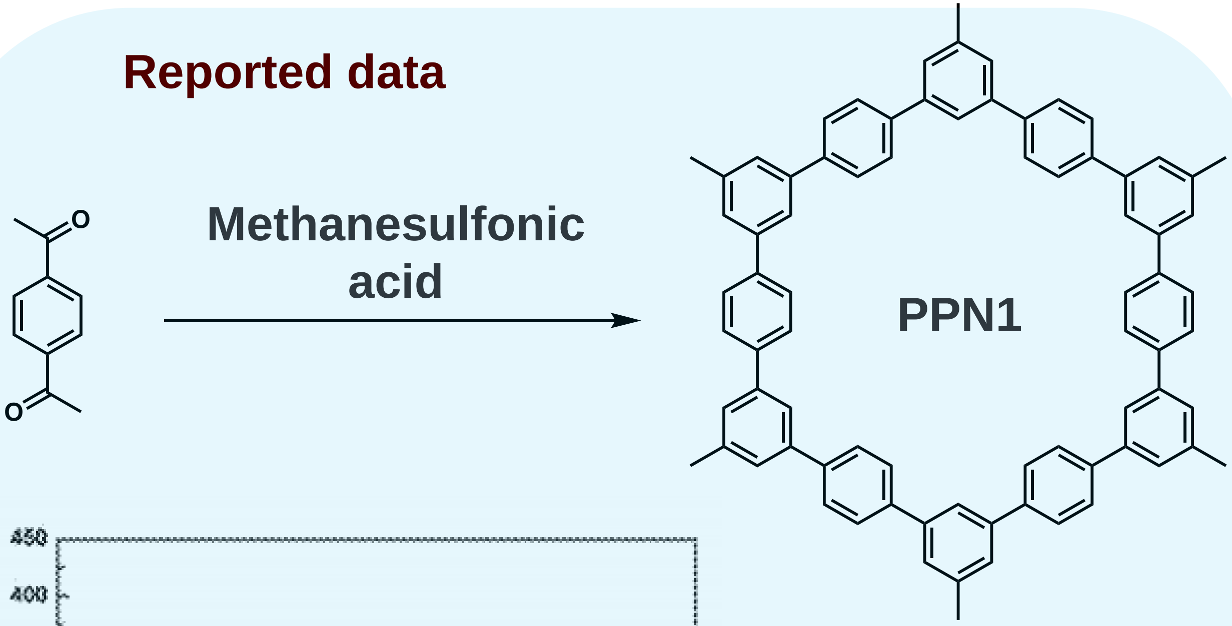
After DETA tethering:

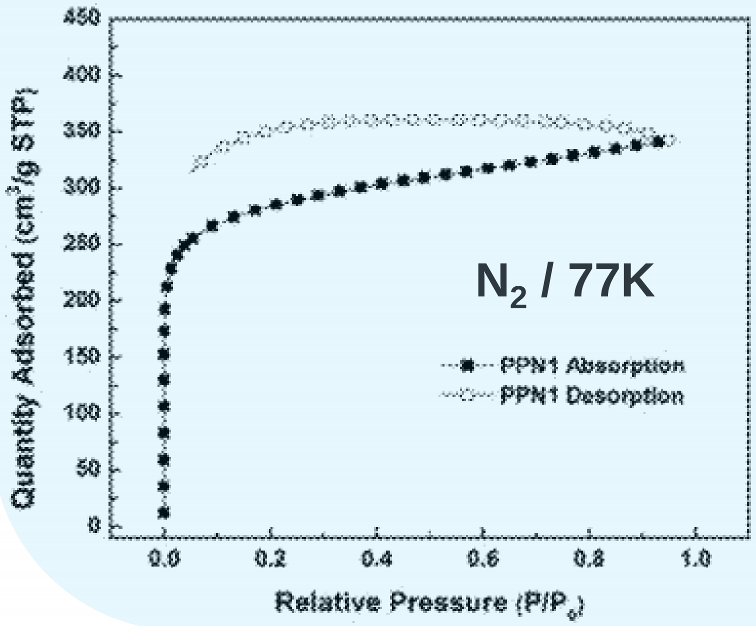
1. BET surface area decrease from 615 to 477 m^2/g
2. CO_2 adsorption increased significantly both at low and high relative pressure

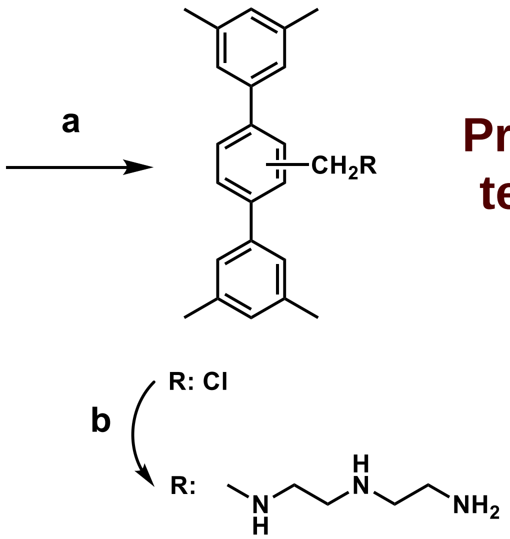
Unpublished results

All Carbon PPN Scaffold

Reported data







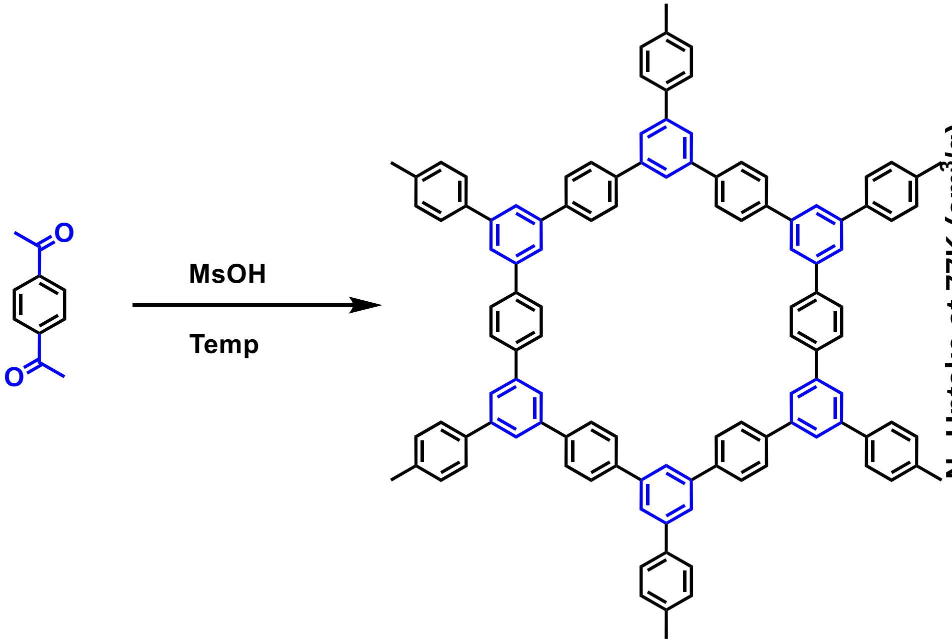
Proposed amine tethering route

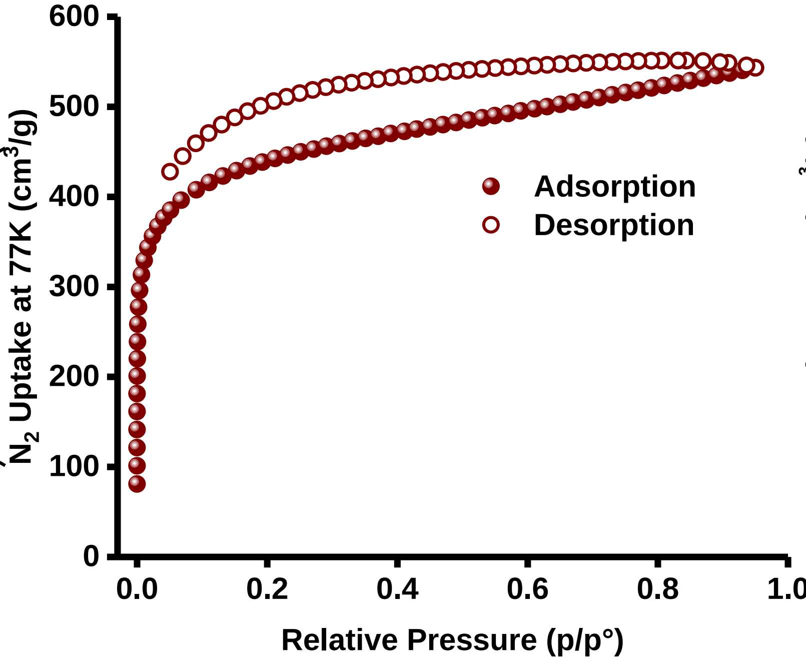
PPN1-DETA

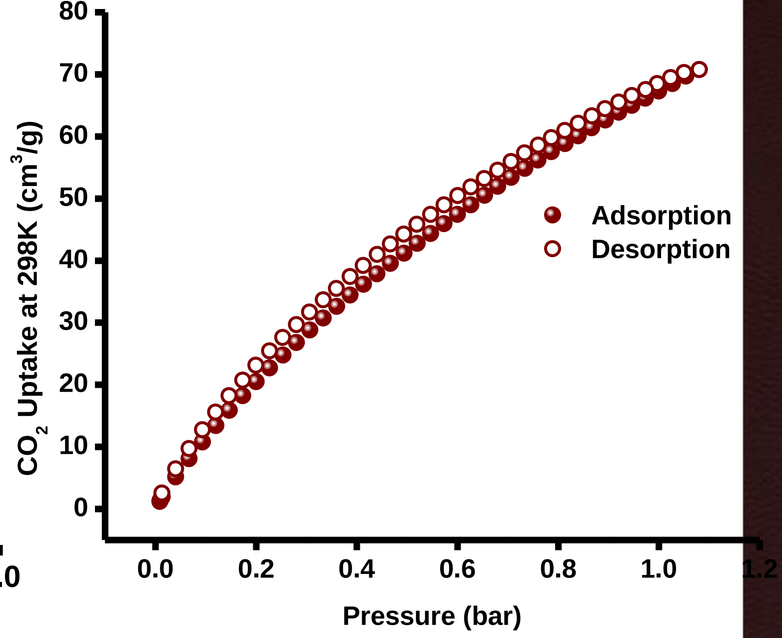
Fang, L. Zhou, H.-C. et al.,
Pub. No. US 20210230359A1

Porosity Optimization

PPN-KF3D



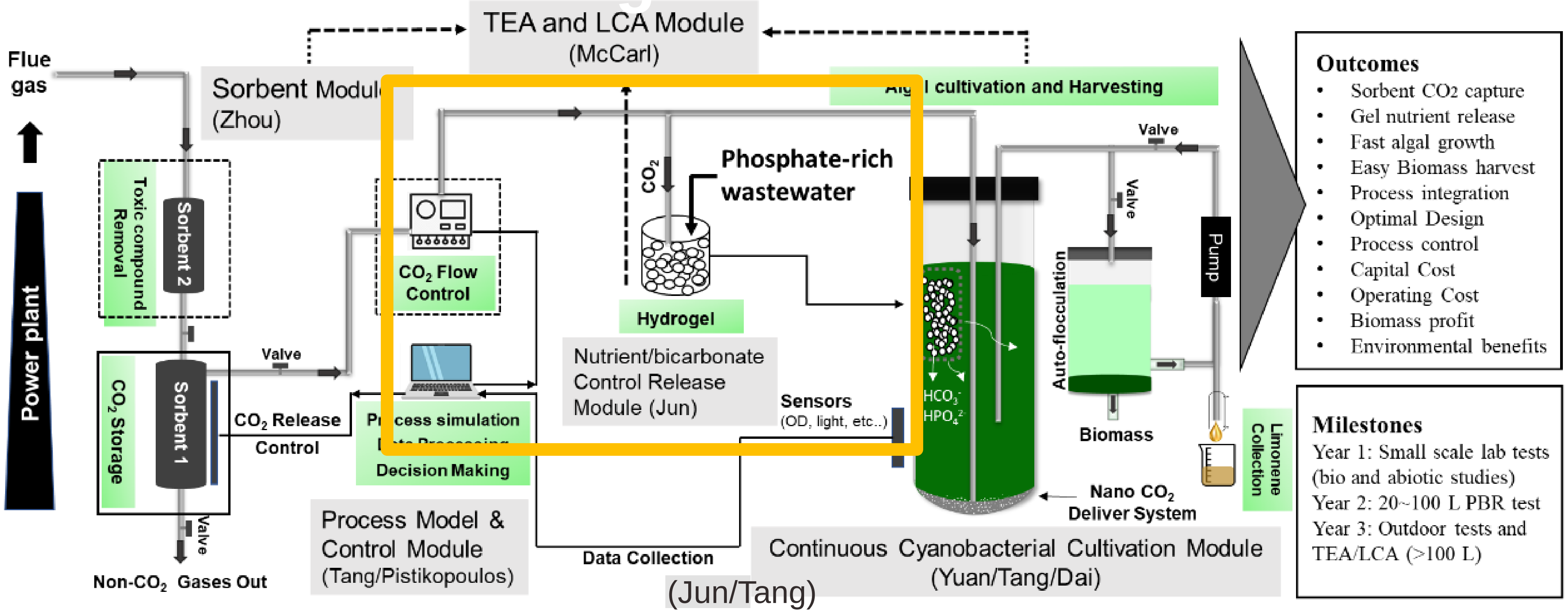




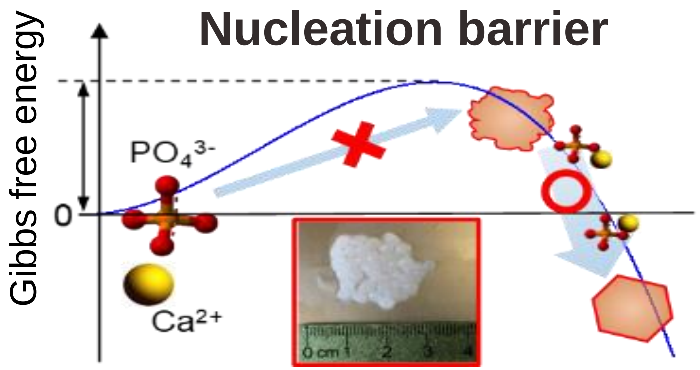
OPTIMIZED REACTION
- ✓ High BET surface area
- ✓ Cheap starting materials
- ✓ Easy reaction

