DOE Bioenergy Technologies Office (BETO) 2017 Project Peer Review

Integration of Nutrient and Water Recycling for Sustainable Algal Biorefineries

03/06/2017
ALGAE TECHNOLOGY AREA

Presenter: Sridhar Viamajala, The University of Toledo

Goal Statement

Achieve high biomass productivity and recovery at lower cost through:

- Microalgae cultivation in high pH and high alkalinity media.
- Develop methods for harvesting and media recovery (for reuse) AND without use of contaminating chemicals (e.g. flocculants).

Quad Chart Overview

Timeline

- Project start : 2/1/2013
- Project end : 8/31/17
- Percent complete: 90%

Barriers

- Barriers addressed
  - Al-B. Algal Fuel Production
  - Feedstock development and nutrient supply
  - Harvest - Dewatering and water recycle

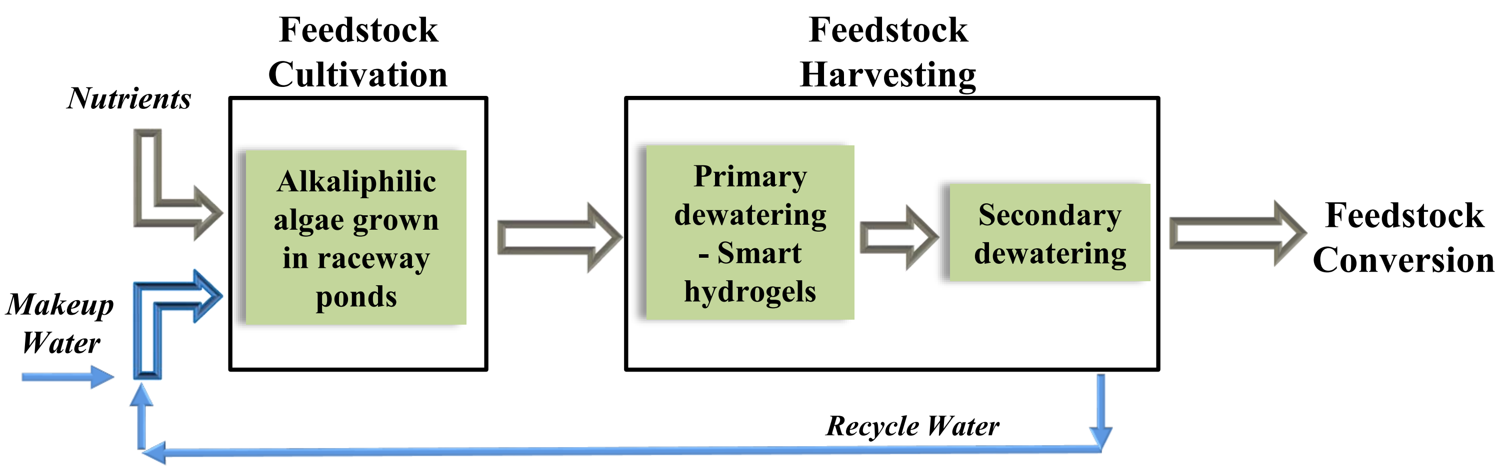
Budget

	Total Costs FY 12 –FY 14	FY 15 Costs	FY 16 Costs	Total Planned Funding (FY 17-Project End Date)
DOE Funded	868,860	861,717	837,776	431,581
Project Cost Share (Comp.)*	201,377	213,137	221,482	114,097

Partners

- The University of Toledo – Lead (37%)
- Montana State University (37%)
- University of North Carolina (12%)
- University of Minnesota (6%)
- Clearas Water Recovery, Inc. (8%)

Project Overview



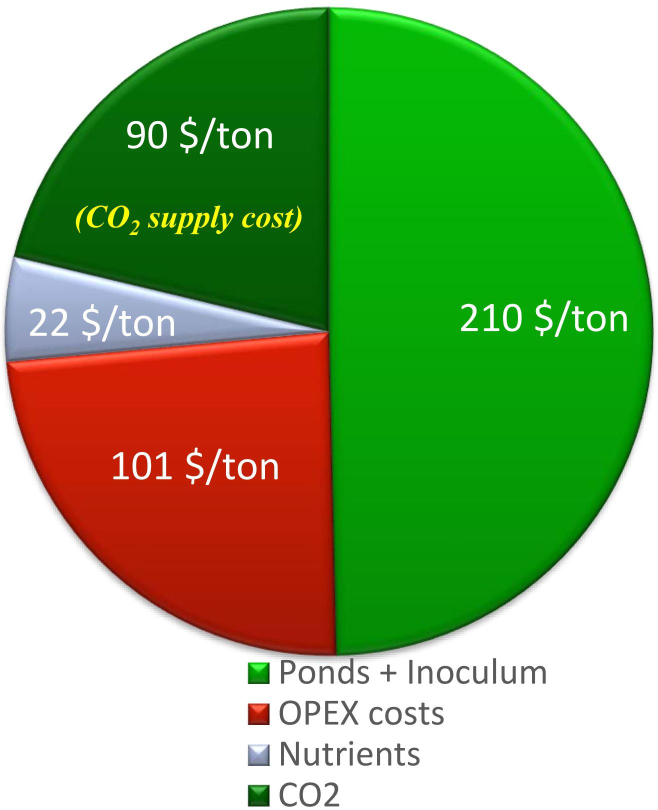
PROJECT OBJECTIVES:

- Decrease cost of cultivation through reduction in CO_2 supply cost and improvements in productivity.
- Develop low-cost water-recovery/harvesting methods.
- Characterize the development, structure, and stability of microbial communities in alkaline algal systems[†].
- Perform economic and life cycle assessments (LCA) for sustainable algal biorefineries[‡].

[†]Fields, M.W., et al. (2014) Applied Microbiology and Biotechnology. 98: 4805-4816
[†]Bell T.A.S., et al. (2016) Frontiers in Microbiology. 6:1480.
[‡]Hise, A.M., et al., (2016) Bioresource Technology. 220:. 271-281.
[‡]Kern, J.D., et al., (2017) Bioresource Technology. 225: 418-428.

