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Harnessing Algal Biomass to Contain Power Plant Emissions

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Addressing the Nation's Energy Needs Through Technology Innovation – 2019 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting

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Outline

- Current challenges of biological CO_2 capture from power industry
- Our strategy - The combined biological and chemical solution
- The pilot-scale photobioreactor algal cultivation
- The algal amino acid salt solution of CO_2 capture
- Mass and energy balance of the combined solution

100 MW T.B. Simon Power Plant, MSU

160 MW Erickson Power Plant, Lansing, MI

Algal cultivation on flue gas and wastewater from the power plant

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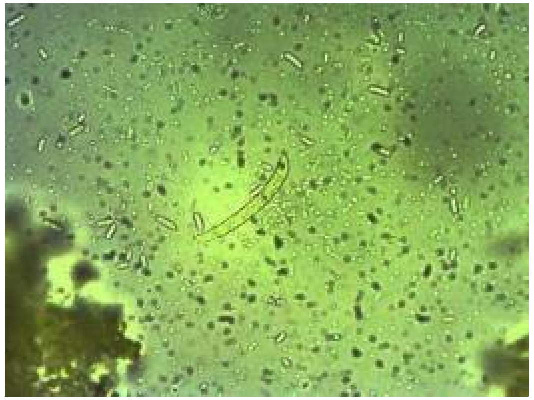
1. Current challenges of biological CO_2 capture from flue gas

- Algal biomass yield and algal biomass productivity
  - Very good biomass yield (considering photosynthesis)
  - Unmatched biomass productivity (considering the rate of CO_2 emission)

- Land and water demands for large algal cultivation systems required to completely capture CO_2 from a commercial coal-fired power plant
  - Erickson Power Plant (150 MW): ~3,000 metric ton CO_2 per day requires ~150,000,000 m^2 area for the open pond reactor and ~45,000,000 m^3 volume for the photobioreactor (based on the current algae biomass productivity of 20 $g/m^2/day$)

- Stability and robustness of algal strains for long-term cultivation on flue gas

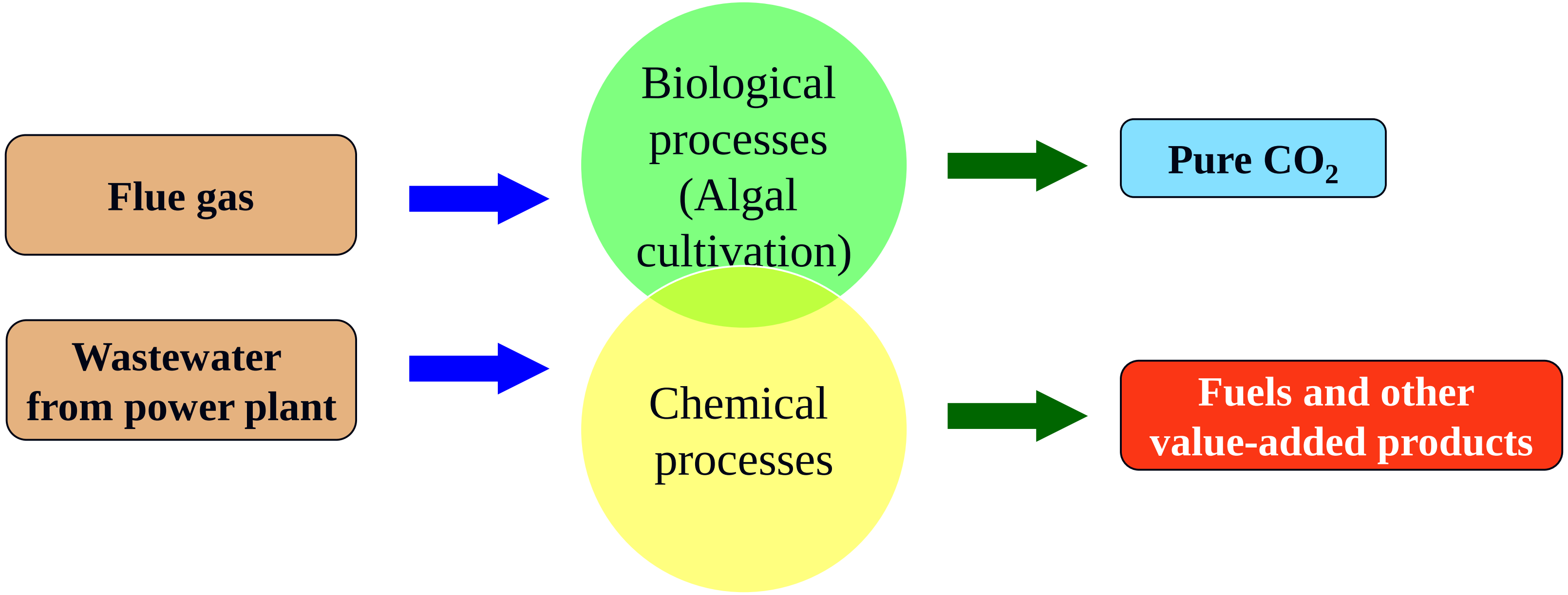
Large footprint of algal cultivation From: http://www.cyanotech.com/company/facility.html



Contaminated algal cultivation From: https://www.youtube.com/watch?v=H4DQTeNamPE

2. Our Strategy – A combined biological and chemical solution

Synergistically integrating biological and chemical processes to efficiently capture CO_2 from flue gas and completely utilize the algal biomass for value-added chemical and fuel production



Objectives:

1. The selected algal strain to maximize biomass accumulation from the coal-fired flue gas
2. A cascade biomass utilization to produce **amino acid absorbents**, polyurethanes, biodiesel, and methane
3. Techno-economic analysis (TEA) and life cycle assessment (LCA)

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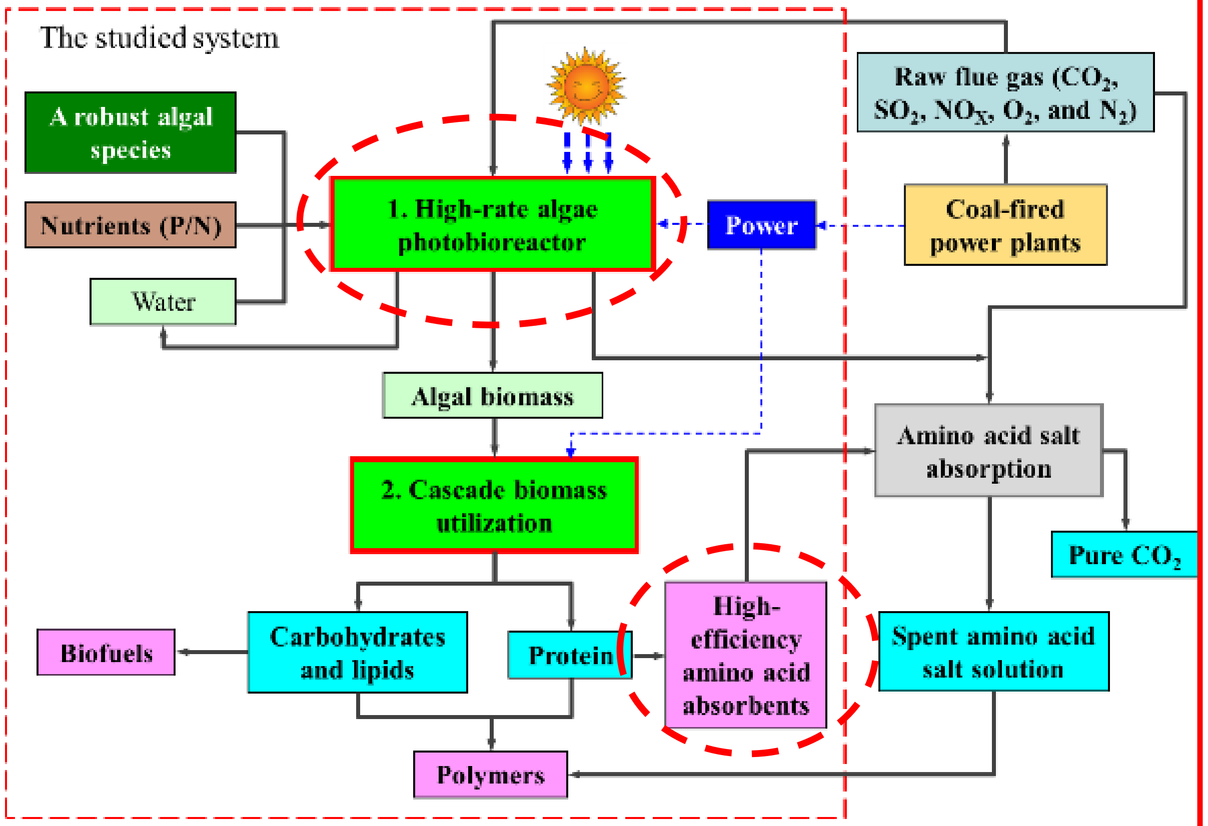
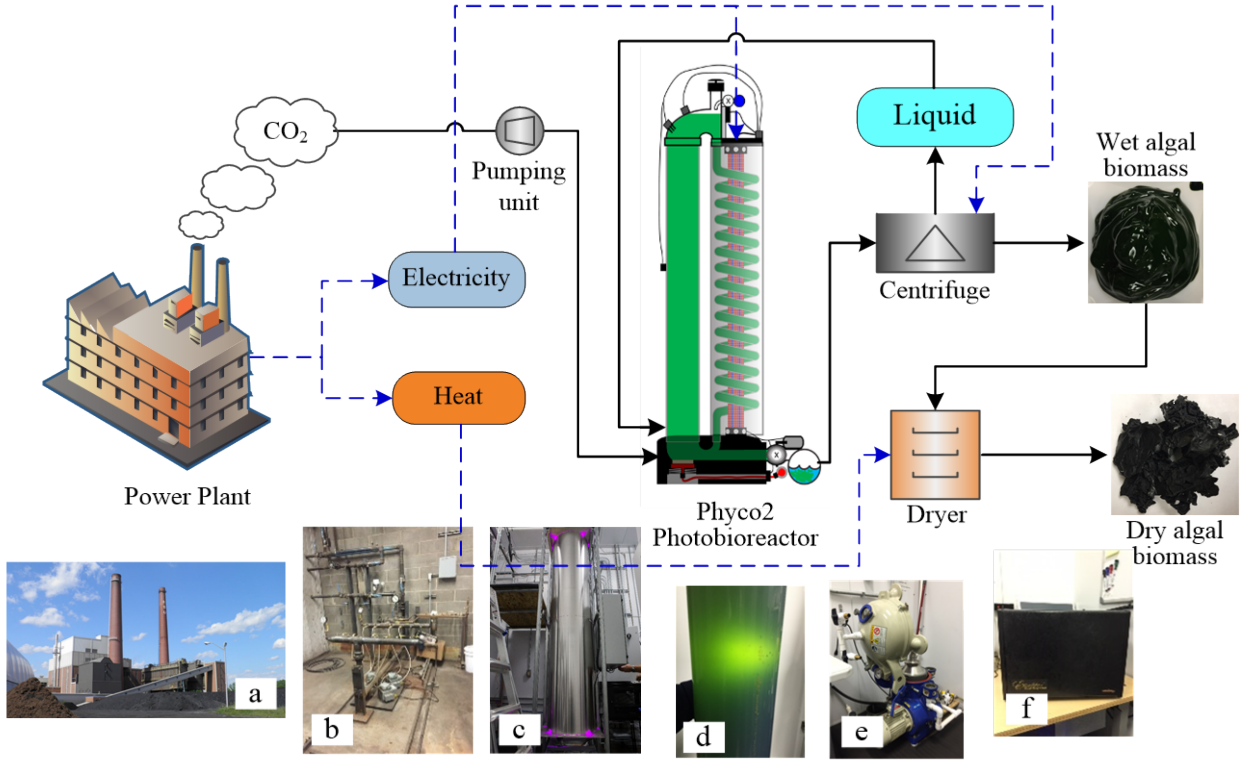
2. Our Strategy – A combined biological and chemical solution