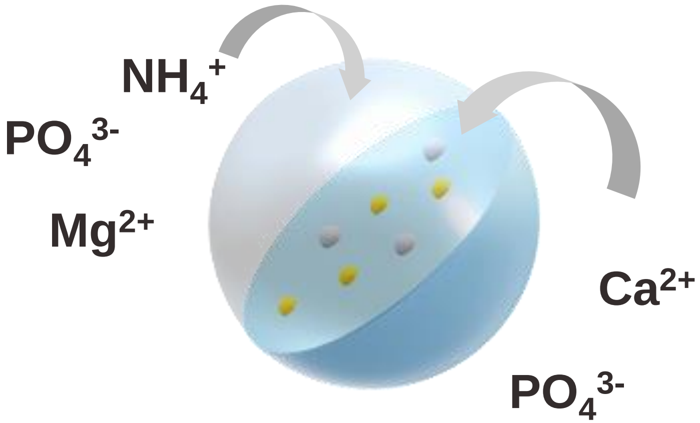
BET surface area 1600 m^2/g

Maximum CO_2 uptake at room temperature 71 cm^3/g



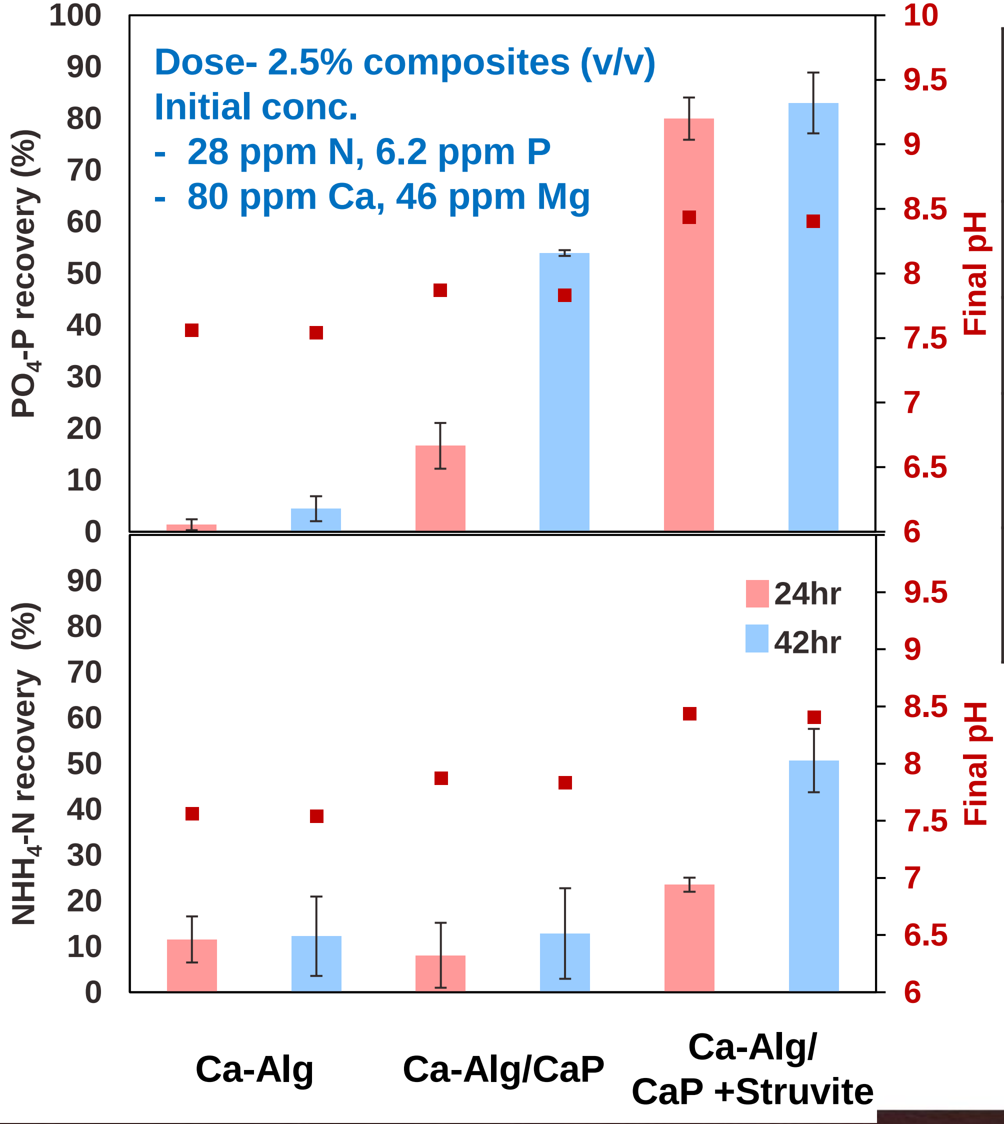
Jun's group @WashU





Simultaneous N/P Recovery: Ca-Alg/CaP+Struvite

N & P Recovery by struvite mineral composites



Ammonium and Phosphate Recovery Capacity

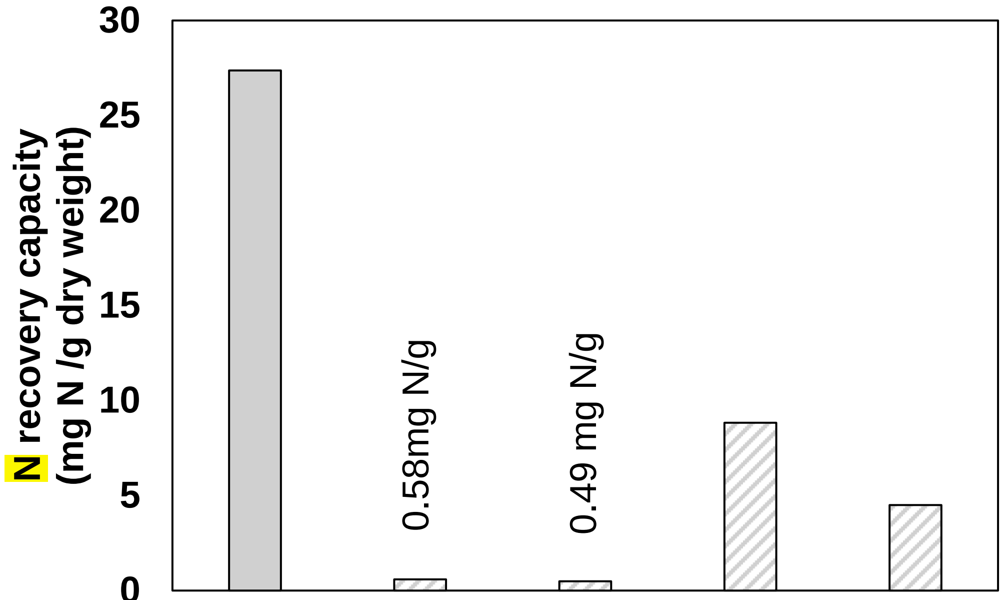
Hydrogels	Composites	Dry weight (mg)	Mineral Seed (mg)	N, P recovery capacity (mg of N,P per 5mL precursor)
Ca-Alg (n=3)	0.6% Calcium Alginate	30.2 ± 2.1	N/A	N – 136.9 ± 12.9 P – 11.05 ± 6.05
Ca-Alg/CaP (n=3)	0.6% Calcium Alginate + 20 mM P	52.7 ± 0.8	22.5 ± 2.9	N – 143.9 ± 53.9 P - 133.9 ± 1.39
Ca-Alg/CaP+Struvite (n=4)	0.6% Calcium Alginate + 40 mM P + 20 mM Mg, N	110 ± 3.2	80.8 ± 5.1	**N – 567.4 ± 77.5** **P – 205.9 ± 13.8**
Ca-Alg/CaP+Wollastonite (n=3)	0.6% Calcium Alginate + 40 mM P + 5.2 g/L Wollastonite	95.3 ± 3.9	65.3 ± 3.9	N- ND P- 242 + 18.1

- **For ammonium recovery,** the composites showed significant improvement at **longer treatment times**
- Around 10 % ammonium can be adsorbed on the hydrogel surface
- Struvite mineral-hydrogel composites enhanced the recovery efficiency to above **80% for P and above 40% for N**.

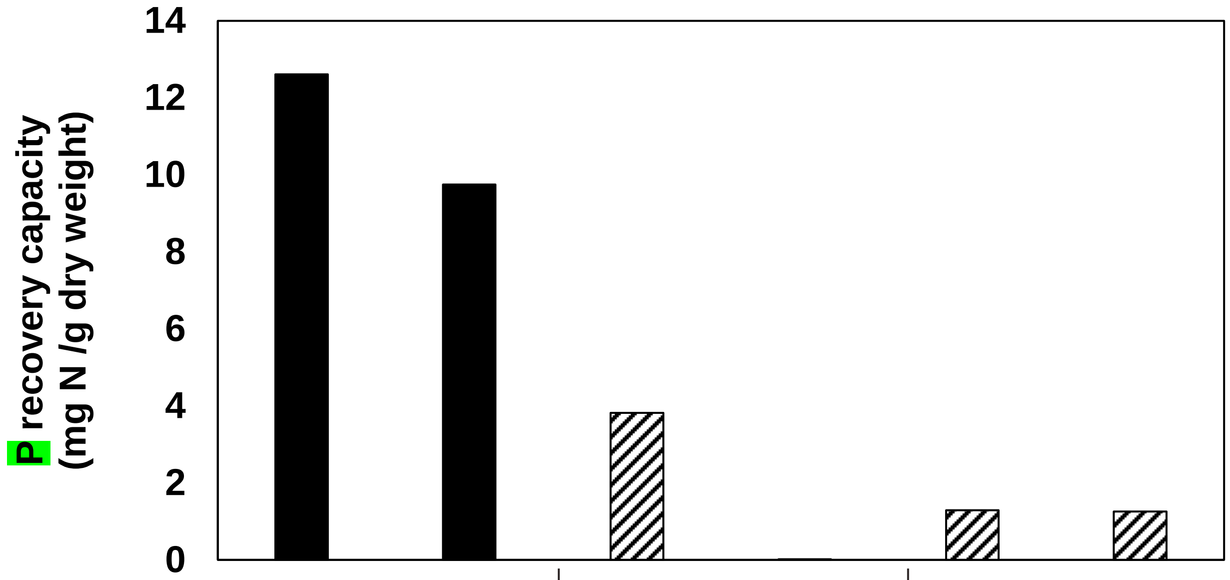
Nitrogen and Phosphate Recovery Capacity

Ammonium and Phosphate Recovery Capacity

*Normalized by final concentrations calculated from Langmuir isotherms



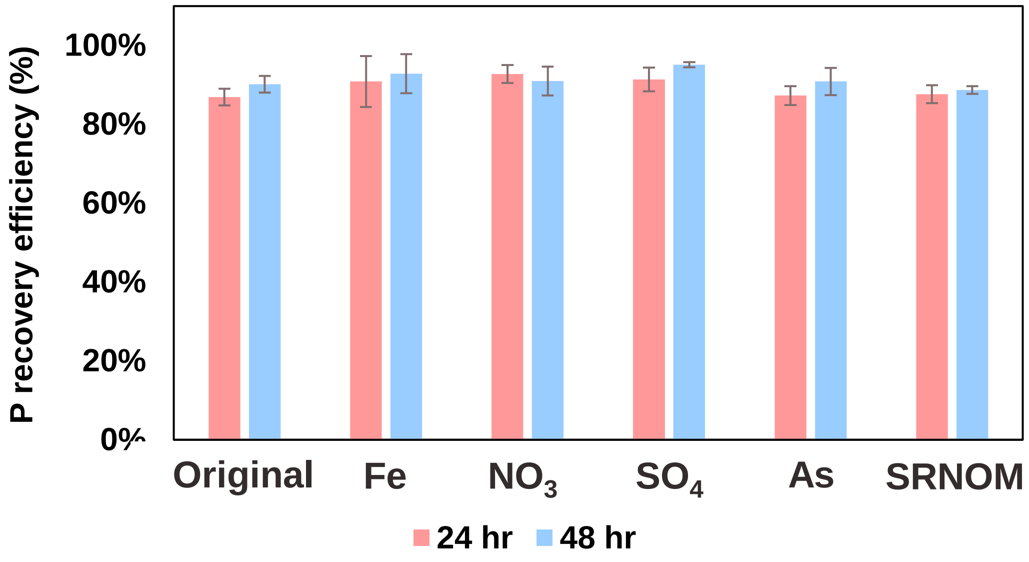
Active part	CaP+Stru-Alg	Montmorillonite	Walnut	Wood	Bentonite
substrate	Mineral hydrogel	Biochar			Clay
	This study	Chen, L., et al 2017	Yin, Q., et al. 2019	Kizito, S., et al. 2015	Zaini, N. S.M. et al. 2021