Technical Approach - Challenges

- <u>Challenge 1</u>: High cost of CO_2 supply

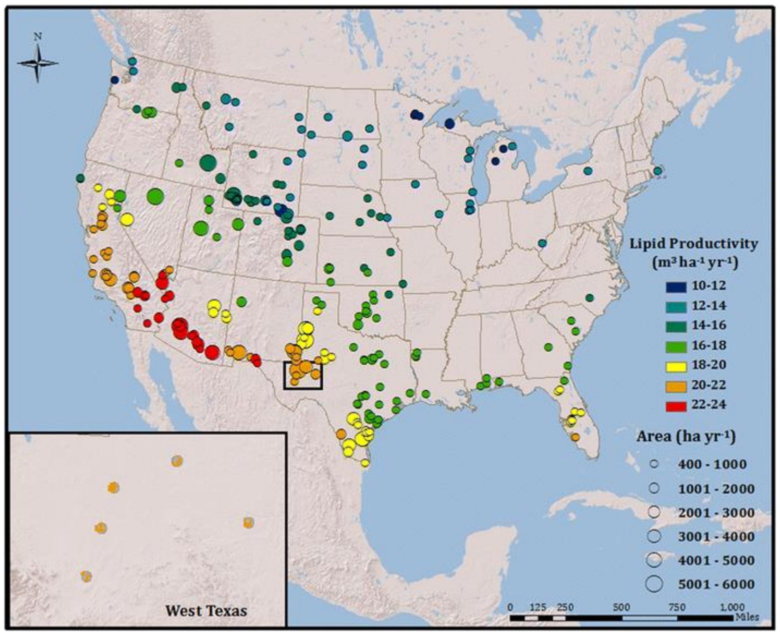


- Total algal biomass selling price
  ≈ **$420/ton-biomass** (excluding harvesting costs)
- Cost for CO_2 supply
  = **$90/ton-biomass**
  >20% of total biomass cost
  ~50% of variable operating costs

Davis, R., et al. (2016). Process Design and Economics for the Production of Algal Biomass. *Technical Report NREL/TP-5100-64772*
Huntley, M.E., et al. (2015) Demonstrated large-scale production of marine microalgae for fuels and feed. *Algal Research*, **10**: 249-265.

Technical Approach - Challenges

- <u>Challenge 2</u>: Simultaneous availability of land and CO_2 resources



- Constraints
  - Land – *barren, slope <2%*

    AND

  - CO_2 transport distance – *<4.8 km* (for economically viable CO_2 transport)
- Max. biofuel production

  = 44 million barrels per year
- EISA mandate for non-cellulosic advanced biofuel

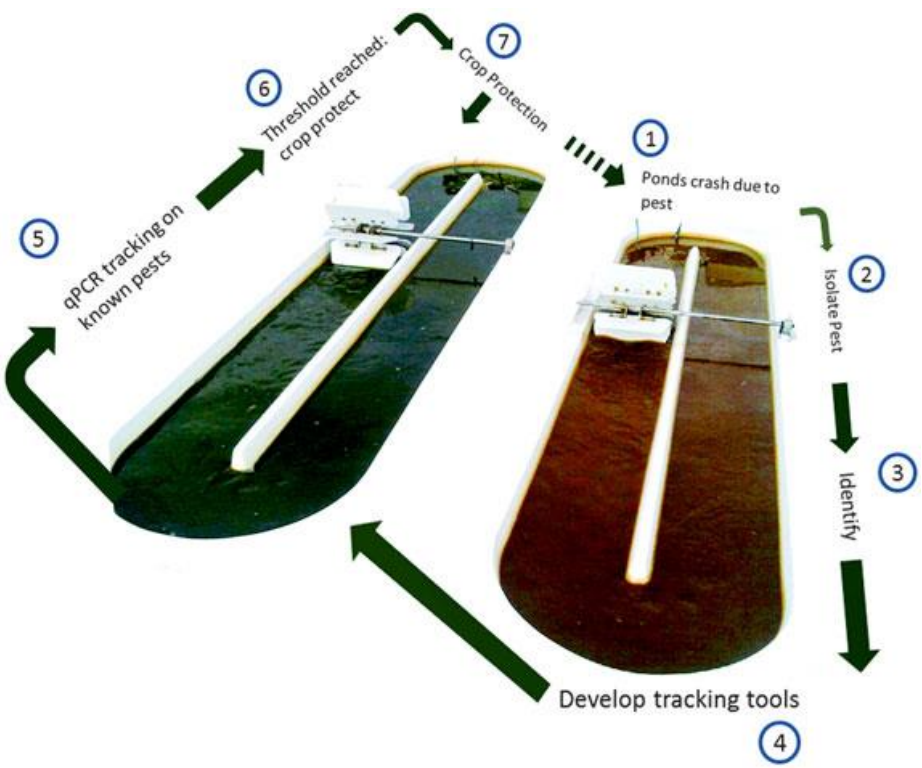
  = 100 million barrels per year

If constrained by CO_2 availability, microalgae biofuels will likely be limited to <50% of the EISA “advanced biofuel” mandate

Quinn, J. C., et al. (2012). Geographical assessment of microalgae biofuels potential incorporating resource availability. *BioEnergy Res.* ***6****: 591-600*
Bracmort, K. 2014. Congressional Research Service Report 7-5700. https://www.fas.org/sgp/crs/misc/R42122.pdf.

Technical Approach - Challenges

- <u>Challenge 3</u>: Frequent culture crashes



- Bacteria, viruses, zooplankton, invasive algae
- Productivity loss and/or "predator management costs"

McBride R.C. et al. (2014). Contamination management in low cost open algae ponds for biofuels production. *Ind. Biotechnol. 10: 221 -227*

“Possible solution – Cultivation of microalgae at *high alkalinity*”

- Advantage 1: Alkaline solutions scavenge CO_2 from the atmosphere at rapid rates.
  - Costs and geographical constraints associated with CO_2 supply can be mitigated (or eliminated)
- Advantage 2: Harsh pH conditions (pH>10) can mitigate detrimental contamination and predator populations
    - *e.g.* Daphnia (zooplankton) egg and neonate viability is low
  - Allows sustained maintenance of desired culture
    - *e.g.* Commercial *Spirulina* production is successfully carried out in high pH media

Pendyala, B., et al., (2016) High yield algal biomass production without concentrated CO_2 supply. *US/62/328,296 filed 04-27-16*.
Vijverberg, J. et al. (1996). Decrease in Daphnia egg viability at elevated pH. *Limnology and Oceanography, 41:789-794* .

Approach – Critical success factors

- Biomass productivity of $20 g/m^2/d$ or higher
- "Crash free" cultivation for extended periods (>3 months)
- Biomass composition favorable for biofuel production
  - High carbohydrate and/or lipid content
  - Low protein and ash content
- Low residence time (<3h) and high output concentrations (>20 g/L) for the hydrogel harvesting process
- Demonstrated reusability of media after harvesting

CO_2 transfer from the atmosphere into alkaline media

J_{CO_2} = CO_2 transfer flux (mol/m^2/h)

$CO^*_{2(aq)}$ = Dissolved CO_2 in equilibrium with the atmosphere; calculated from Henry's constant.