The flowchart of the biological and chemical solution*



*: Solid black lines are the mass flow. Dashed blue lines are the energy flow. The red frame is the system that will be studied by this project.

The pilot photobioreactor system in the MSU power plant

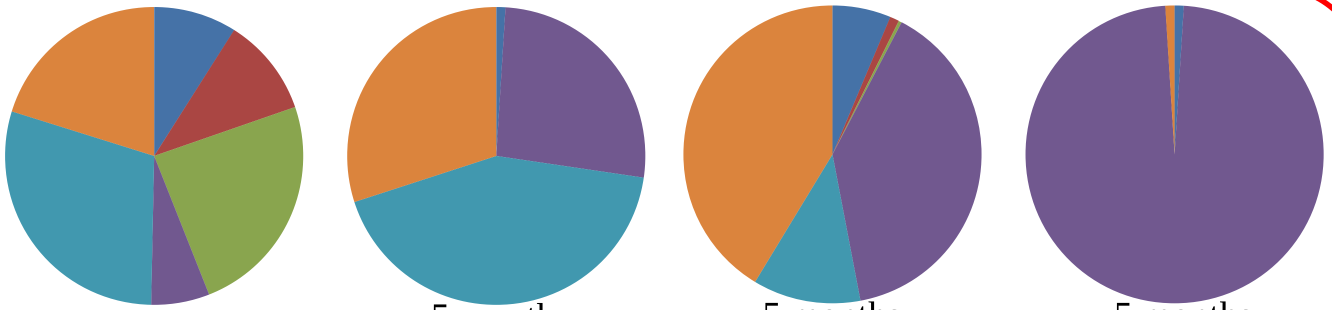


a. T.B. Simon power plant; b. Flue gas pumping unit; c. Photobioreactor; d. Algae growing in the reactor; e. Centrifuge; f. Dryer

3. The Pilot-scale photobioreactor algal cultivation

A. A robust algal strain from the Great Lakes region

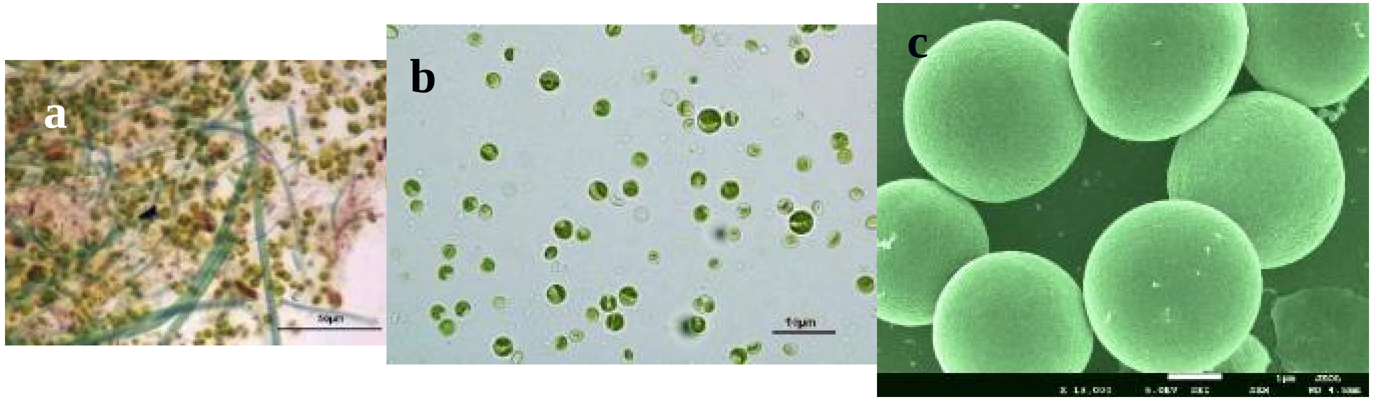
- A robust alga, *Chlorella sorokiniana* MSU, has been selected from the Great Lake region.



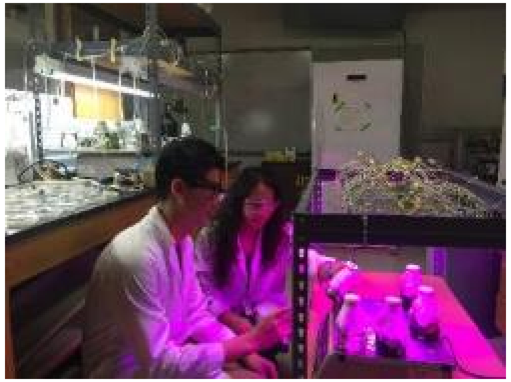
Original seed | 5 months 40 g m^{-3} TN | 5 months 100 g m^{-3} TN | 5 months 200 g m^{-3} TN

Pseudanabaena *Phormidium* *Limnothrix*
Chlorella *Synechocystis* *Scenedesmus*

Changes of the algal assemblage during 5 months continuous culture



Algal community assemblages before (a) and after (b) cultured in AD effluent for 5 months, and (c) SEM picture of the pure *Chlorella sorokiniana* MSU



Effects of different wavelengths on algae

Flask culture (250 ml)

Bench scale photobioreactor (10 L)

Bench scale photobioreactor (2 L)

3. The Pilot-scale photobioreactor algal cultivation

B. Pilot operation

- This task optimizes and validates continuous algae cultivation using the pilot photobioreactors

- Pilot experiments
  - **The algal strain:**
    - The selected *Chlorella sorokiniana* MSU with several bacteria
  - **Culture system preparation:**
    - The **boiler water (12 mg/L TP)** is the water source for the culture.
    - The flue gas from the T.B. Simon power plant is the CO_2 source.
    - Na_2SO_3 and NH_4NO_3 are used to mimic SO_2 and NO_2 in the flue gas.