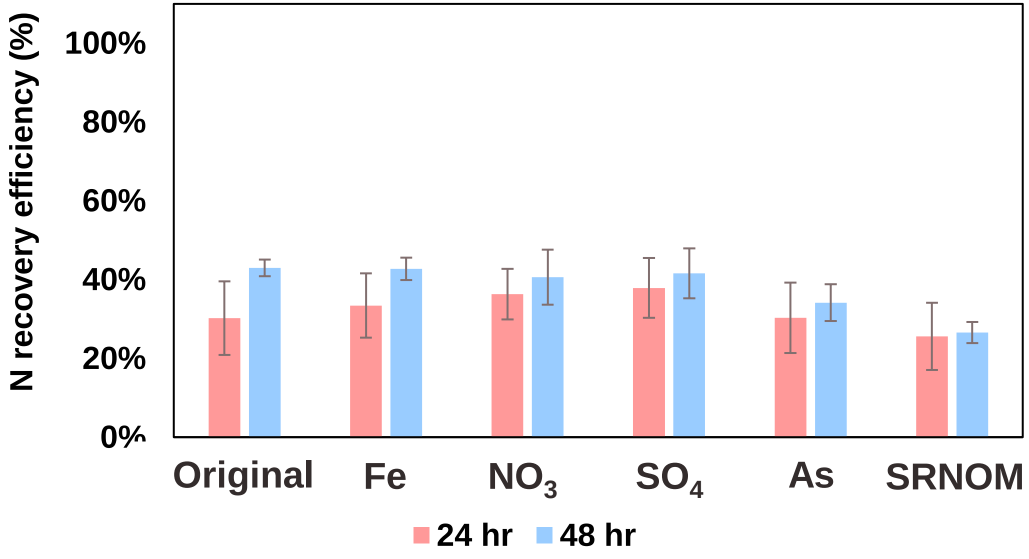


Active part	CaP+Woll-Alg	CaP+Stru-Alg	La-magnetic	Montmorillonite	Zr	Chitosan
substrate	Mineral hydrogel		Biochar		Carbon-nanotube	
	This study		Li, T, et al. 2018	Chen, L., et al 2017	Gu et al., 2019	Huang et al., 2018

For N & P recovery, mineral-hydrogel composites showed the highest capacity among other recent techniques

Simultaneous N and P Recovery: Ca-Alg/CaP+Struvite





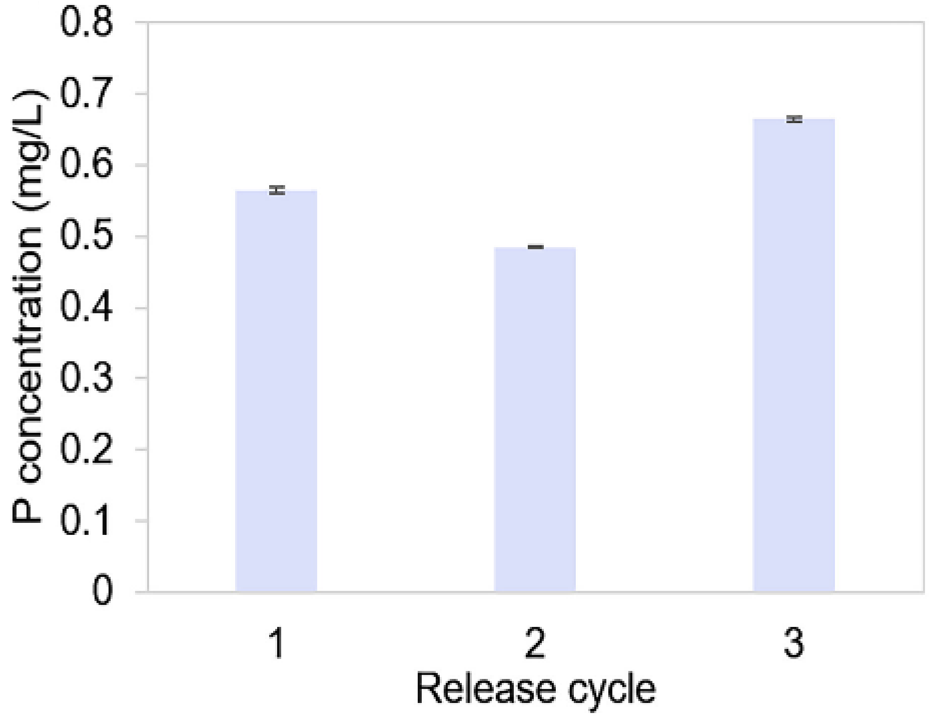
Dose- 2.5% composites (v/v)
Initial conc.
- **28 ppm N, 6.2 ppm P**
- **80 ppm Ca, 46 ppm Mg**

Interference	Initial conc. (ppm)
Fe	2
NO_3	10
SO_4	50
As	**0.1** (much higher than environmental conditions)
SRDOM	25

- Phosphate is not much affected by interference (within 2%).
- The interference of iron, nitrate, and sulfate on ammonium is insignificant, but arsenic and SRDOM have some interference.
- Adsorption of As on struvite might hinder the struvite growth, so 24 hrs efficiency is identical, but 42 hrs efficiency is low.
- **Mineral-hydrogel composites are applicable for nutrient recovery from wastewater without significant interference.**

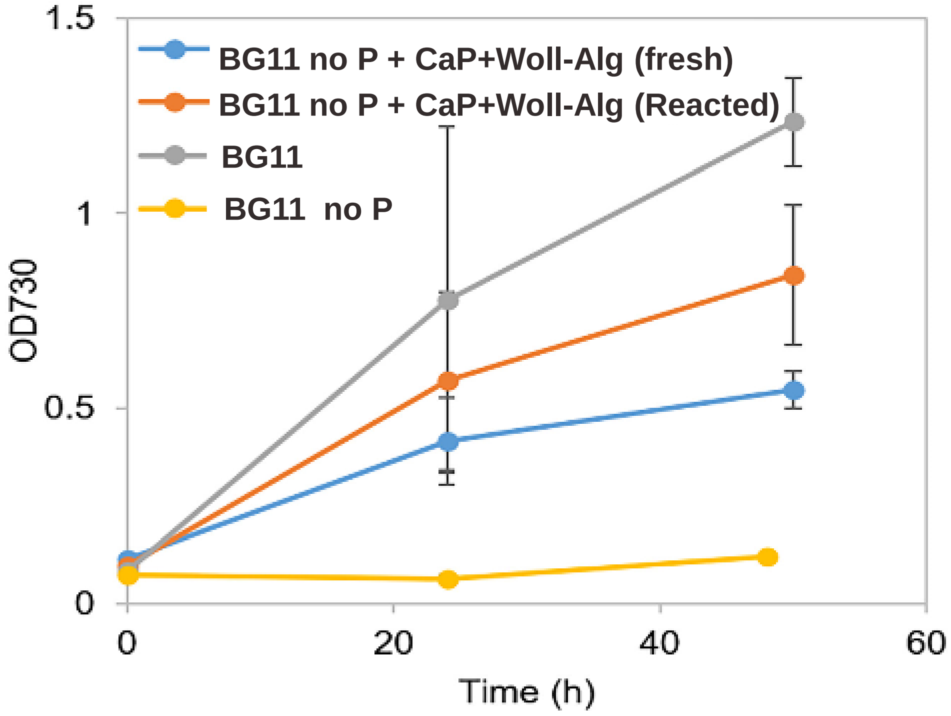
Phosphate Delivery by Composites for Algal Growth: Ca-Alg/CaP+Wollastonite

Media: BG11 Media without P
Dose: 5% (wet weight of hydrogel /v of media)



24 hours/cycle in P-free BG11 medium

Media: BG11 Media without P
Dose: 1% (wet weight of hydrogel /v of media)



Xiao et al. Science of the total environment, 2022, 247, 157533

In our recent study, we found Ca-Alg/CaP+Wollastonite composites can release phosphate to grow algal species.

N/Phosphate Delivery: Dissolution Rates of Ca-Alg/CaP+Struvite

❖ N, P in BG11 media were already subtracted

- **Media**

Medium #1: BG11
Medium #2: 32 mM $NaNO_3$
(same ionic strength as BG11)
Medium #3: BG11 without critical elements
(Ca, Mg, NH_4, PO_4)

pH did not change (media #1,3: 8.08 and medium# 2: 7.25)

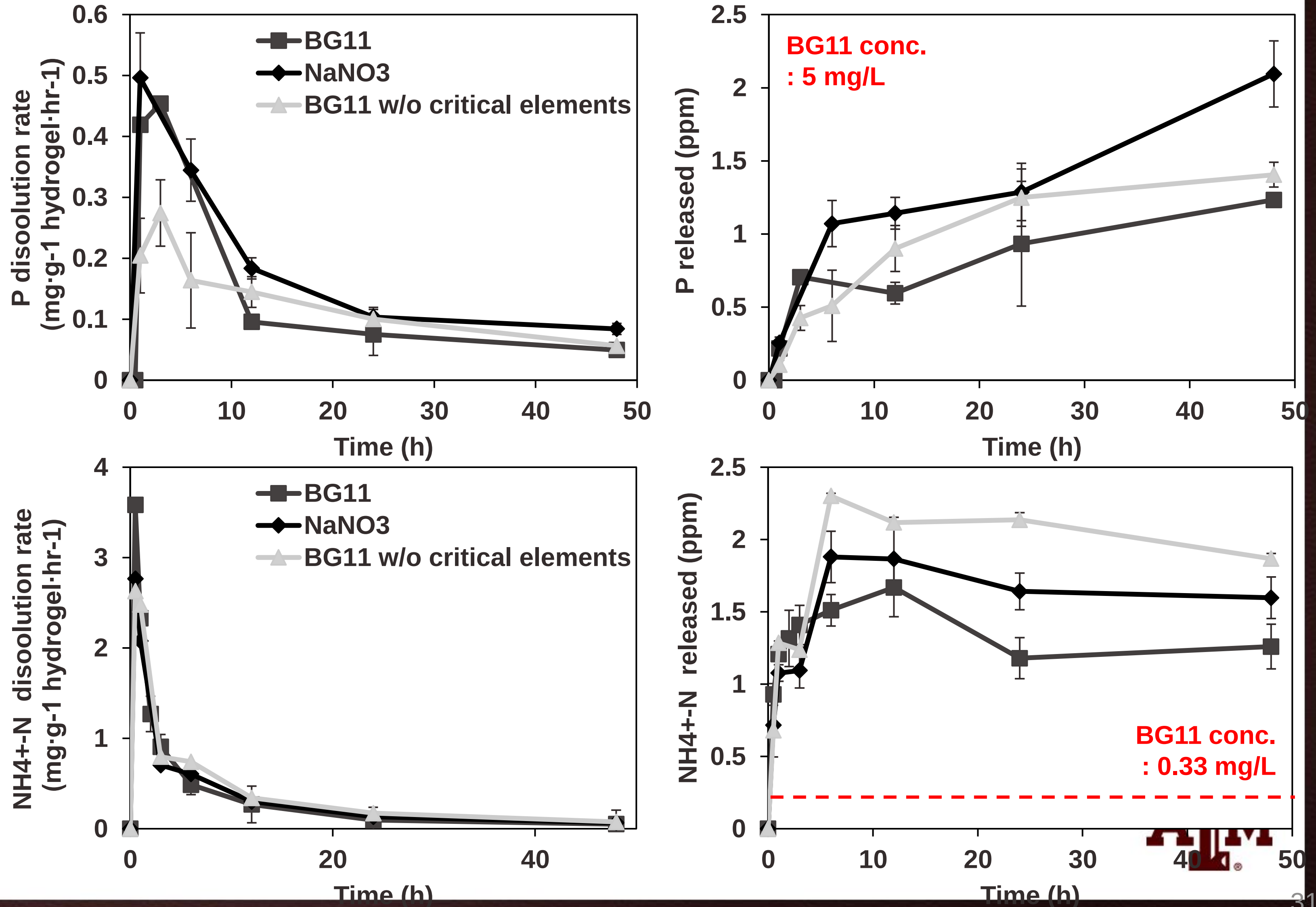
- **Dose**

2.5 % (v of hydrogel precursor/v of media)

- With a 2.5 % dose, P has released **1.2 ppm** for 24 hrs in BG11 without critical elements

- To reach the original BG11 P level, around **4 times of the hydrogel dose** is required.

- Insufficient nitrogen concentration can be solved by adding **nitrate salts**.