$CO^{bulk}_{2(aq)}$ = Aqueous CO_2 concentration; determined by the equilibrium established with HCO_3^-, OH^- and CO_3^{2-} ions in the medium (Eqs. 1 and 2) $CO^{bulk}_{2(aq)} = \frac{K_2}{K_1} \times \frac{[HCO_3^-]^2}{[CO_3^{2-}]}$

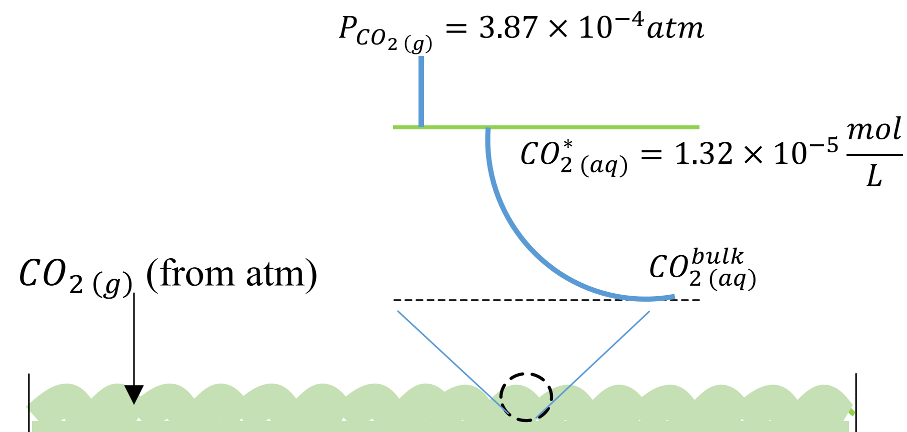
k_L = Mass transfer coefficient; governed by mixing rates and pond depth

= 0.1m/h for 20cm ponds mixed at 30cm/s

E = Enhancement factor for mass transfer due to chemical reaction;

$$= 1 + \frac{\mathcal{D}_{OH^-} \cdot \mathcal{D}_{HCO_3^-} \cdot K_1 \cdot [OH^-]}{\mathcal{D}_{CO_2}(K_1 \cdot [CO^*_{2\,(aq)}] \cdot \mathcal{D}_{HCO_3^-} + \mathcal{D}_{OH^-})}$$

where, the subscripted $\mathcal{D}$'s represent diffusion coefficients of the various dissolved species



Mass transfer flux:

$$\boldsymbol{J_{CO_2} = k_L \cdot E \cdot ([CO^*_{2\,(aq)}] - [CO^{bulk}_{2\,(aq)}])}$$

Bulk reactions:

$$CO_{2,\,bulk\,(aq)} + OH^- \rightleftharpoons HCO_3^-,\ K_{eq} = 4.5 \times 10^7 \frac{L}{mol}$$

$$HCO_3^- + OH^- \rightleftharpoons CO_3^{2-} + H_2O,\ K_{eq} = 4.9 \times 10^3 \frac{L}{mol}$$

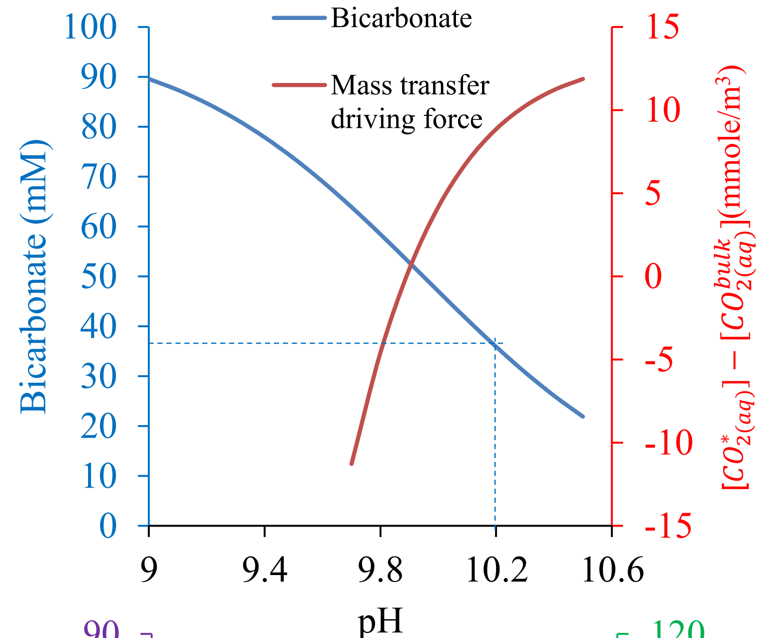
$$H_2O \rightleftharpoons OH^- + H^+,\ K_{eq} = 1 \times 10^{-14} \frac{mol^2}{L^2}$$

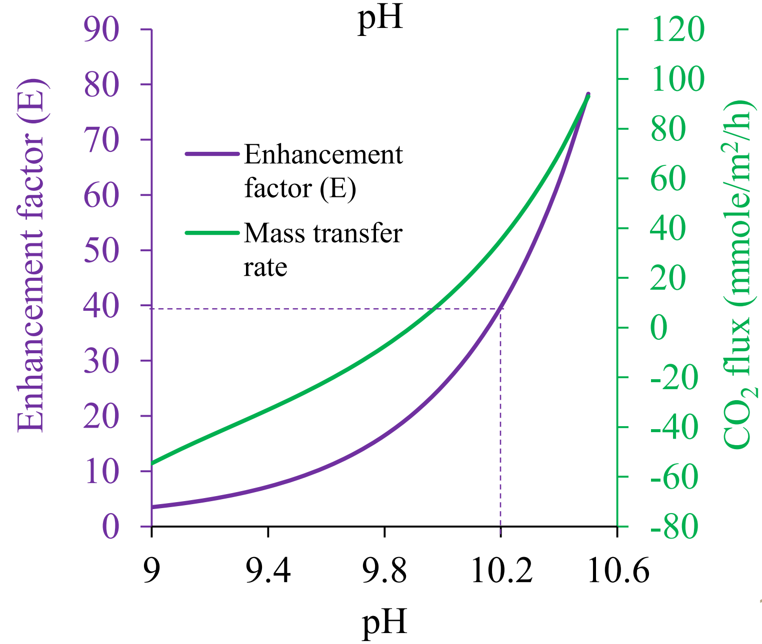
Danckwerts, P.V., *Gas-liquid reactions*. 1970: McGraw-Hill Book Co.
Cents, A. H. G., et al. (2005). Absorption in carbonate/bicarbonate solutions: The Danckwerts-criterion revisited. *Chem. Eng. Sci. 60: 5830-5835.*
Weissman, J.C., et al. (1988). Photobioreactor design: Mixing, carbon utilization, and oxygen accumulation. *Biotech. Bioeng.* 31: 336-344.