  - **Operation of the algal cultivation:**
    - Flue gas flow rate: 120 L/1000 L solution/min
    - The reactor volume: 100 L
    - Harvesting frequency: 12 hours and 24 hours
    - Harvesting amount: 30 L/harvesting, 50 L/harvesting, 60 L/harvesting, 70 L/harvesting
    - Water recirculation: 50 L/harvesting and recirculation

PHYCO2-MSU pilot algal cultivation facility at the power plant

100 L pilot unit

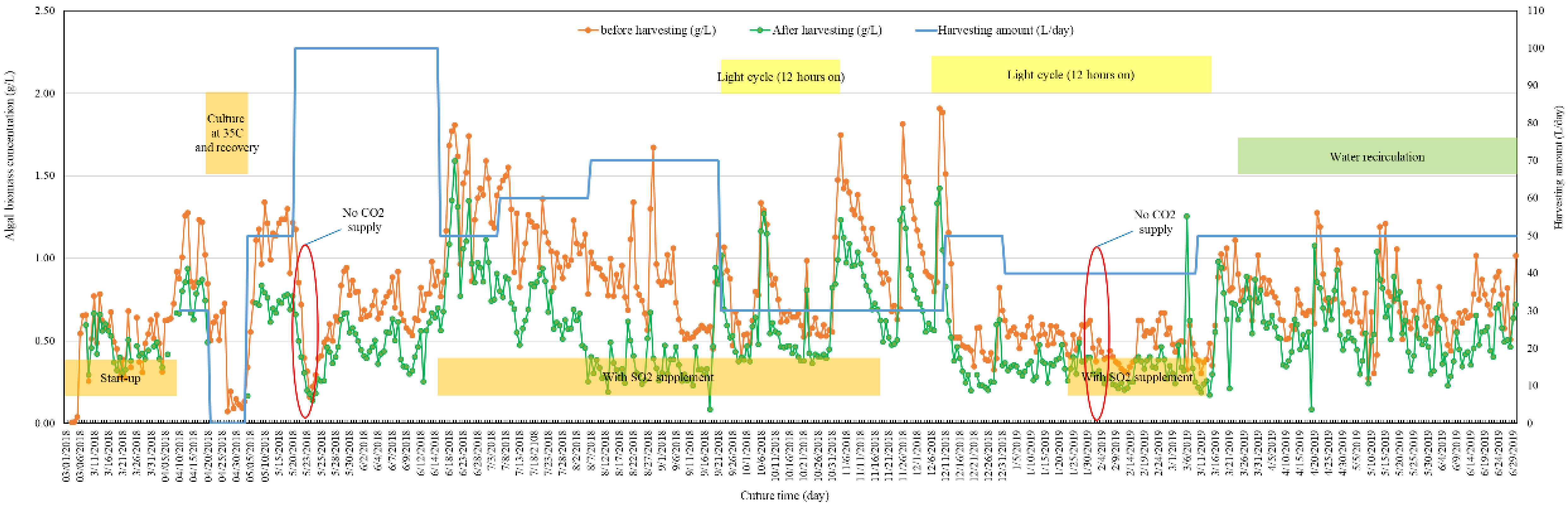
The culture started

The normal growth

3. The pilot-scale photobioreactor algal cultivation

B. Pilot operation

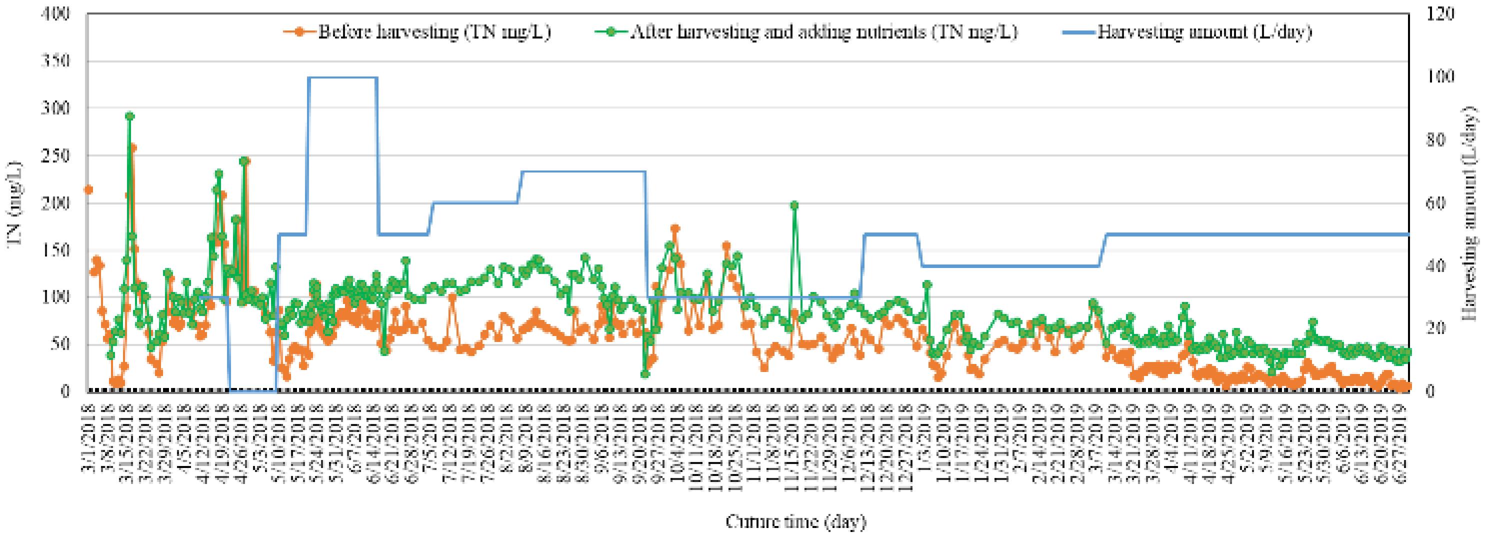
Biomass concentration under different culture conditions (from March 2018 to June, 2019)



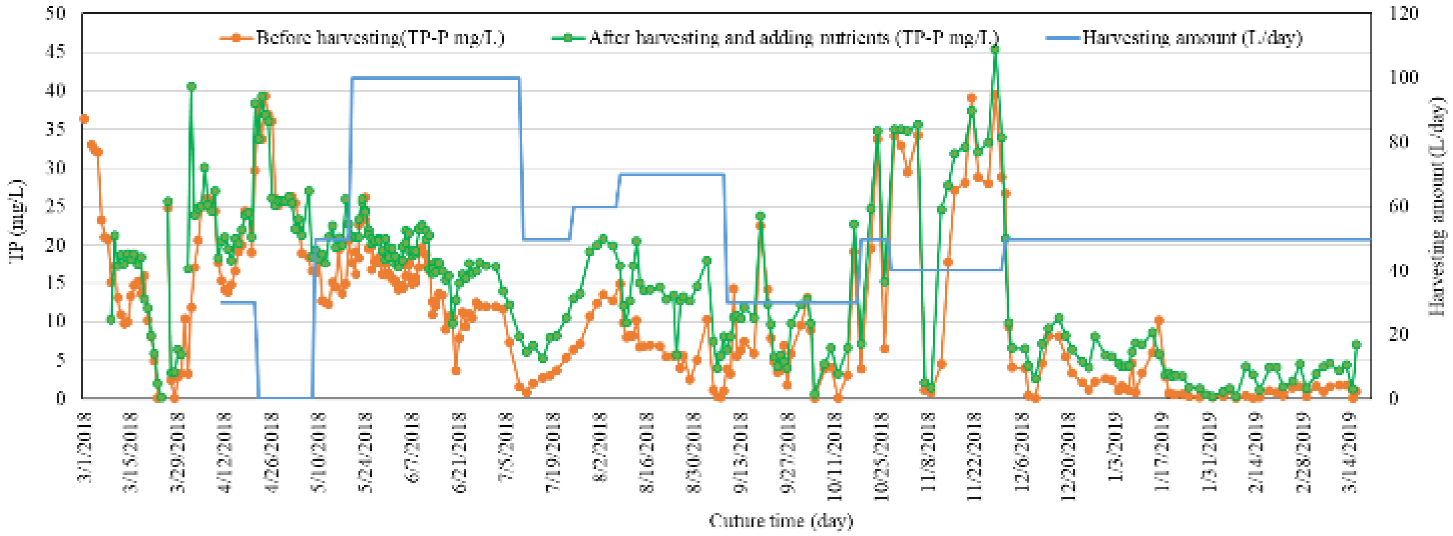
3. The pilot-scale photobioreactor algal cultivation