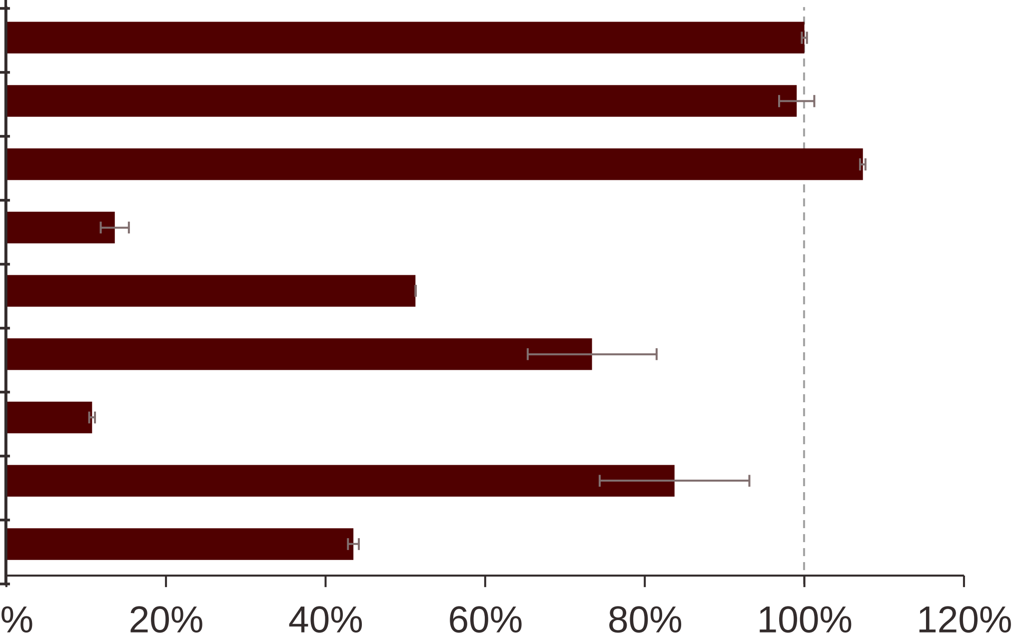


Capability of Mineral-Hydrogel Composites for Algal growth: Ca-Alg/CaP+Struvite

Struvite hydrogels nutrient release and algal growth: log phase (day 3)

Conditions	Phosphate	Ammonium	Nitrate
1	BG11	BG11	BG11
2	BG11+20% CaP+Stru Alg	BG11+20% CaP+Stru Alg	BG11
3	BG11+40% CaP+Stru Alg	BG11+40% CaP+Stru Alg	BG11
4	-	-	-
5	20% CaP+Stru Alg	20% CaP+Stru Alg	-
6	40% CaP+Stru Alg	40% CaP+Stru Alg	-
7	-	-	BG11
8	20% CaP+Stru Alg	20% CaP+Stru Alg	BG11
9	40% CaP+Stru Alg	40% CaP+Stru Alg	BG11

Relative OD730 over standard BG11 culture



- With the addition of 40% v/v struvite hydrogel composites in BG11, UTEX 2973 culture can increase the OD by 7% compared to standard BG11 (conditions 1 (OD: 1.32) and 3 (OD: 1.42) in the same batch).
- With 40% v/v struvite hydrogels as the only phosphate and ammonium source, UTEX 2973 can reach 73.4% agal growth in standard BG11 (conditions 1 and 6).
- Still, we need the nitrate source for comparable algal growth with BG11 (conditions 5 and 8).

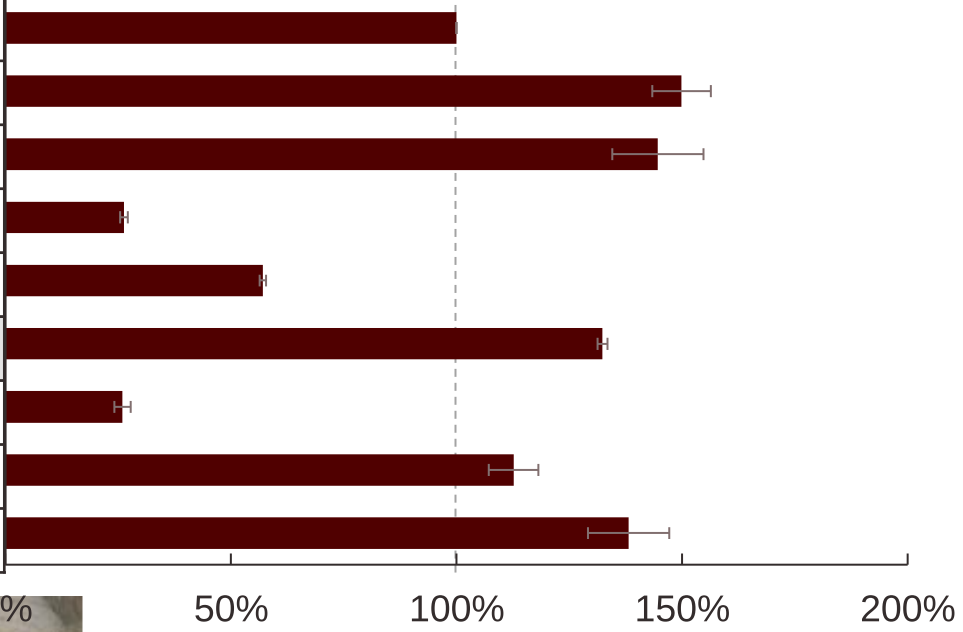
Impacts of Mineral-Hydrogel Composites for Algal Growth:

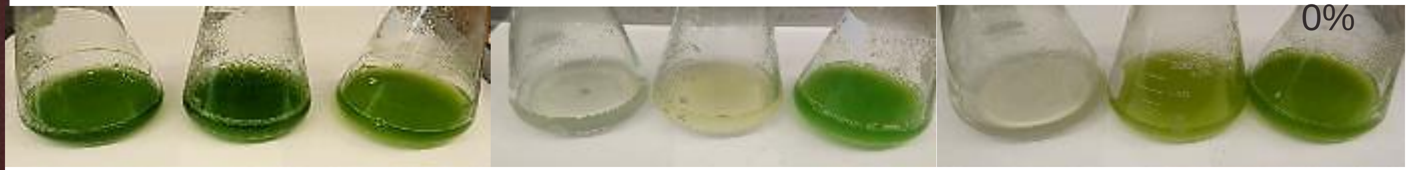
Ca-Alg/CaP+Struvite with Ca-Alg/$NaNO_3$ Composites

Nitrate embedded hydrogel nutrients release and agal growth: log phase (day 3)

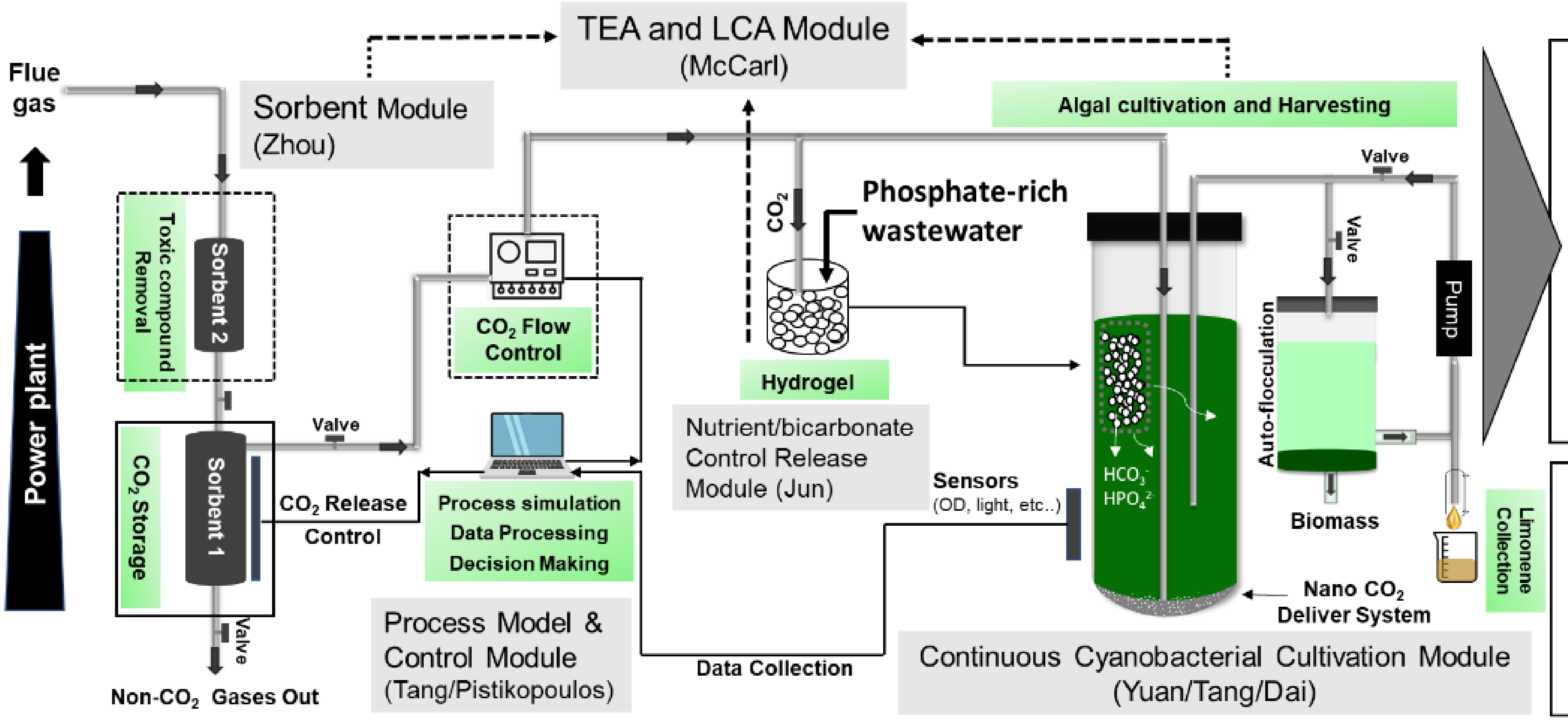
	Phosphate	Ammonium	Nitrate
1	BG11	BG11	BG11
2	BG11+40% CaP+Stru Alg	BG11+40% CaP+Stru Alg	BG11
3	BG11+40% CaP+Stru Alg	BG11+40% CaP+Stru Alg	BG11+10% NO_3-Alg
4	-	-	-
5	40% CaP+Stru Alg	40% CaP+Stru Alg	-
6	40% CaP+Stru Alg	40% CaP+Stru Alg	10% NO_3-Alg
7	-	-	BG11
8	40% CaP+Stru Alg	40% CaP+Stru Alg	BG11
9	40% CaP+Stru Alg	40% CaP+Stru Alg	BG11+10% NO_3-Alg

Relative OD730 over standard BG11 culture





- **By using struvite and nitrate mineral-hydrogel composites as the only P and N sources, the growth of UTEX 2973 growth improves 32% more than standard BG11 (conditions 1 and 6).**
- **Balancing N/P ratio and ammonium toxicity are the main key factors for future optimization.**



Outcomes

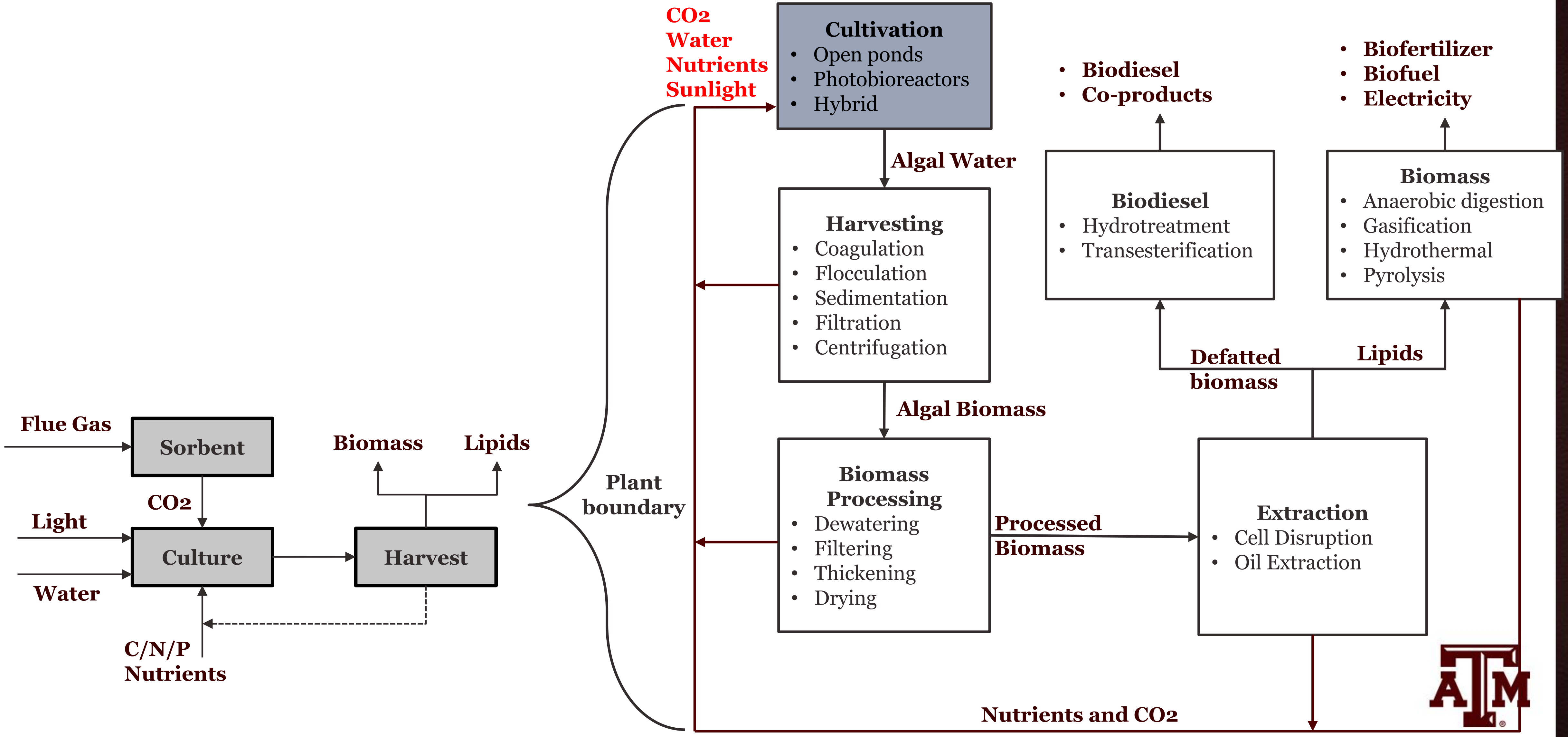
- Sorbent CO2 capture
- Gel nutrient release
- Fast algal growth
- Easy Biomass harvest
- Process integration
- Optimal Design
- Process control
- Capital Cost
- Operating Cost
- Biomass profit
- Environmental benefits