CO_2 transfer from the atmosphere into alkaline media

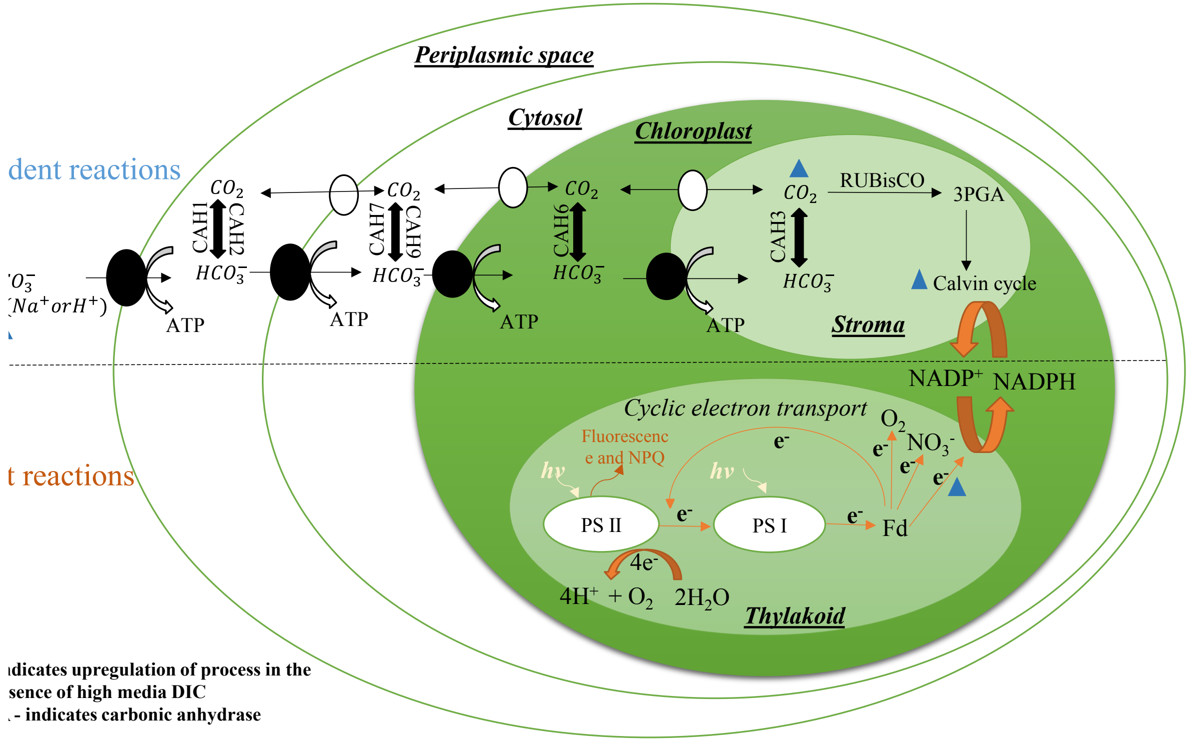
To maintain high atmospheric CO_2 flux and allow growth without concentrated CO_2 input,

- Maximize mass transfer driving force ($[CO^*_{2\,(aq)}] - [CO^{bulk}_{2\,(aq)}]$)
- Maximize enhancement factor (E) by maintaining high pH; E~40 at pH 10.2
- High media alkalinity to maintain high HCO_3^- concentrations in the medium for photosynthesis to occur without inorganic carbon limitations





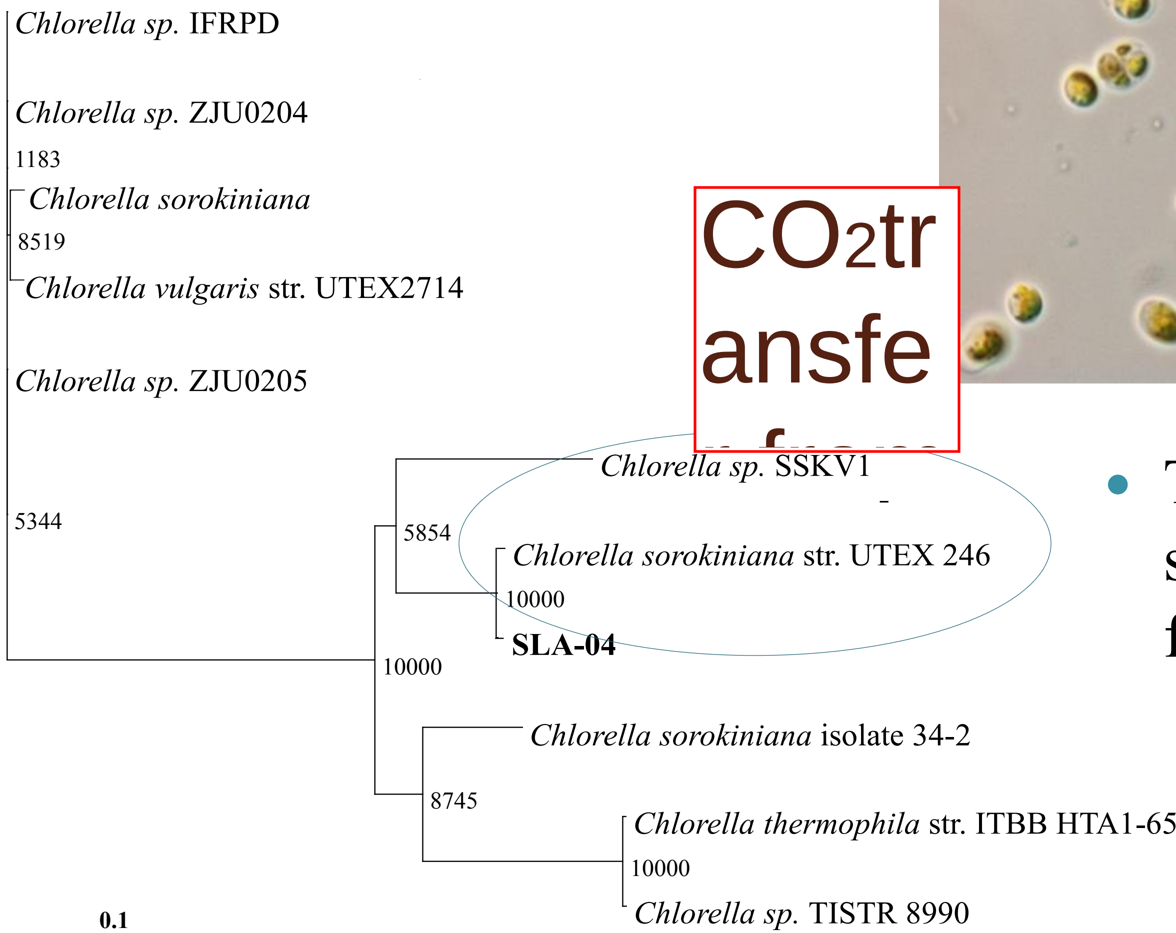
Cellular DIC transport and fixation in alkaline media



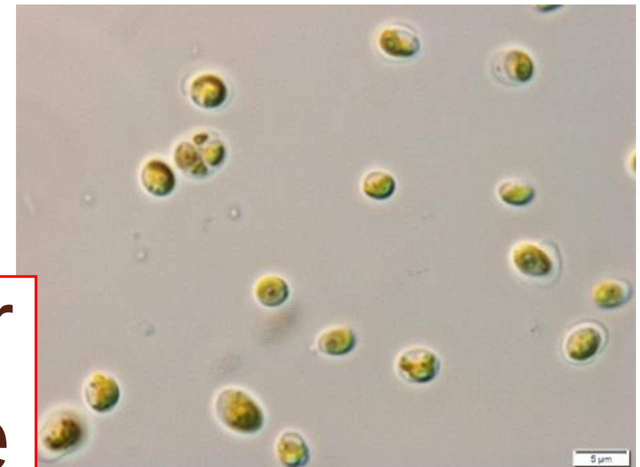
- Under alkaline conditions, DIC uptake occurs via CCMs
- High media DIC increases rate of cellular DIC transport
- Simultaneously, the high cellular DIC flux is also expected to drive the light dependent reactions towards higher production of NADPH for use in carbon fixation.