B. Pilot operation

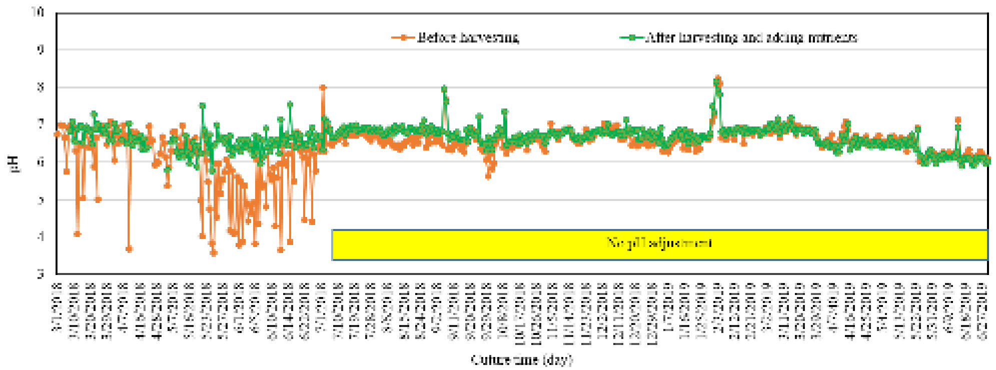
Nitrogen consumption (from March 2018 to June 2019)



Phosphorus consumption (from March 2018 to June 2019)



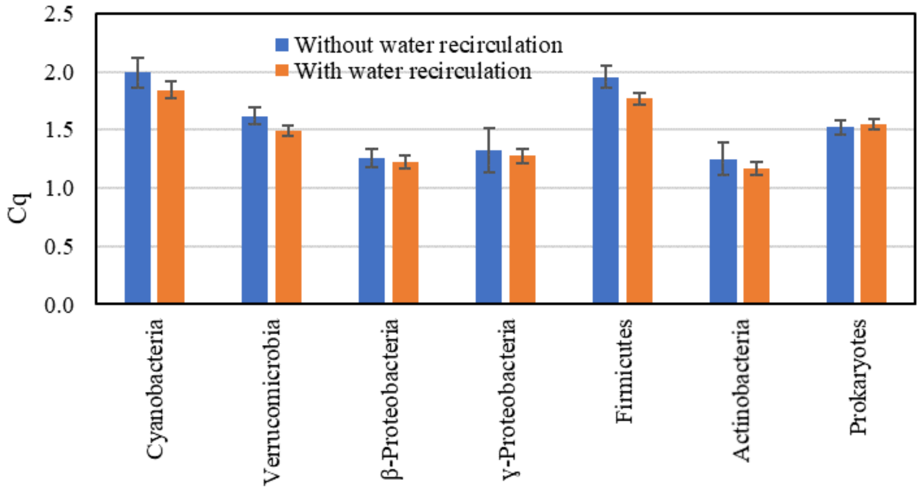
pH (from March 2018 to June 2019) [a, b]



a: A strategy using ammonia and nitrate to balance pH has been developed applied to control pH without acid and alkali usages

b: NxO in the flue gas can be beneficial for the pH control.

Cq ratio of alga and bacteria (from March 2018 to June 2019) [a]



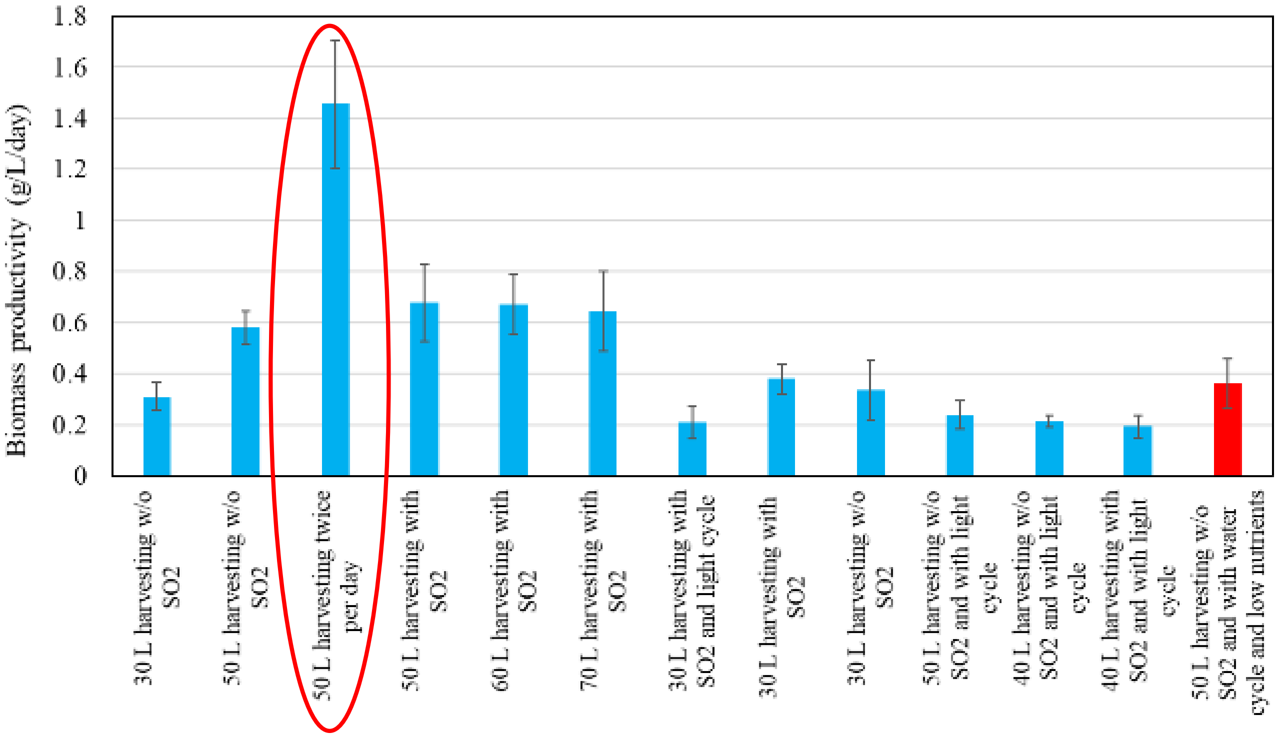
a: Cq is the number from qPCR analysis.

3. The pilot-scale photobioreactor algal cultivation

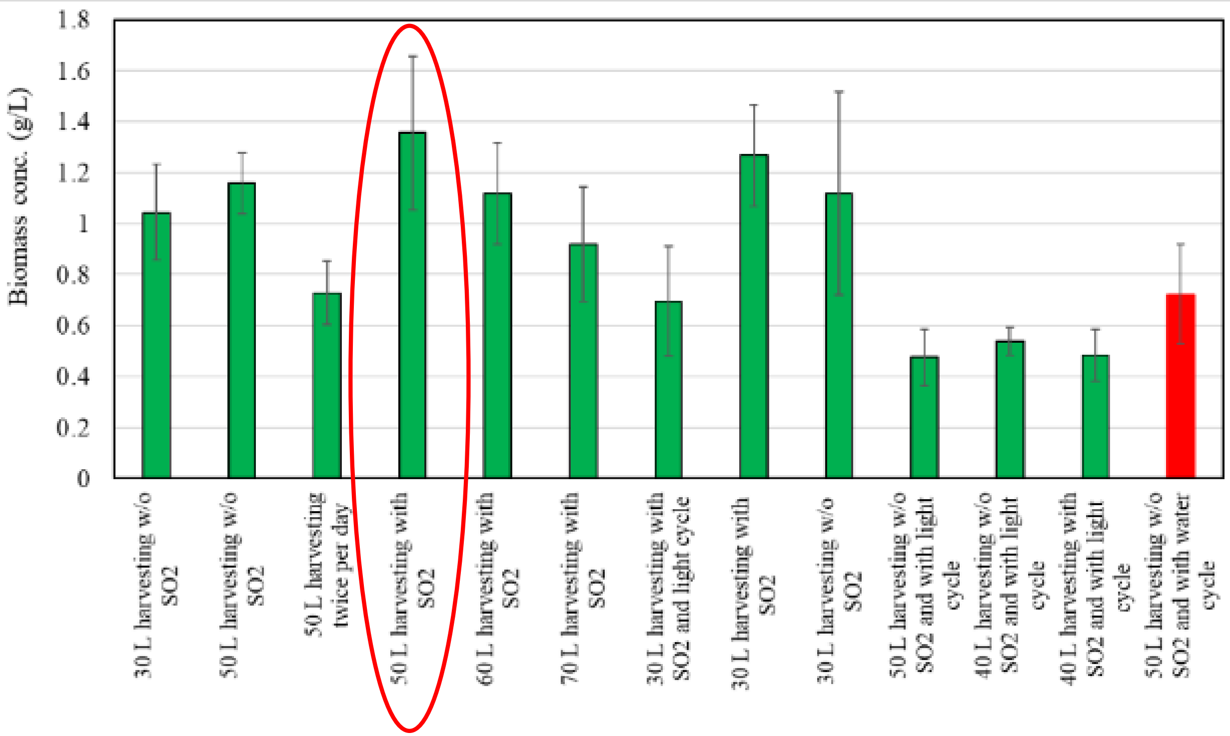
B. Pilot pperation

Biomass concentration and productivity

Biomass productivity



Biomass concentration



- **50 L harvesting twice per day had the highest ($P<0.05$) biomass productivity of 1.45 g/L/day.**
- **50 L harvesting with SO_2 supplement had the highest ($P<0.05$) biomass concentration of 1.36 g/L.**
- **50 L harvesting with SO_2 and water cycle had the biomass productivity and biomass concentration of 0.36 g/L/day and 0.72 g/L.**