Milestones

Year 1: Small scale lab tests (bio and abiotic studies)
Year 2: 20~100 L PBR test
Year 3: Outdoor tests and TEA/LCA (>100 L)

Modeling

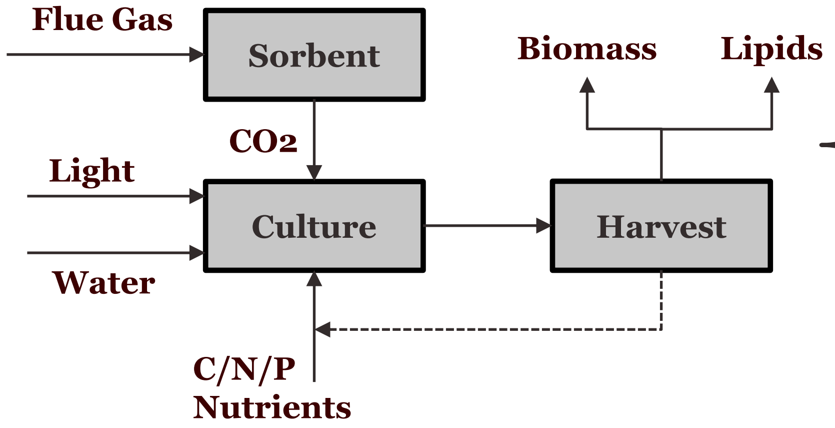
Algae Cultivation Process

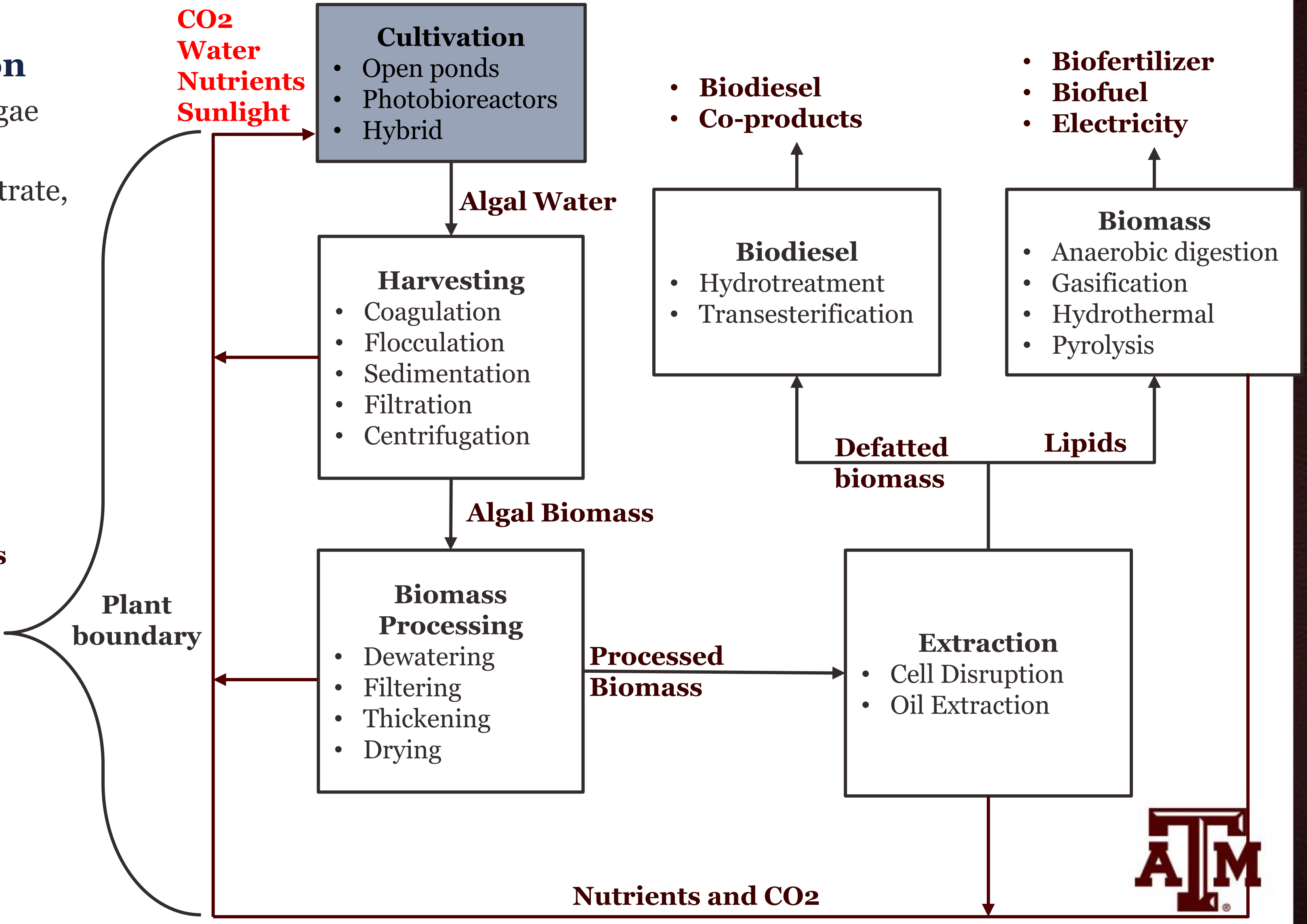


Equations Based Process modeling

Process modeling of algae cultivation

- Nonlinear dynamic modeling framework for algae cultivation in *pyomo.dae* package
- Understand the interaction between carbon, nitrate, phosphate, light intensity, and their impact on biomass yield
- Parameter estimation
- Design of explicit control scheme





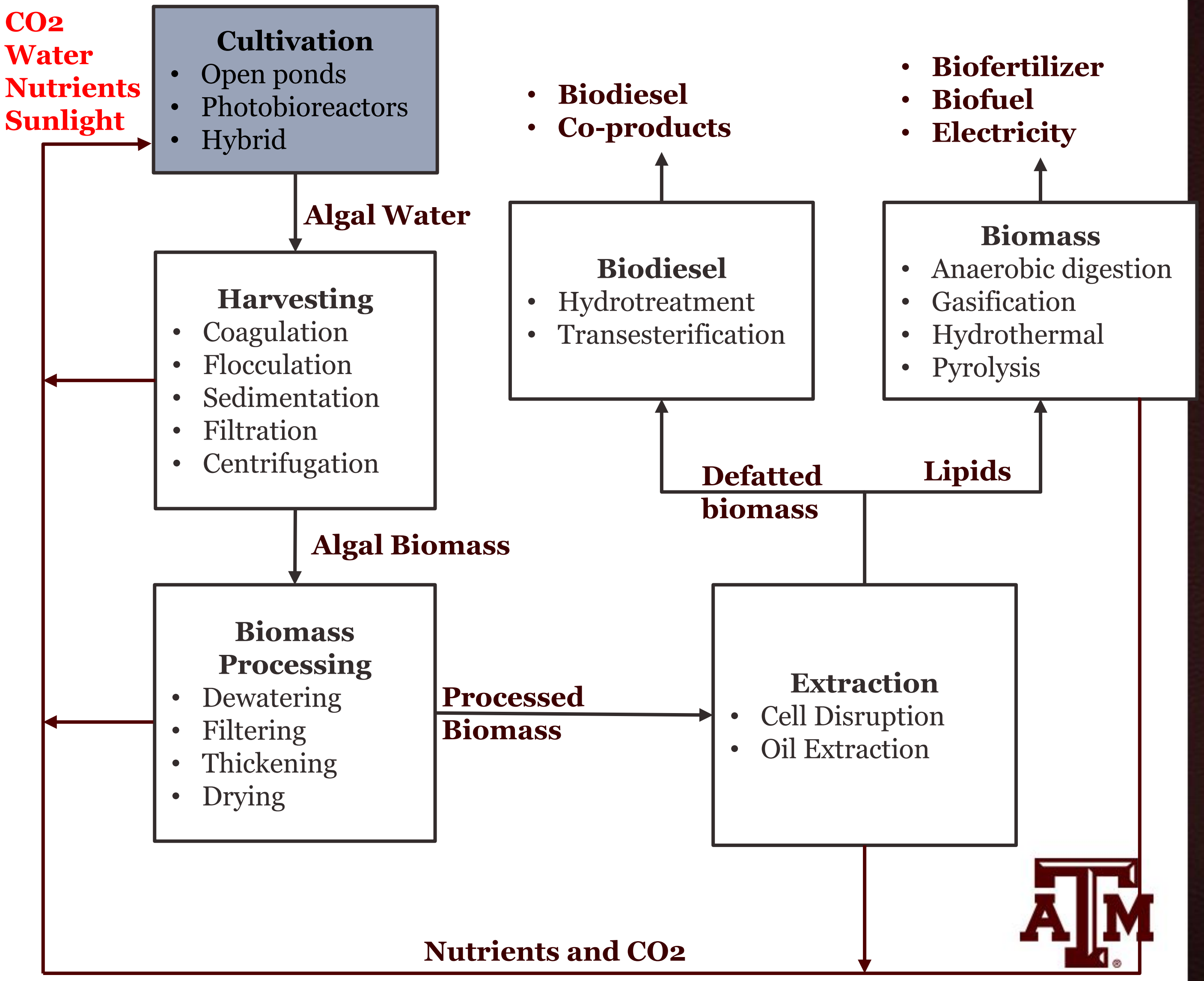
Equations Based Process modeling

Process modeling of algae cultivation

- Nonlinear dynamic modeling framework for algae cultivation in *pyomo.dae* package
- Understand the interaction between carbon, nitrate, phosphate, light intensity, and their impact on biomass yield.
- Parameter estimation
- Design of explicit control scheme

Multi-scale systems engineering framework

- Develop linear surrogate of dynamic process model
- Append to energy systems framework
- Scenario analysis to understand the at scale impact of process
- Benchmark against competing technology pathways: system costs, carbon intensity, circularity
- Post-validation of solutions against process model



Process model dynamics

Modeling components

Input parameters

1. CO_2 release rates
2. Cell composition
3. Nutrient sources
4. Nutrient release rates

Measured

1. pH
2. Nutrient levels
3. Temperature
4. CO_2 levels

Control variables

1. Light intensity
2. Nutrient feed rates
3. CO2 feed rates

Optimization

1. Biomass production
2. Lipid production
3. CO2 utilization
4. Harvest Schedule

Experimental data

[Zhou] CO2 release rates
[Yuan] Strain specific data
[Jun] Nutrient release rates

Process dynamics

[Tang] Algae production model

Process optimization and control

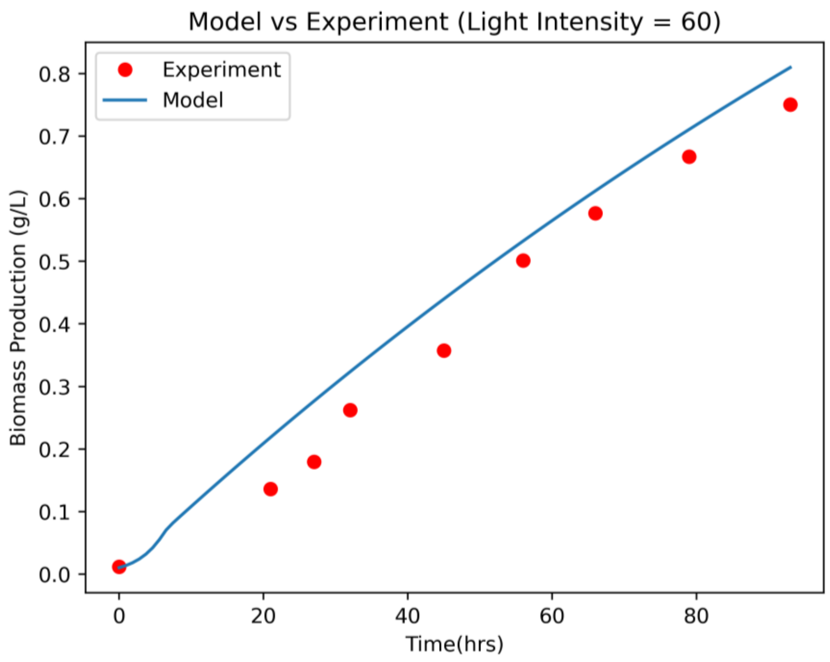
Phases of algae growth

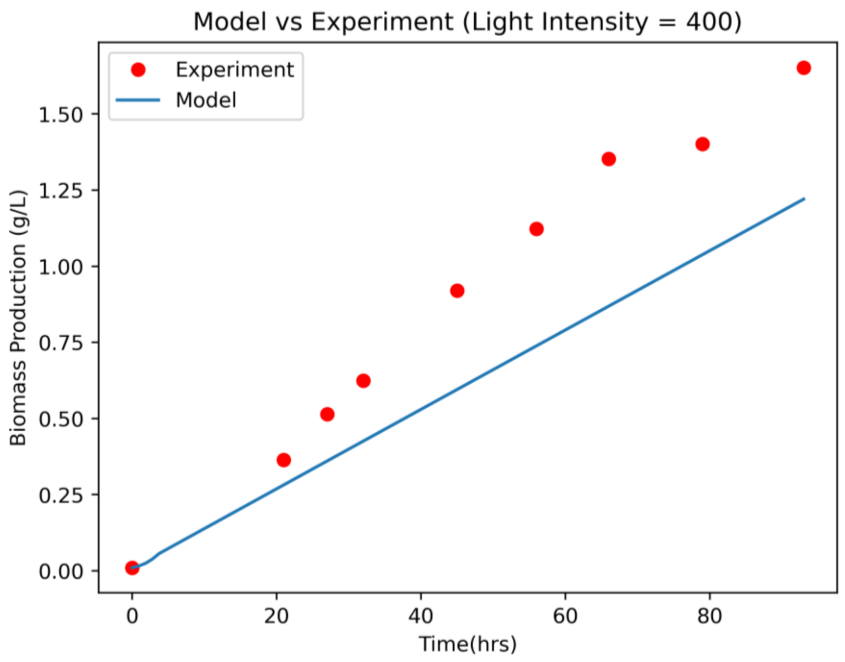
1. **Lag** - initial delay in growth
2. **Exponential** – contingent on supply of nutrients and light
3. **Linear**
4. **Stationary** – constant growth rate
5. **Death** – accumulation of waste, decrease in nutrients