Moroney, J. V.; Ynalvez, R. A. (2007) Proposed CO_2 concentrating mechanism in Chlamydomonas reinhardtii. *Eukaryotic Cell.* 6: 1251-1259.

Results – Isolation and strain identification



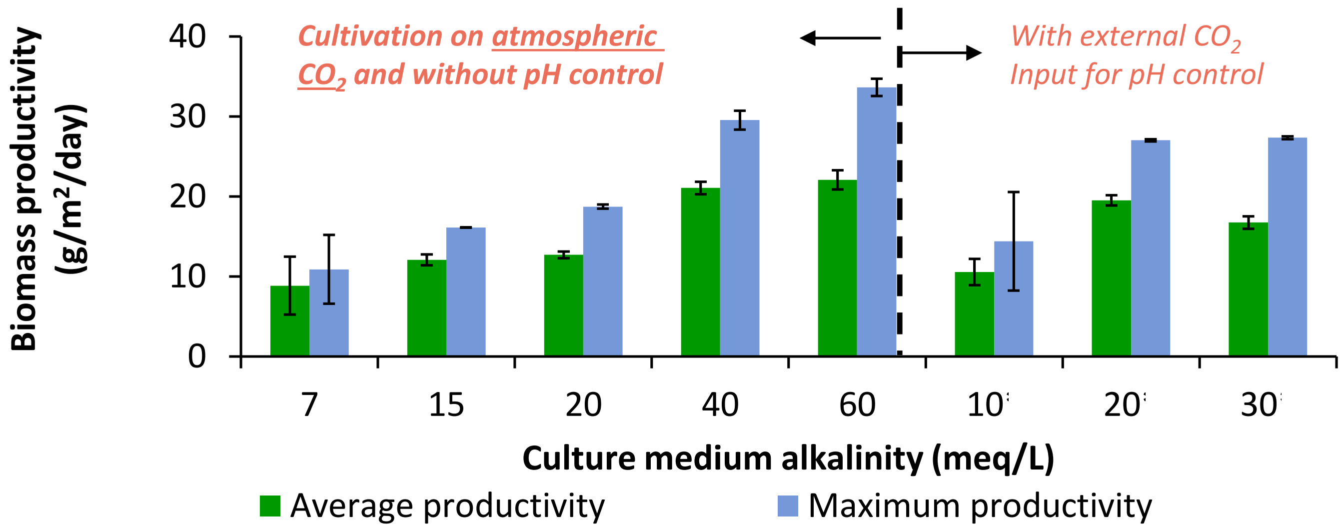
CO_2tr
ansfe



- The alkaliphilic strain was isolated from Soap Lake, WA.

Vadlamani, A. 2016. “Enhanced biomass and lipid productivities of outdoor alkaliphilic microalgae cultures through increased media alkalinity” PhD Thesis. The University of Toledo.

Results – Cultivation in high pH and high alkalinity media



- Experiments were performed in 30L outdoor raceway ponds.
- Without concentrated CO_2 inputs in high alkalinity media (40-60 meq/L),
  - Average areal productivities were **22 $g/m^2/d$**
  - Maximum productivity of **32 $g/m^2/d$** was measured.
- Average productivities of cultures grown without concentrated CO_2 inputs were similar to productivities of cultures grown with concentrated CO_2 input (pH maintained at 8.5).

Vadlamani, A. 2016. "Enhanced biomass and lipid productivities of outdoor alkaliphilic microalgae cultures through increased media alkalinity" PhD Thesis. The University of Toledo.

Results – Cultivation in high pH and high alkalinity media

Energy flow	Description	Notation	High Alk. (60meq/L)	Low Alk. (7meq/L)
Towards carbon fixation	Effective PS II quantum yield *(photons utilized per incident photons)*	Y(II)	0.409	0.252
	Photosynthetic efficiency *(electrons per photon)*	α	0.217	0.13
	Maximum electron transfer rate *($\mu mole/m^2/s$)*	ETR_{max}	33.2	13.8
Dissipation	Quantum yield of regulated dissipation *(photons dissipated per incident photon)*	Y(NPQ)	0.047	0.085
	Quantum yield of unregulated dissipation *(photons dissipated per incident photon)*	Y(NO)	0.544	0.663

- Cultures growing at pH>10 and in the presence of high media DIC show high ETR_{max}, Y(II), and α values.
  - Better utilization of incident light for photosynthetic carbon fixation
- Cultures growing in low DIC media (pH>10) show high dissipation of electrons (cyclic electron transport)
  - Electron generation is inhibited due to low availability of cellular DIC.

Vadlamani, A. 2016. "Enhanced biomass and lipid productivities of outdoor alkaliphilic microalgae cultures through increased media alkalinity" PhD Thesis. The University of Toledo.