3. The pilot-scale photobioreactor algal cultivation

C. Harvested biomass from the pilot operation

Characteristics of algal biomass from the pilot operation

Elements

Elements	value
Carbon (%, dry biomass)	48.2
Nitrogen (%, dry biomass)	**9.1**
Sulfur (%, dry biomass)	0.5

Components

Components	value
Crude proteins (% dry biomass)	**56.8**
Lipids (% dry biomass)	6.8
Carbohydrates (% dry biomass)	30.4
Ash (% dry biomass)	6.0

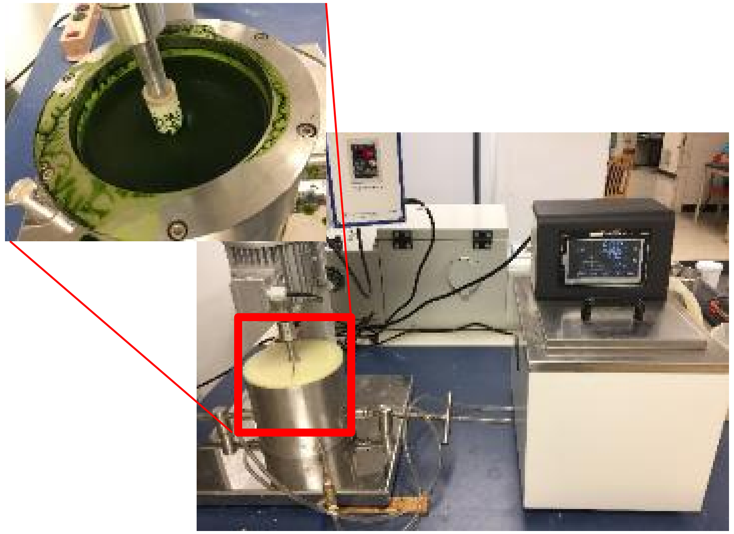
Amino acids

Amino acids	Content (Mole %)
histidine	1.63
isoleucine	4.24
leucine	8.52
lysine	**10.32**
methionine	3.90
phenylalanine	3.58
threonine	3.62
tryptophan	-
valine	7.96
arginine	4.88
cysteine	1.43
glycine	**11.04**
proline	**5.66**
tyrosine	1.00
alanine	**13.35**
aspartic Acid	5.79
glutamic Acid	10.51
serine	2.53

4. The algal amino acid salt solution of CO_2 capture

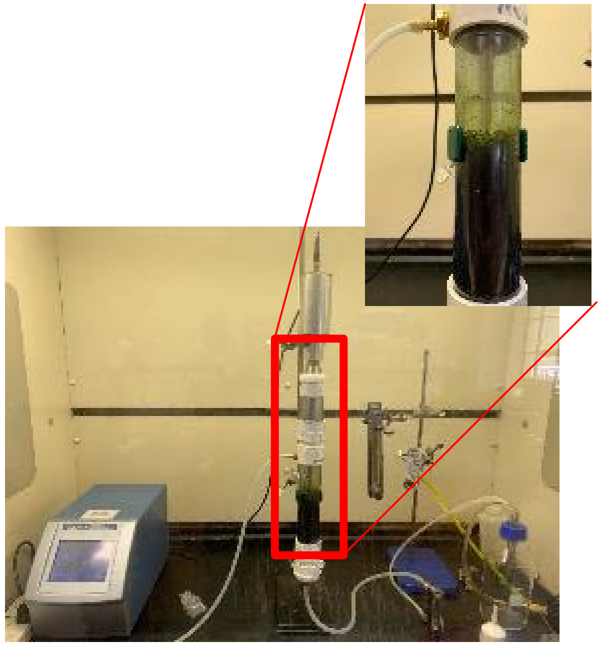
A. Flowchart

Wet algal biomass → Mechanical alkali protein extraction and hydrolysis → Mixed amino acid salt solution → CO_2 capture → Spent amino acids



2 L ball mill unit for mechanical alkali protein extraction

2 L Parr reactor for protein hydrolysis



Bench-scale CO_2 absorption unit

Bench-scale CO_2 desorption unit

4. The algal amino acid salt solution of CO_2 capture

B. Protein extraction and amino acid CO_2 absorption results

Mechano-chemical protein extraction process*

Sample No.	Ball material	Ball:Biomass mass ratio	Reaction time (min)	KOH	Protein extraction efficiency (%)	Amino acid conversion efficiency (%)
1	Zirconia	4:1	60	KOH	87	10
2	Zirconia	4:1	30	KOH	41	8
7	Agate	4:1	30	KOH	81	9
9	Agate	2:1	30	KOH	17	7

*: The effects of selected ball/biomass ratio, reaction time on protein extraction efficiency of ball mill treated algal biomass. The milled slurry was treated under 130C for 2 hours before using for absorption.

- **Both agate and zirconia had high protein extraction efficiency.**
- **Amino acid conversion efficiency is still low.**
- **Major amino acids from algal biomass can efficiently absorb CO_2 and release them under an elevated temperature.**

Single amino acid salt solution of CO_2 absorption and desorption*

Solutions	Total carbon of original solution (mol carbon/L)	Total carbon after absorption (mol carbon/L)	Total carbon after desorption (mol carbon/L)	Total carbon captured (mol carbon/mol amino acid salt)
Glycine salt	1.82	2.69	1.68	1.01
Alanine salt	2.37	4	2.73	1.27
Lysine salt	5.08	5.75	5.14	0.61
Proline salt	4.34	5.35	4.51	0.84
KOH (control)	0	0.43	0.28	0.15

*: the amino acid solution used for this test is 1 M.

Chemical reactions of amino acid salt CO2 absorption

Amine formation: $^{-}OOC\text{-}R\text{-}NH_3^{+} + KOH \rightarrow K^{+} + {}^{-}OOC\text{-}R\text{-}NH_2 + H_2O$

amino acid — amine

Carbamate formation: $CO_2 + 2\,{}^{-}OOC\text{-}R\text{-}NH_2 \leftrightarrow {}^{-}OOC\text{-}R\text{-}NH\text{-}COO^{-} + {}^{-}OOC\text{-}R\text{-}NH_3^{+}$

carbamate

Carbamate hydrolysis: $^{-}OOC\text{-}R\text{-}NH\text{-}COO^{-} + H_2O \leftrightarrow {}^{-}OOC\text{-}R\text{-}NH_2 + HCO_3^{-}$

bicarbonate

Biocarbonate formation: $CO_2 + {}^{-}OOC\text{-}R\text{-}NH_2 + H_2O \leftrightarrow {}^{-}OOC\text{-}R\text{-}NH_3^{+} + HCO_3^{-}$

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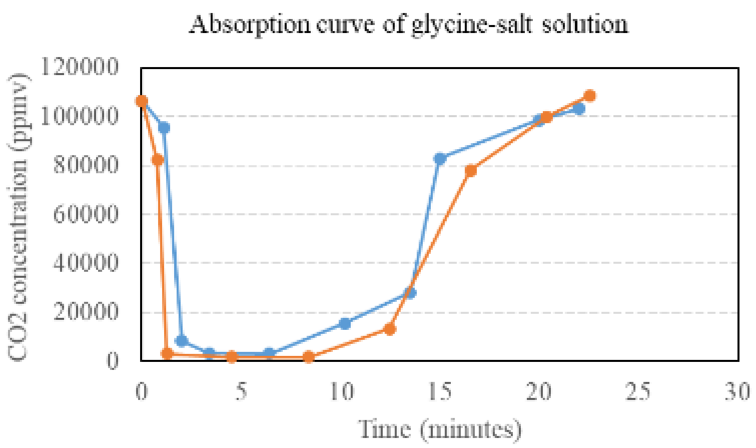
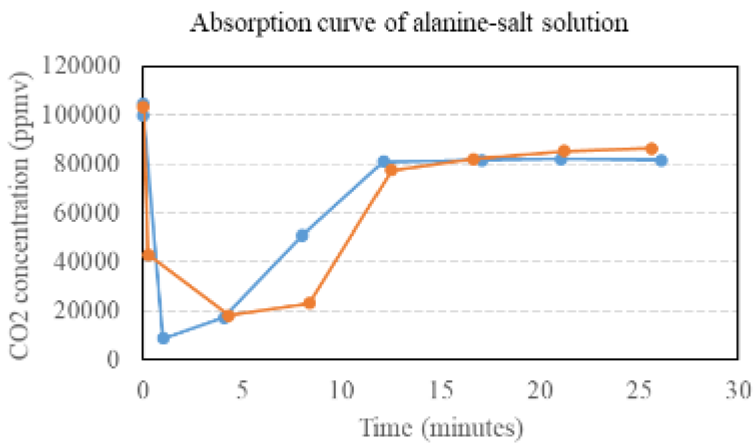
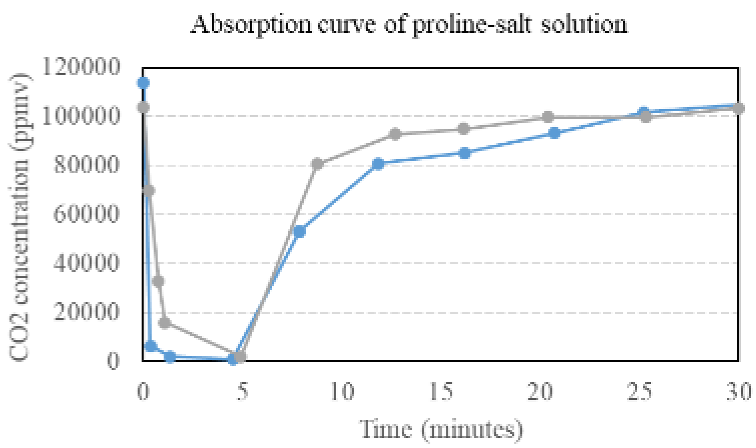
4. The algal amino acid salt solution of CO_2 capture