Quantify impact of strain characteristics and process design considerations on phases and composition of algae growth

- Initialization of Model is key to achieve feasibility
- Develop appropriate control scheme
- Identify bottlenecks
- Propose experiments

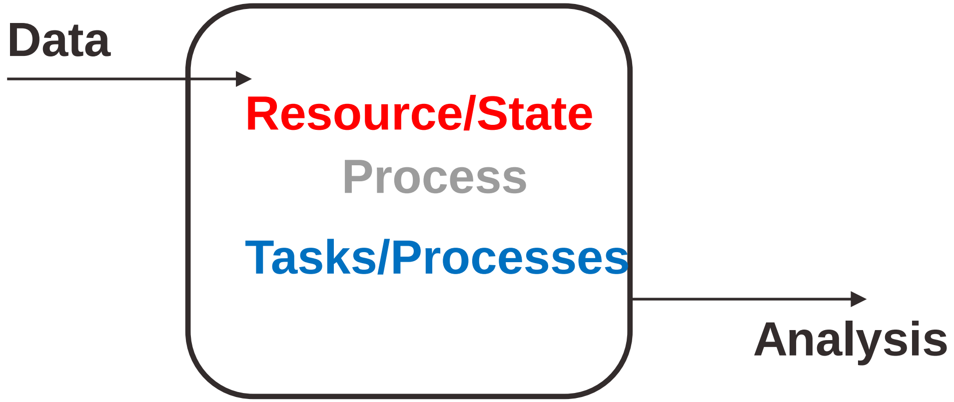
Process Dynamic Model





- Model performs better under low light intensities than under high light intensities
- To add design equations within the model to improve the prediction
- Model requires more experimental data at different operating points to improve the accuracy of parameter estimation

Integrated TEA and LCA Framework



Hierarchical modeling paradigm

Features

- Self-contained and modular modeling blocks
- Tailored generation of set, variables, and constraints

Advantages

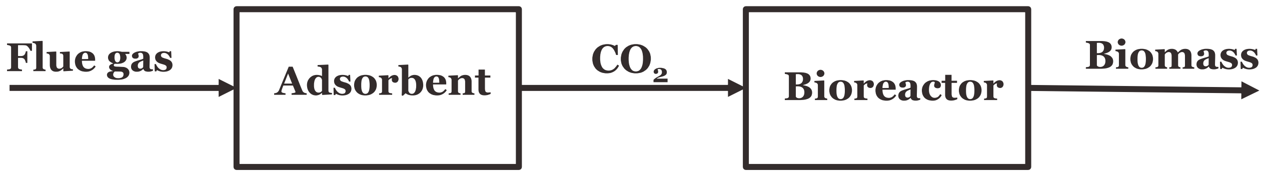
- Seamless translation to object-oriented scripts
- Minimizes redundancy
- Generalizable approach

- Makes use of Component based approach in *energiapy*
- Processes are represented as a set of States/Resources and Tasks/Processes
- Capability to evaluate alternative options for each tasks

Initial Techno Economic Analysis

Assumptions:

- Number of adsorbent cycles is assumed to be 10.
- Number of times DMSO Solvent can be reused to produce the adsorbent is 100
- There are no downstream or upstream processing costs considered
- Fixed Capital cost data was estimated from the Algae Farm Model report [1]



Levelized Cost of Biomass is estimated to be $475/ton of Biomass which is much lower than $1137/ton estimation by the Algae Farm Model [1]

Parameters	Value	Unit
Algae Growth Rate	1.94	g/L/day
Adsorbent Efficiency	0.05	kg CO_2 captured/kg adsorbent
Photobioreactor Bag Life	5	years
Photobioreactor Bag Volume	50	L
Photobioreactor Bags per module	18000	# of Bags
Module Area	5	acres
Payback Period	10	years
Interest Rate	8	%
No. of working days in a year	330	days
Cultivation Land area	1000	acres
Composition of Carbon in Biomass	0.53	kg carbon/kg biomass
Number of Adsorbent Cycles	10	# of cycles

Table 1: List of Parameters

Parameter	Cost	Unit
Melamine	0.7	$/kg
Paraformaldehyde	0.8	$/kg
Cyanuric Acid	1.3	$/kg
DMSO Solvent	1.1	$/kg
Cost of Bioreactor	43748	$/acre
Unit CO_2 Price	15	$/ton
Photobioreactor Bag Cost	10	$/Bag
Photobioreactor Structure Cost	20	$/Bag
Cleaning in Place(CIP) chemical cost	1000	$/acre

Table 2: Cost of Materials and Equipment's

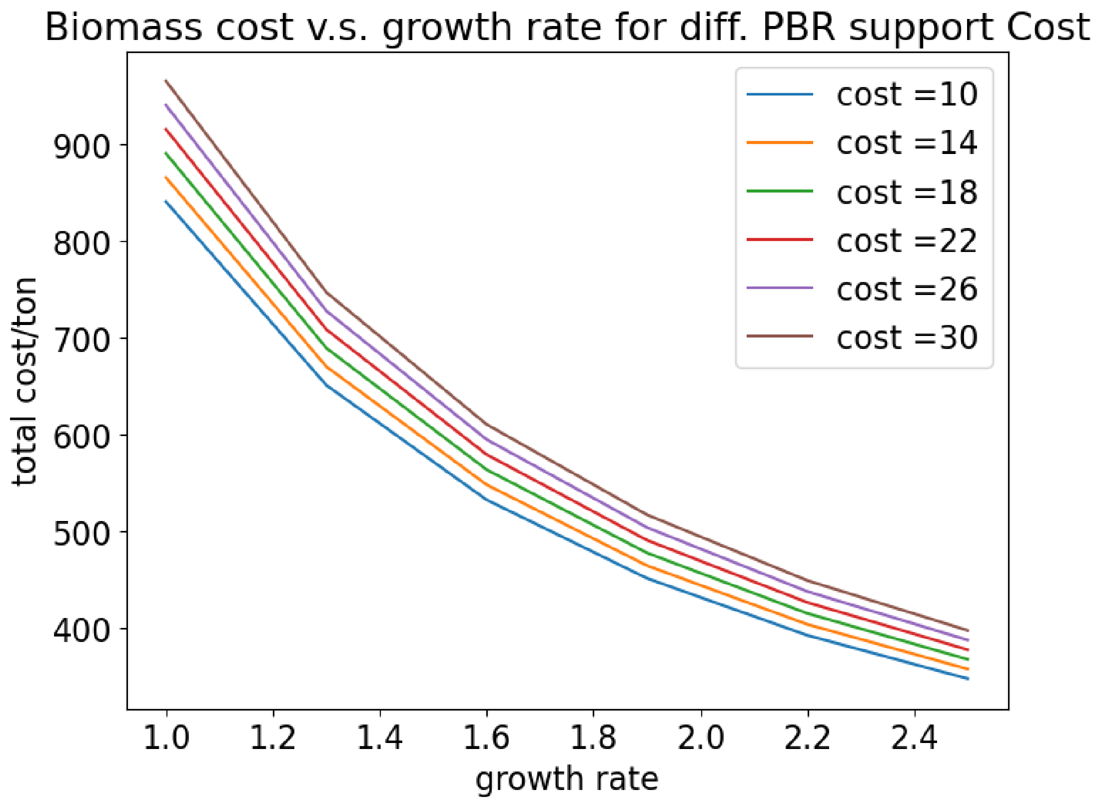
Material	Quantity	Unit
Melamine	201.62	g
Paraformaldehyde	108	g
Cyanuric Acid	15.48	g
DMSO Solvent	2080	mL

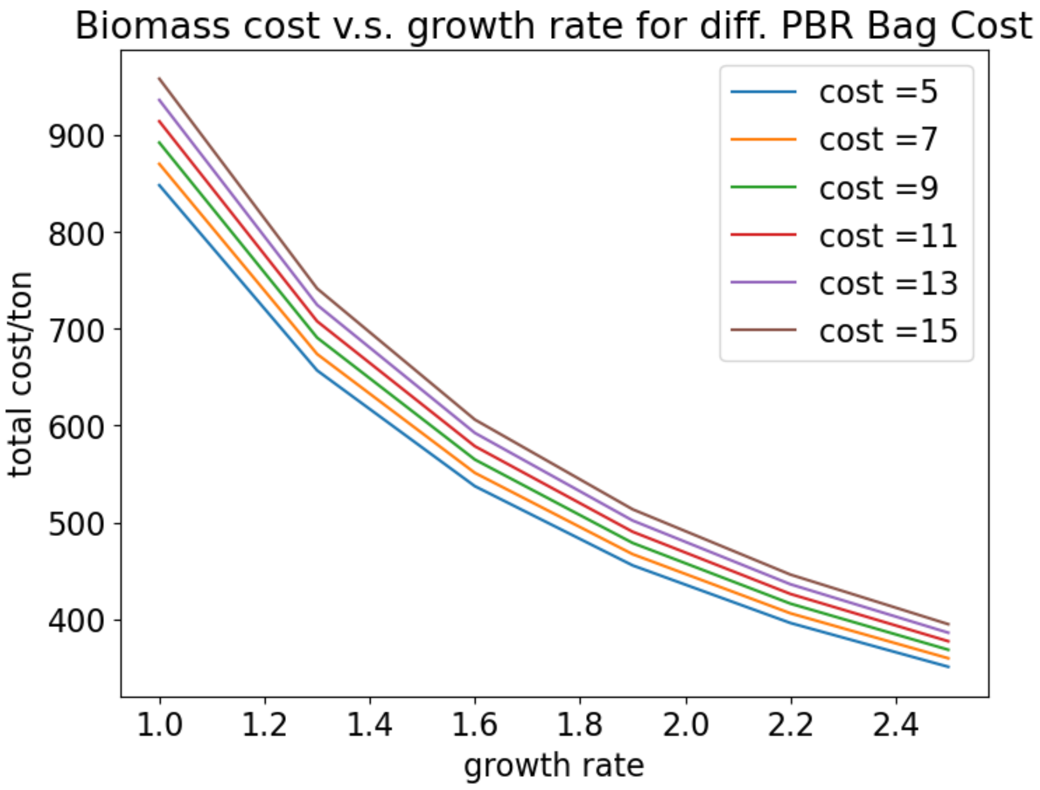
Table 3: Chemicals required to produce PPN-151-DETA

[1] Zhu Y, Jones SB, Anderson DB. Algae farm cost model: Considerations for photobioreactors. Pacific Northwest National Lab.(PNNL), Richland, WA (United States); 2018 Oct 31.

TEA Sensitivity analysis – Bioreactor Design

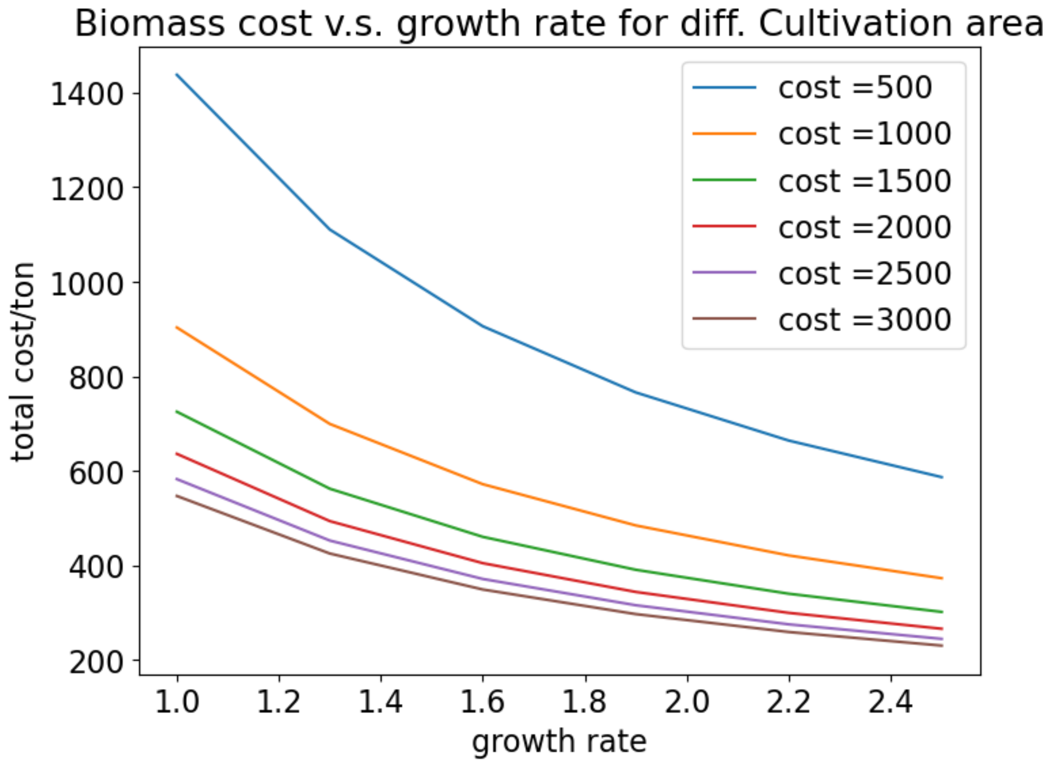
- Lowering the bioreactor bag cost and structure cost improves the levelized cost of biomass considerably
- At low biomass growth rates, the effect of parameters is more pronounced