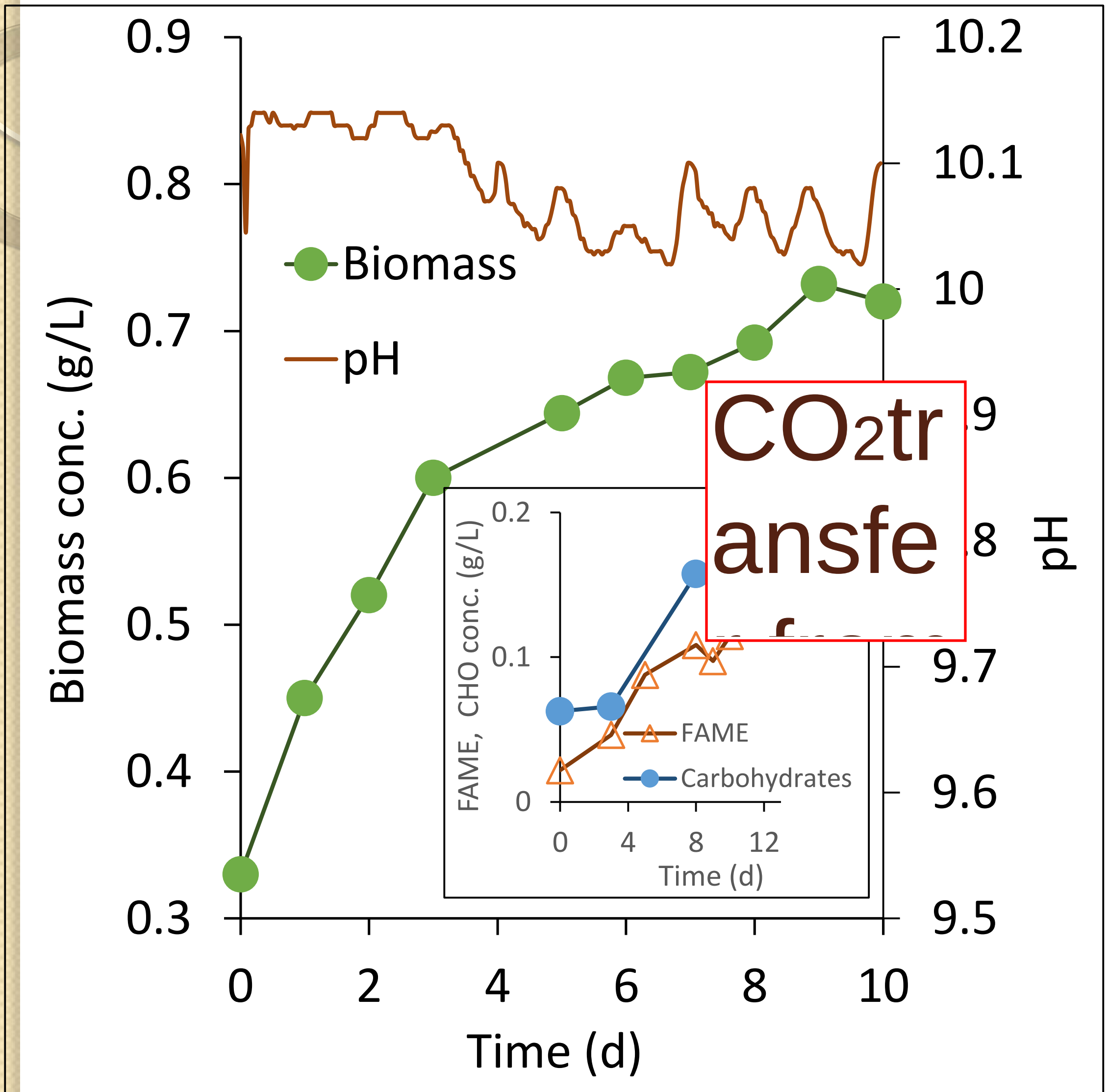
Results – Correlation of theoretical mass transfer prediction with experimental measurements

- CO_2 transfer rates were experimentally determined in alkaline cultures and abiotic controls.
- Measurements of DIC increase were made at night by assessing changes in carbonate alkalinity
- k_L values were estimated from previous experimental measurements corrected using scaling factors (for linear velocity and pond depth) recommended by Weissman et al.
- E was estimated from measured pH.

Experiment	Predicted			Experimental
	k_L ($m \cdot h^{-1}$)	$k_L \cdot E$ ($m \cdot h^{-1}$)	Mass transfer flux ($g\text{-}C \cdot m^{-2} \cdot d^{-1}$)	Mass transfer flux ($g\text{-}C \cdot m^{-2} \cdot d^{-1}$)
Trial 1	0.04	1.51	5.25	6.18 ± 0.61
Trial 2	0.09	2.48	7.80	8.63 ± 0.85
Trial 3	0.13	4.70	7.46	8.25 ± 0.81
Abiotic Control	0.05	2.55	8.4	7.7 ± 0.2

Weissman, J.C., et al. (1988). Photobioreactor design: Mixing, carbon utilization, and oxygen accumulation. *Biotech. Bioeng.* 31: 336-344.

Results – Outdoor cultivation at 750L

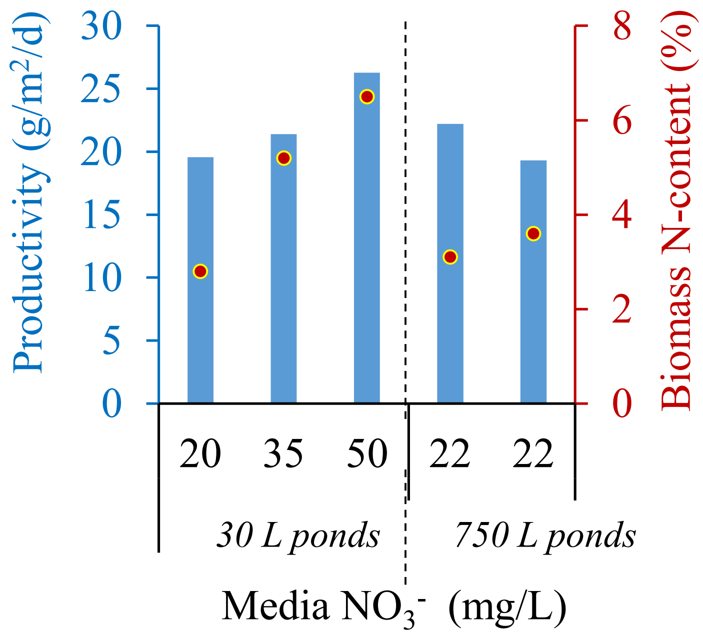


<u>Phototrophic cultivation</u>

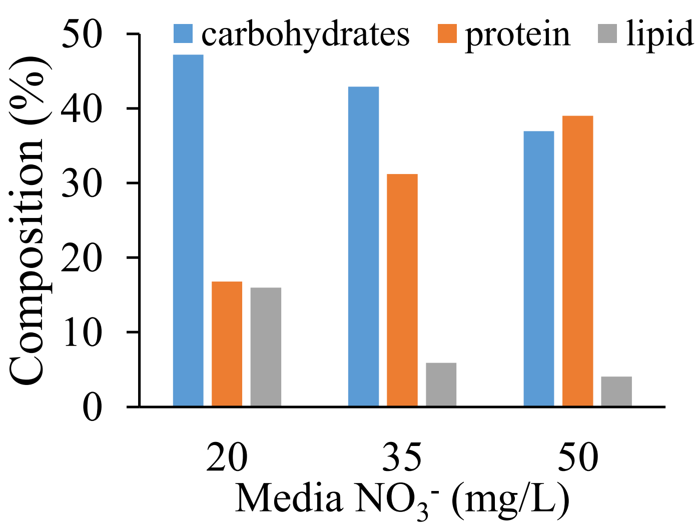
- Biomass productivity
  = 23 g/m^2/day
- Lipid productivity
  = 2 g/m^2/day
- Carbohydrate productivity
  = 1.8 g/m^2/day

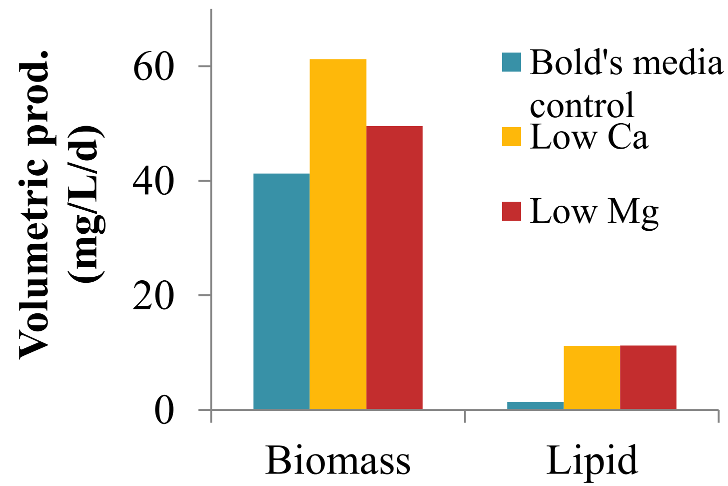
Vadlamani, A. 2016. “Enhanced biomass and lipid productivities of outdoor alkaliphilic microalgae cultures through increased media alkalinity” PhD Thesis. The University of Toledo.