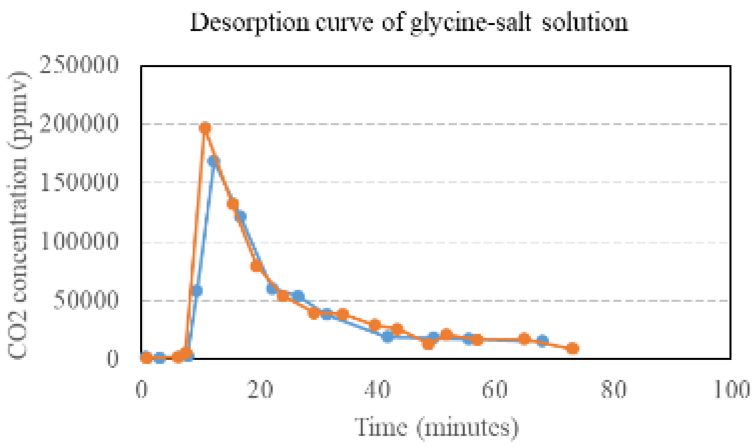
B. Amino acid salt CO_2 absorption

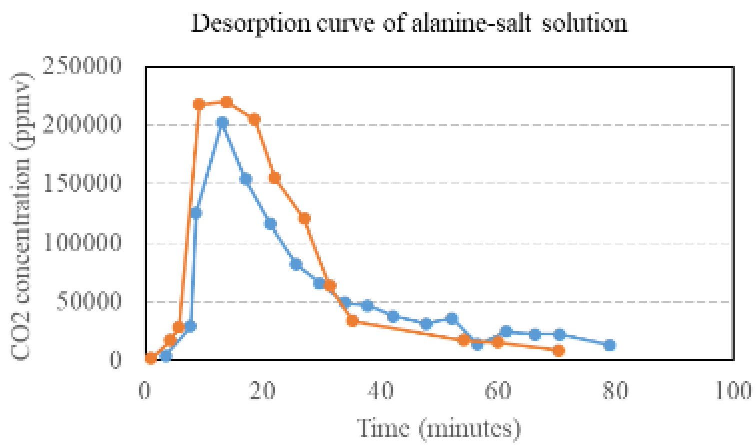
Kinetics of absorption and desorption of single amino acids

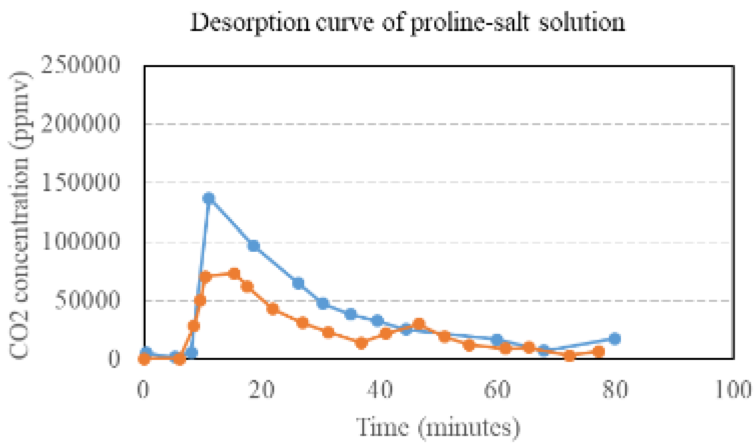








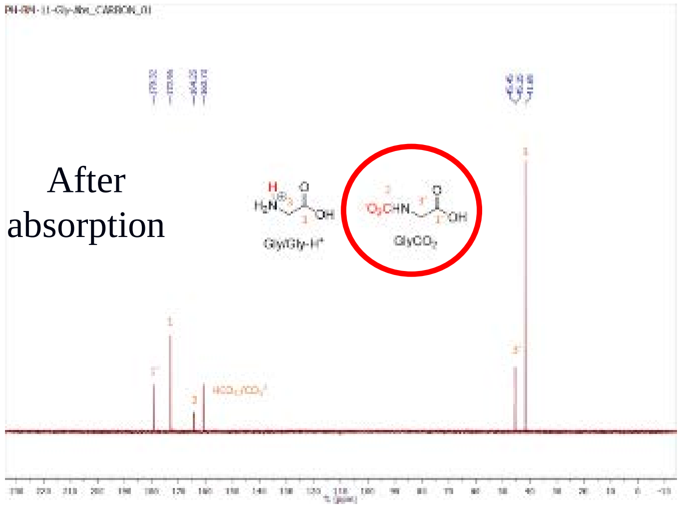


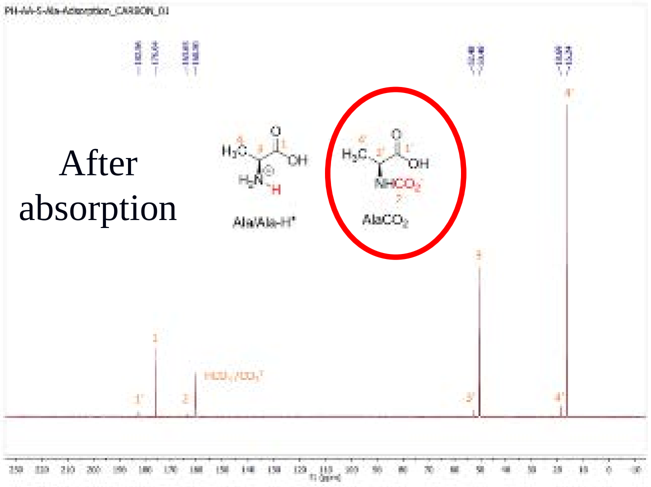


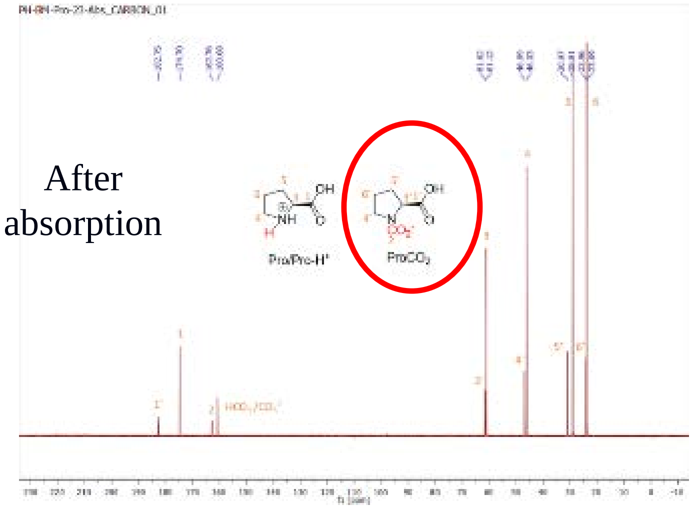
4. The algal amino acid salt solution of CO_2 capture