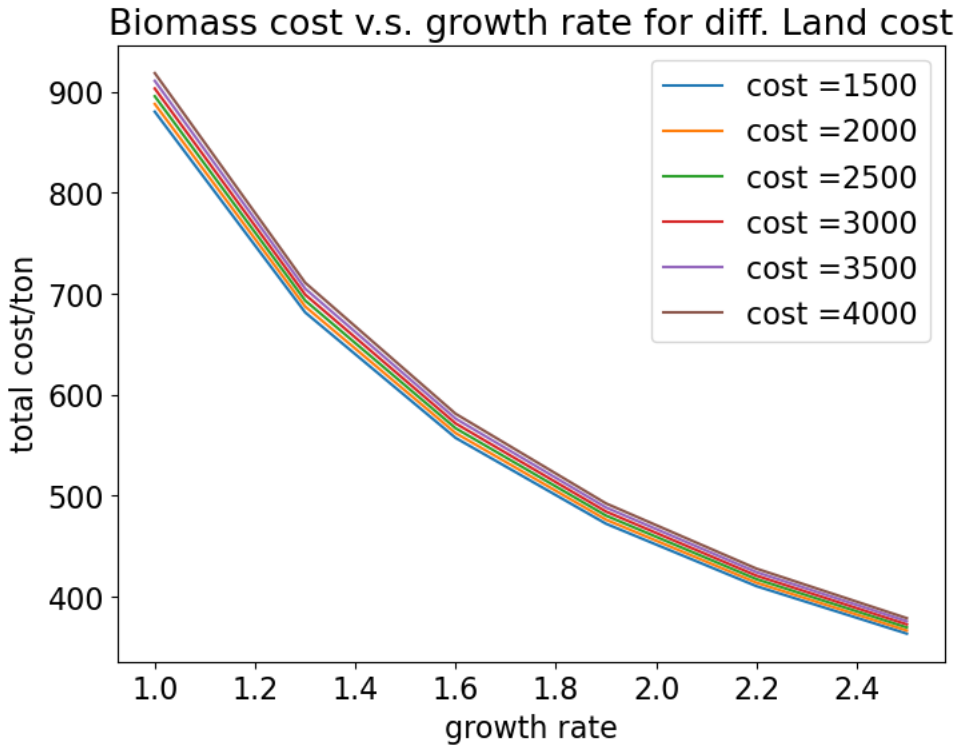




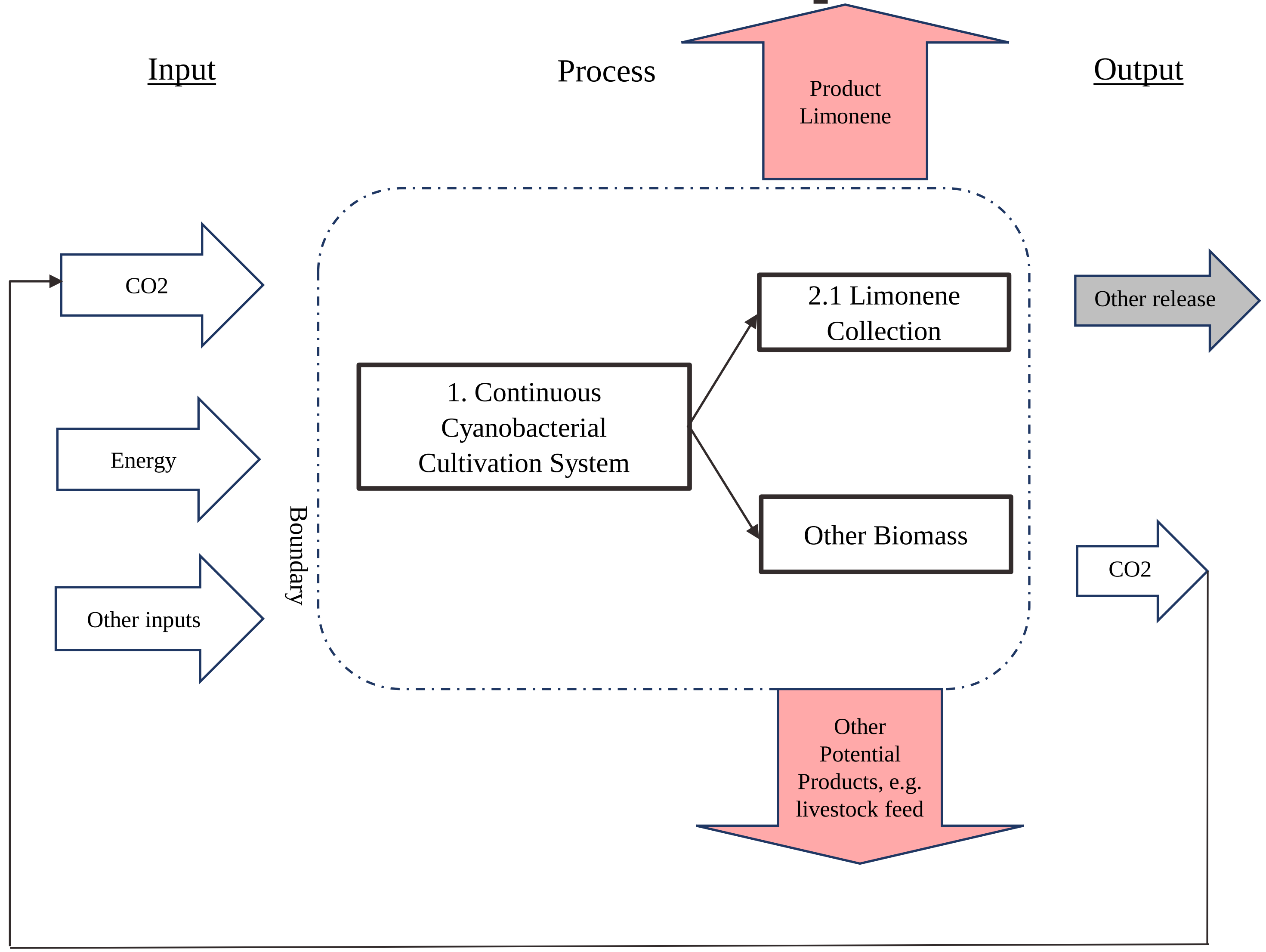
TEA Sensitivity analysis – Cultivation Land

- Increasing the Cultivation Land area has a large influence on levelized cost of biomass
- At low biomass growth rates, the effect of parameters is more pronounced
- The TEA is more sensitive to cultivated area compared to land cost





LCA Goal and Scope Definition



Inventory Analysis

- The pond level algae cultivation system with CO_2 intake efficiency of 65%, and 90%
- To produce algae in the lab or pond, CO_2, NH_3, and DAP associated with electricity input are required
- Main products from this system are limonene, and algae biomass (may use as animal feed etc.)

Input and Output Information of 1 squared meter pond in a day with various CO2 intake Efficiency

		Low CO2 Efficiency Rate	High CO2 Efficiency Rate
Input	Efficiency	65%	90%
	Pond (m2)	1	1
	Algae (g/m2/day)	43	43
	CO2 100% Intake	79.11	79.11
	CO2 with Efficiency Counted (g)	121.71	87.90
	Electricity Use per m2 (kwh)	0.10	0.10
	NH3 (g)	0.86	0.86
	DAP (g)	0.42	0.42
Output	CO2 rate	35%	10%
	Limonene (g)	0.086	0.086
	Biomass (g)	43	43

Notes: SAC unleashes cyanobacterial growth potential with 0.1 g/L/hour biomass productivity and 0.2 mg/L/hour limonene productivity over a sustained period in photobioreactors.
Source: https://www.nature.com/articles/s41467-021-27665-y

Impact Assessment

- Net carbon emission reduction
- Benchmark: Corn Stover ~0g CO_2eq emission per gram (GREET)

CO_2 Sequestration Associated with Efficiency

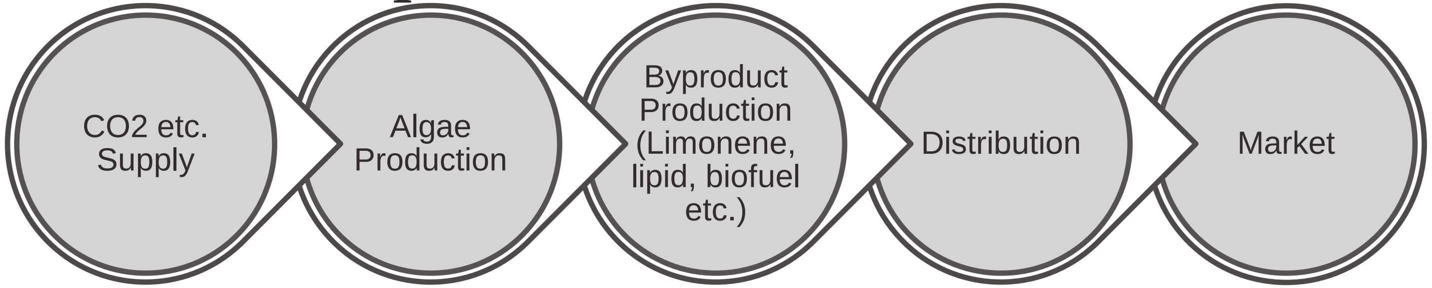
Emission from Electricity (g CO2eq)	42.06
Emission from NH3 (g CO2eq)	2.05
Emission from DAP (g CO2eq)	0.59
Net Emission (g CO2eq)	-34.41
Carbon Utilization Rate (counting Non-Carbon)	56%

Interpretation

- Current technology by Dai/Yuan group can produce 43.3g algae and about 86 mg limonene per day per squared meter pond
- It can sequestrate 34.4 g CO_2 equivalent per day into the algae biomass and limonene
- The carbon utilization rate is 56%
- In this LCA analysis, we didn’t consider the emissions from CO_2 production and transporting the materials.

Algae Farm Supply Chain

- Optimum sites to cultivate algae
- Determine the optimum size of algae farm designs
- The objective is to simulate the algae supply chain, including production (from current TEA), operating, and transportation costs, the impacts on input and output markets, farm profits and the carbon credit.



- CO_2 (Prof. Zhou)

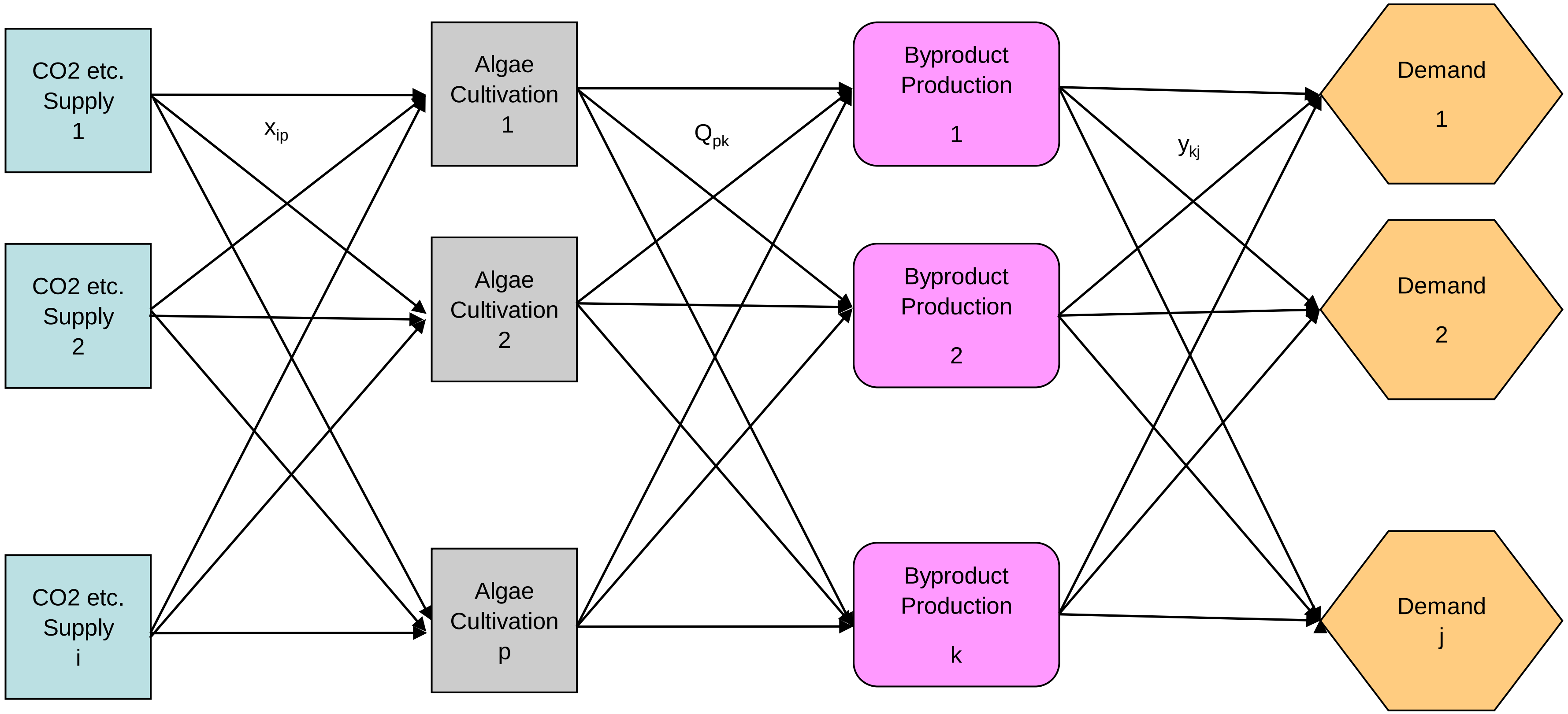
- Light (Prof. Tang)
- Water
- Nutrients (Prof. Jun)
- Climate

Supply Chain Design Considerations

- Factors:
  - Farm design with land requirements and yields
    - Solar duration
    - Solar radiation
    - Temperature
    - Water resources
    - Photobioreactor (PBR) costs etc.
  - Power plant capacity (source for CO_2)
    - Distance to the algae farm
    - Sorbent efficiency and reuse
    - Alternatives to ship sorbent and CO_2
  - Nutrients from wastewater treatment
    - Distance from hydrogel producing facility to the algae farm
    - Hydrogel efficiency and reuse
  - Limonene and biomass processing
  - Emission and Reduction from all processes

Supply Chain Model

- The model has three layers
  - Layer 1 connects the CO2 supply locations i to algae farm p
  - Layer 2 connects algae cultivations to the byproduct production site k
  - Layer 3 connects the products to the potential market j



Future Plans

- Integration of different modules
- Scale-up to 2 liter, 20 liter and 100 liter

Our Team

Dai

McCarl

NCCC at Southern Company
Scale up and on-site testing

Morten

TAMU Plant Pathology & Microbiology
Microbial engineering and development of continuous algal cultivation platform

TAMU Agriculture Economics
Life cycle analysis and environmental analysis

Jun

Yuan

Zhou

Pistikopoulos

Chemical Engineering
System modeling and TEA

TAMU Chemistry
Amine-based porous sorbent advancement

WUSTL Chemical, Energy & Environmental Engineering
Unique hydrogel technologies and process design

Tang

Acknowledgement

- DOE Office of Fossil Energy
- Dr. Lei Hong

- Questions?