Results – Macro/micro nutrient utilization



- High biomass productivities were maintained with low N in the media
- The resulting biomass also has a low N-content and higher carbohydrate and lipid content
  - Low-N biomass is desirable for conversion processes such as hydrothermal liquefaction
- Biomass and lipid productivities are improved (up to 33%) in low-Ca (1.5 mg/L and low-Mg (0.5mg/L) media



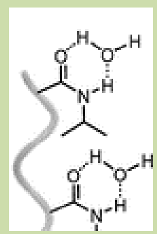
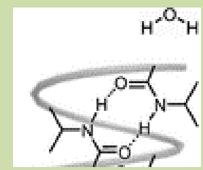
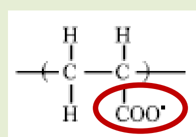
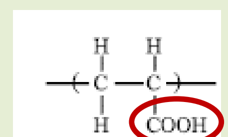


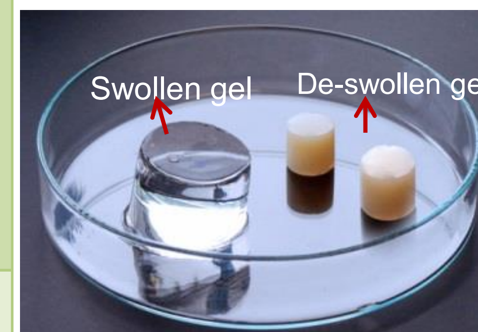
Summary of cultivation studies

- High media pH (>10) drives rapid transfer of CO_2 from the atmosphere to growth media
- High DIC concentrations "buffer" the media allow high media concentration of HCO_3^-
  - Improves "electron transfer rates" – Likely due to higher rate of delivery of CO_2 to RuBisCO
- Under high-pH AND high-alkalinity conditions, cultures achieve high productivity *even in the absence of* concentrated CO_2 inputs.
- In outdoor cultivation experiments over 2 years, we haven't observed a "culture crash"
- Biomass composition can be improved by "adjusting" nutrient composition without significantly compromising biomass productivity

Media recovery and harvesting through use of stimuli-sensitive hydrogels

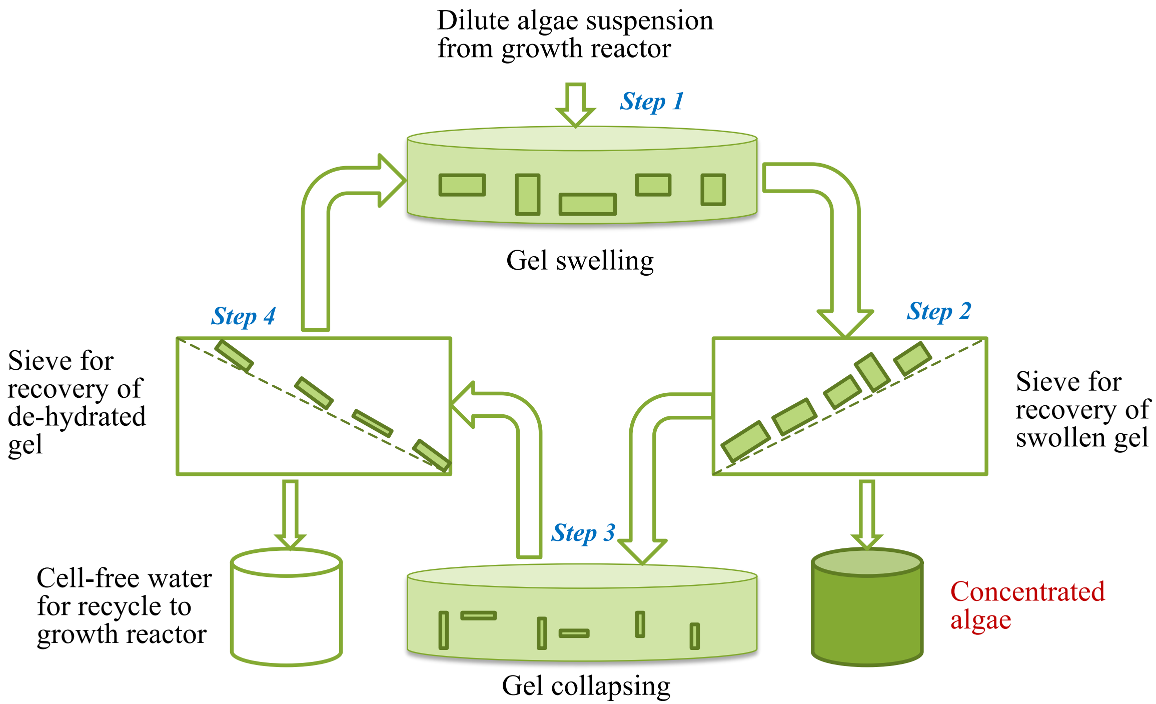
- Hydrogels that absorb and release water in response to an external stimulus

Stimulus type	Water absorption	Water release
Temperature	T <30˚C 	> 33˚C 
pH sensitive	high pH (>7) 	low pH (<5) 



- Examples –
  - N-isopropyl acrylamide (pNIPAAm) is a temperature-sensitive hydrogel
  - Poly acrylic acid (PAA) is a pH-sensitive hydrogel