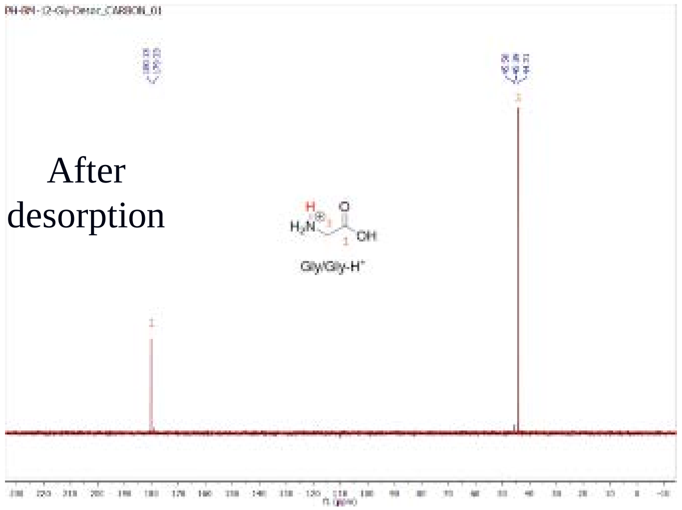
B. Amino acid salt CO_2 absorption

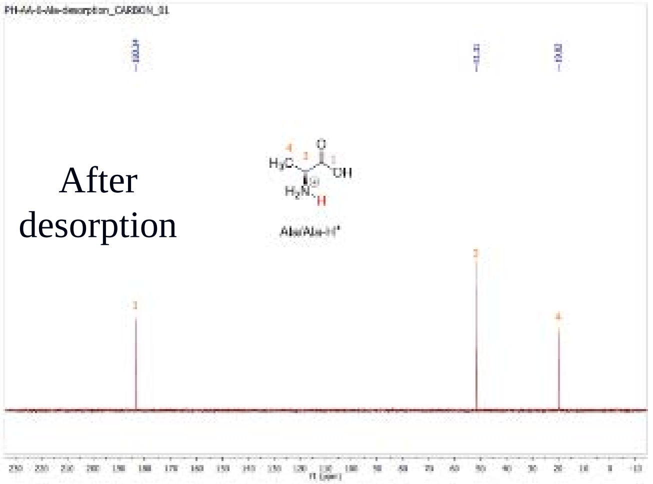
NMR results of absorption and desorption of single amino acids

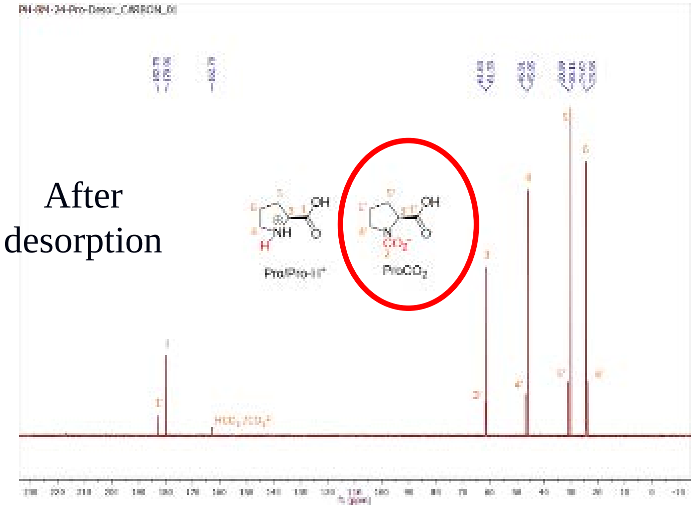












Glycine

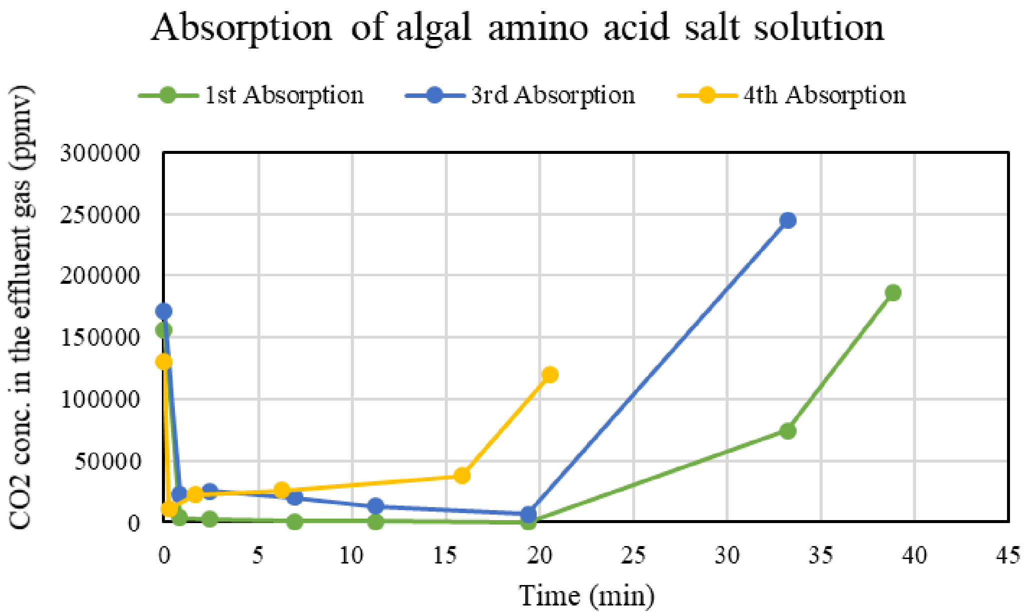
Alanine

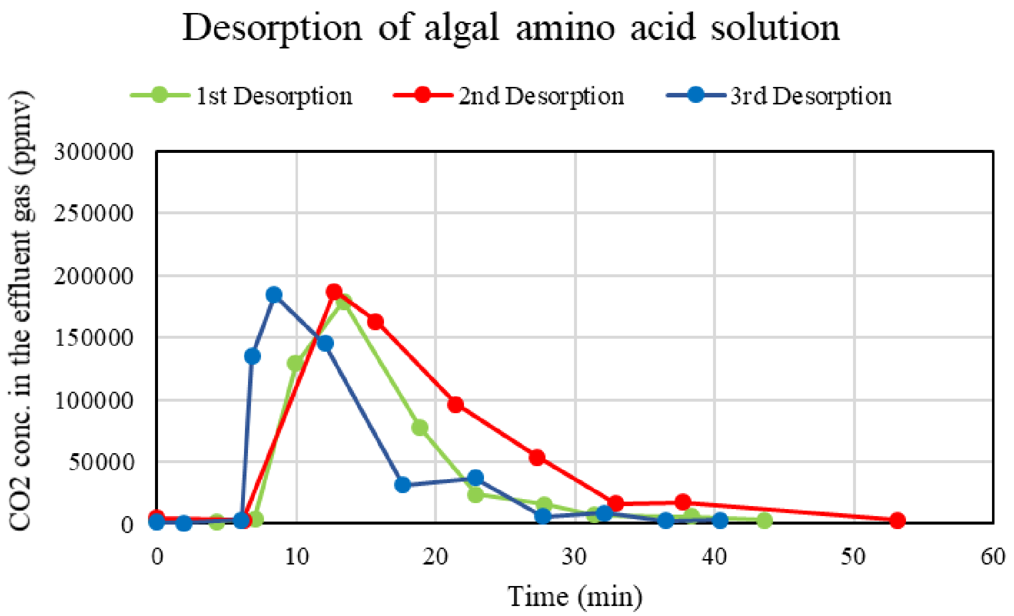
Proline

4. The algal amino acid salt solution of CO_2 capture

B. Amino acid salt CO_2 absorption

Kinetics of repeated absorption and desorption of algal amino acids salt solution





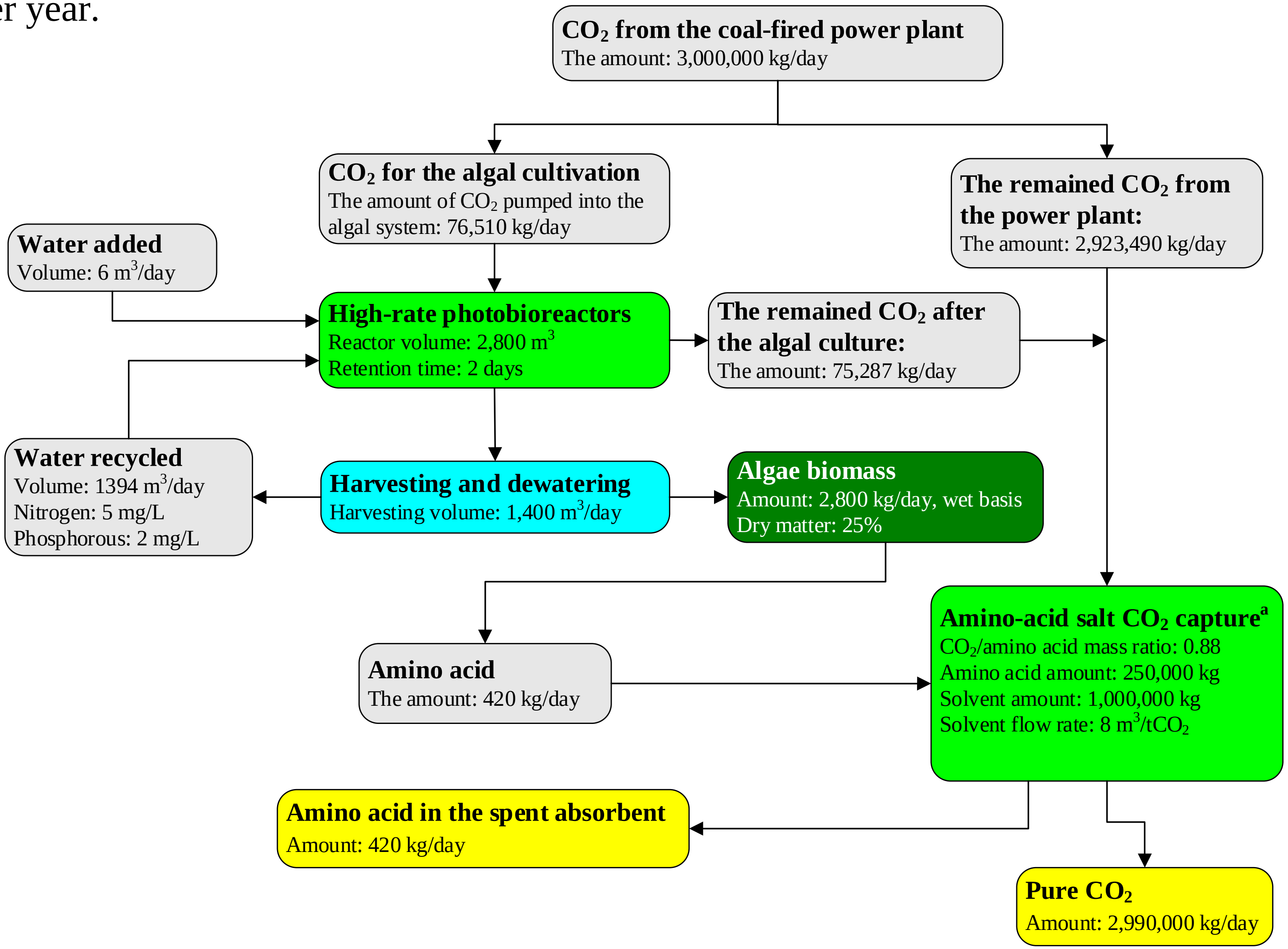
Solution	Average CO2 amount absorbed (mol carbon/L)	Average CO2 amount desorbed (mol carbon/L)	Total CO2 captured (mol CO2/mol algal amino acids)	Total CO2 captured (g CO2/g algal amino acids)	Total CO2 captured (g CO2/g dry algal biomass)
Algal amino acid salt solution	0.2	0.19	2.2	0.88	0.044