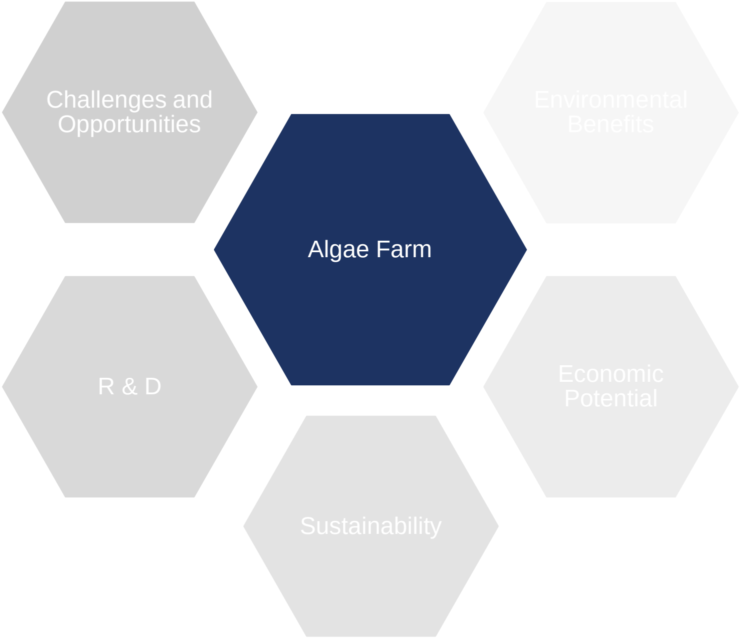
- Ca-Alg/CaP + Wollastonite can achieve P recovery up to 97% at 72 hr.
- Ca-Alg/CaP + Struvite can recover N and P simultaneously.
- Mineral-hydrogel composites can recover nutrients from wastewater without significant interference.
- With 10% (v of hydrogel precursor/v of media) dose, composites can deliver sufficient P for algal growth.
- Without BG11, 40% (v/v) Ca-Alg/CaP + Struvite can make 73.4% of algal growth with BG11 media.
- The ammonium dissolution rate of Ca-Alg/CaP + Struvite is slow. To provide N in a nitrate form, we developed Ca-Alg/$NaNO_3$ composites.
- Adding Ca-Alg/$NaNO_3$ composites can improve the algal growth by 2.3 folds compared to only N, P recovered mineral hydrogels.

- **Task 2.2 Hydrogel advancement and cultivation integration**

Milestone	**Achieve average dry weight percent of carbonate/ P/ N-containing minerals -- mineral 40 wt.% at 50g scale by 6/30/2023**
Current status	✓ **Ca-Alg/CaP: 41.7% dry weight of CaP/dry weight of the composites** ✓ **Ca-Alg/CaP + Struvite: 68% dry weight of CaP + Struvite/dry weight of the composites; 34.6%CaP/composites and 19.2% struvite/composites** ✓ **Ca-Alg/$CaCO_3$: 14.7% dry weight of $CaCO_3$/dry weight of the composites(This would be sufficient for algal growth)** ✓ **We successfully made composites at 50g scale.**

Why algae farm supply chain design?

- Improve productivity
- Profit maximization
- Location Selection
- Facility Investment
- Carbon credit
- R & D
  - resource efficiency of laboratory experiments
  - identify cost-saving opportunities in procuring laboratory supplies and equipment
  - support informed decision-making (environmental impacts etc.)



Algae Farm Design Alternatives

- Open systems: tanks, circular ponds, raceway ponds
- Closed systems: flat-plate, tubular, vertical-column enclosed systems

Table 1: Comparison of open and closed systems for growth of algae

Parameters	Open systems	Closed systems
Contamination	High	Low
Process control	Difficult	Possible
Species control	Not possible	Possible
Mixing	Not uniform	Uniform
Foot-print	Extremely high	Very low
Area/volume ratio	Low (5 to 10 m^{-1})	High (20-200 m^{-1})
Capital cost	Low	High
Operation cost	Low	High
Water losses	Very high	Low
Light utilization	Low	High
Productivity	Low	High (3-5 times)
Biomass conc.	Low	High (3-5 times)
Mass transfer	Low	High

Source: https://www.e-education.psu.edu/egee439/node/695

Table 2: Factor comparison of different systems

Factors	Open Ponds	Leidos Hanging Bags	Horizontal Tubes	Flat Panel	Helical Tubular
Productivity	low	high	low	high	medium
Cultivation Area	high	low	high	low	medium
Total Area	high	low	high	medium	medium
Annual Power Usage	low	medium	medium	medium	high
Installed Capital Costs	low	medium	medium	high	high
Variable Operating Costs	low	medium	medium	medium	high
Fixed Operating Costs	low	low	medium	high	medium
Minimum Biomass Selling Price	low	medium	medium	high	high

Notes: We compared five different algae farm type, the data is from NREL (NREL, 2019).

Land Requirements

Biomass productivity: 43.3 g/m^2/Day in the open pond.
Algae productivity can be improved using integrated systems (NREL, 2019)

Table 3: The land usage for a 50,000 dry tons/year algae farm

Style					
Cultivation area (acre)	759.69	782.18	455.82	368.91	368.91
Facility size (acre)	1,090.31	1,586.85	730.37	628.87	481.34

Notes: The estimated acre for each algae farm design is based on the annual productivity compared to the open pond system (NREL, 2019).

CO2 Utilization and Power Plant

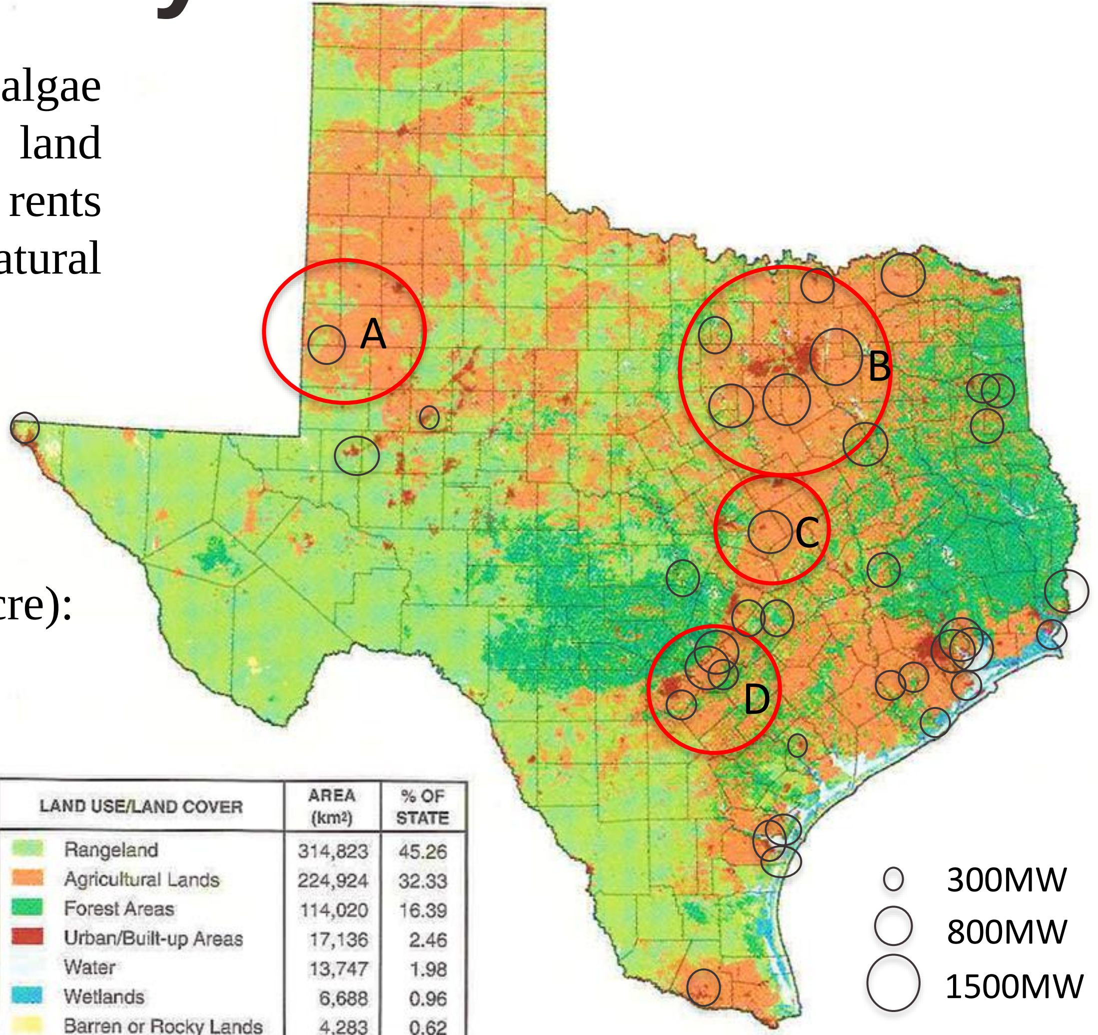
- 1g algae biomass can utilize 0.21 grams of CO2
- A 50,000 dry ton capacity algae farm can capture **10,500 tones** of CO_2 per year
- which is equivalent to **23.86 GWh** of electricity generated from natural gas
- which is approximately **50%** of the total electricity generation in a year from a 10 MW natural gas combined cycle power plant with a capacity factor of 54.4%
- To match up such a 10 MW power plant's CO2 emissions, it requires **961 -3,000** acres for the algae farm.

Reference:
https://www.eia.gov/tools/faqs/faq.php?id=74&t=11
https://www.eia.gov/tools/faqs/faq.php?id=667&t=2

Land Availability and Power Plant

- Ideally, the location of algae farm should be with land availability with lower rents and be closer to the natural gas power plant.

- Average rents in 2022 (non-irrigated cropland $/acre):
  - A: $36.58
  - B: $25.46
  - C: $17.47-$25.46
  - D: $25.46



LAND USE/LAND COVER	AREA (km²)	% OF STATE
Rangeland	314,823	45.26
Agricultural Lands	224,924	32.33
Forest Areas	114,020	16.39
Urban/Built-up Areas	17,136	2.46
Water	13,747	1.98
Wetlands	6,688	0.96
Barren or Rocky Lands	4,283	0.62
TOTAL	695,624	100.00

Notes: all the points are for natural gas combined cycle power plants; the steam plants are not included.

Sources:
http://www.txyoungfarmers.org/default.aspx?ID=23623
https://agrilife.org/texasaglaw/2022/09/12/usda-nass-releases-2022-cash-rent-report/

Supply Chain Model

- Objective Function: Maximize social welfare to simulate market equilibrium
  - Integral of demand curves
  - Simulate market equilibrium price and quantity
  - Costs (capital and operating, land, pumping, transportation etc.)
  - Carbon credits

- Constraints
  - CO_2 and other inputs supply: emission capacity and transport distance
  - Algae cultivation: cultivation types associated with land requirements, total land availability, water requirements, energy consumption, yields with factors like temperature, solar condition etc.
  - Byproduct production: extraction efficiency, transport distance
  - Demand: all products shipped should meet the demand

Ongoing work

- Integrating the algae farm design parameters (light, farm type etc.) within TEA and supply chain model (with Prof. Tang's group and Prof. Pistikopoulos's group)
- Developing the TEA and LCA for the nutrients from wastewater treatment process (with Prof. Jun's group and Prof. Pistikopoulos's group)
- Developing the supply chain model to incorporate all relevant processes and ensure a comprehensive market perspective for the project
- Scenario analysis (with Prof. Pistikopoulos's group and Prof. Tang's group)
- Multi-Objective formulation to assess tradeoffs between economic and environmental objectives