- **Algal amino acid salt solution shows much better CO_2 absorption capacity than single amino acid salt solution.**
- **Increasing amino acid conversion is a critical step for producing high-efficiency algal amino acid salt solution.**
- **Repeatability of algal amino acid salt solution is very good and still under investigation.**

5. Mass and energy balance

A. Preliminary mass balance analysis

- The mass balance analysis is based on a system sized for a 150 MW coal-fired power plant.
- The power plant burns subbituminous coal and generates 1.2 million metric tons of CO_2, 6,000 metric tons of N_2O, and 3,000 metric tons of SO_2 per year.



a. The repeatability of the algal amino acid salt solution is still under investigation. The current calculation is based on single amino acid salt solution.

5. Mass and energy balance

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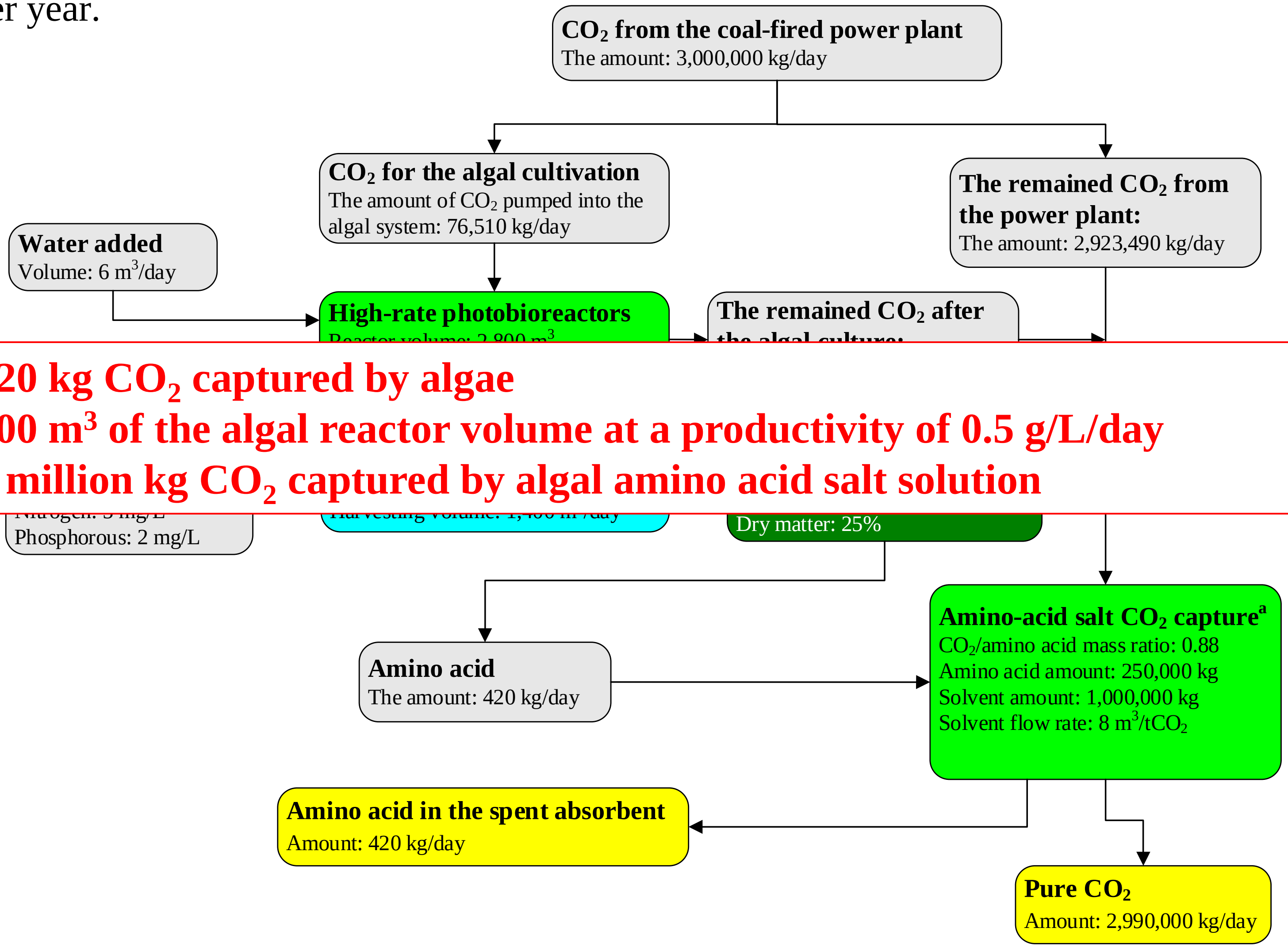

- **1,220 kg CO_2 captured by algae**
- **2,800 m^3 of the algal reactor volume at a productivity of 0.5 g/L/day**
- **2.9 million kg CO_2 captured by algal amino acid salt solution**

a. The repeatability of the algal amino acid salt solution is still under investigation. The current calculation is based on single amino acid salt solution.

5. Mass and energy balance

B. Preliminary energy balance analysis

- The energy balance analysis is based on the previous mass balance.
- The 150 megawatts coal-fired power plant generates14,416,457 GJ/year for both electricity and heat.
- The studied system consumes **19%** of the total energy generated from the power plant to near-completely capture CO_2 in the flue gas, compared to **35%** of MEA process.

System components	Energy value (GJ/year)		
	The studied system [b]	The amino acid salt process [c]	MEA process [d]
Chemical production			
Energy input	-2,184	-	-
Energy output	2,920	-	-
CO_2 capture			
Energy input	-2,759,055	-2,759,055	-5,040,044
Energy output	-	-	-
Total energy input	-2,761,389	-	-5,040,044
Total energy output	1,920	-	-
Net energy	**-2,759,469**	**-2,759,055**	**-5,040,044**

a. Data used in the calculation are from the pilot scale algal cultivation and previous lab-scale utilization experiments. The energy input is assigned as negative. The energy out is assigned as positive.
b. The studied system consists of algae photobioreactor cultivation, cascade biomass utilization, and CO_2 capture.
c. The single amino acid salt process only includes amino acid salt absorption.
d. The MEA process only includes MEA CO_2 capture.

Summary

- Long-term culture stability (~17 months and counting) of the selected algal strains was achieved using flue gas as the carbon source.
- A pH control strategy was achieved to enhance algal growth.
- Algal biomass productivity reaches **0.2-1.4 g/L/day** at a biomass concentration of **0.6-1.4 g/L** from the pilot operation.
- Algal amino acid salt solution shows better performance (**0.88 g CO_2/g algal amino acids**) on CO_2 capture than single amino acid solutions (**average 0.65 g CO_2/g amino acid**).
- The combined biological and chemical flue gas utilization leads to **a technically sound system** to efficiently capture CO_2 in the flue gas.

Next step

- A cascade algal biomass conversion process
  - CO_2 absorbent
  - polyurethane
  - Diesel
  - Methane

- Comprehensive techno-economic analysis and life cycle assessment

Acknowledgments

- NETL FE0030977

- Erickson Power Plant

Go Green !!