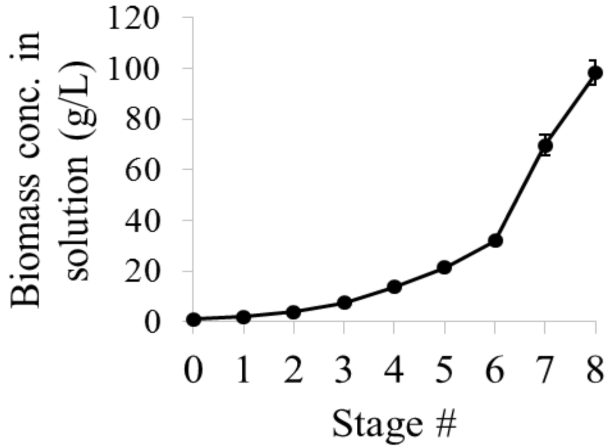
Hydrogel dewatering overview



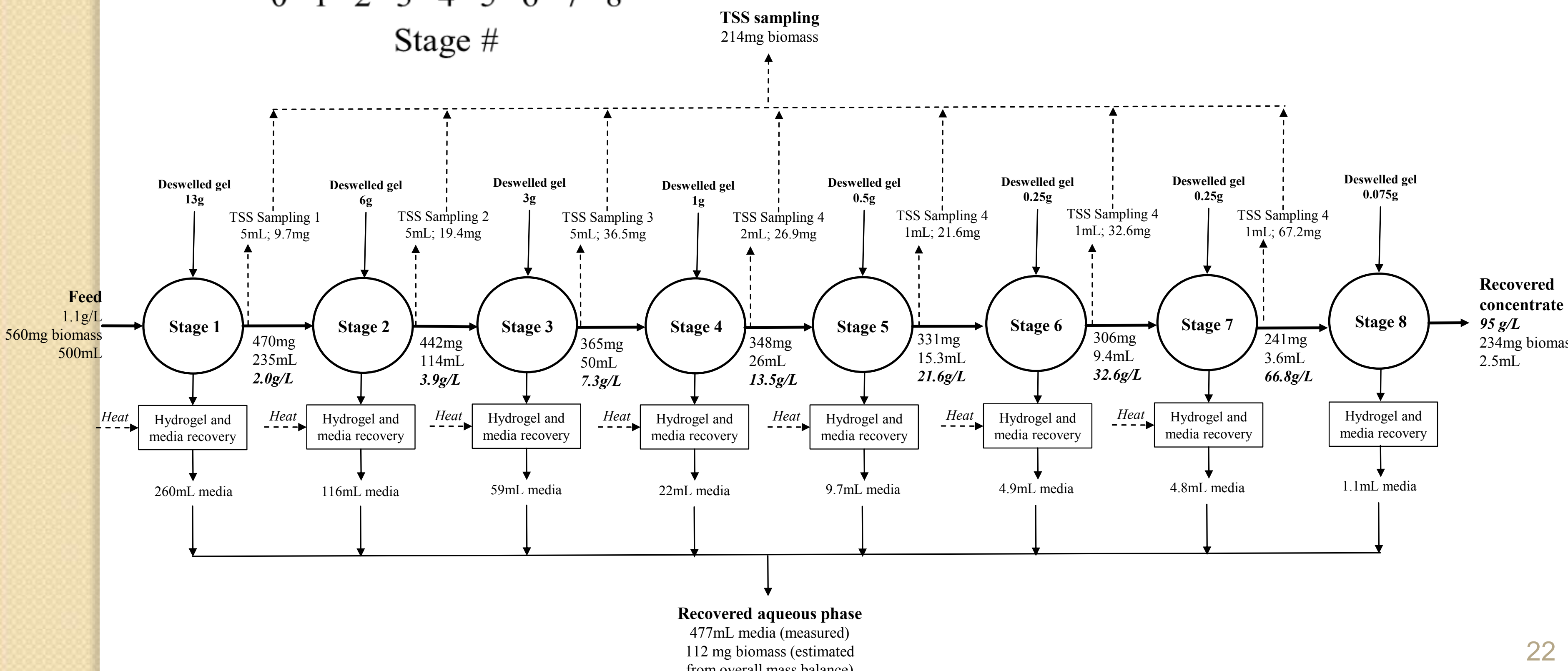
Key process parameters:

- Swelling and de-swelling rates in culture medium
- Water uptake per gram of de-hydrated gel (Swelling ratio)
- Operating conditions
  - Swelling and de-swelling period
  - Culture-swollen gel volume ratio

Stage-wise concentration of microalgae cultures using PNIPAAm hydrogels

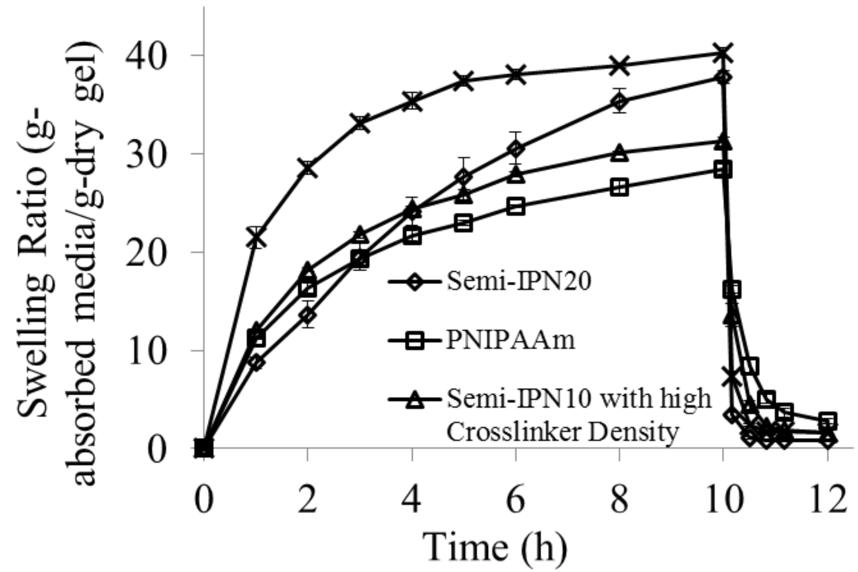


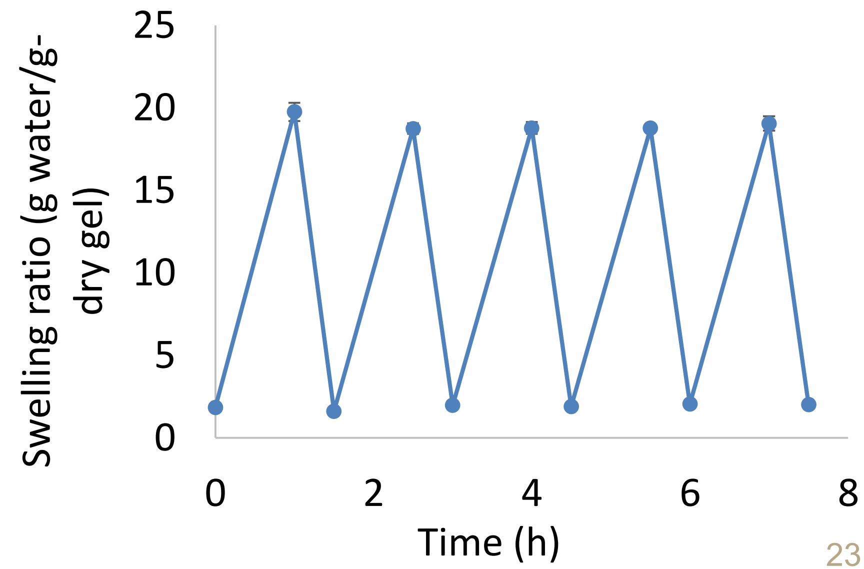
- Concentration was increased from 1g/L to 100 g/L <u>BUT</u> 2h duration per stage (lengthy process time)
  - Slow swelling of PNIPAAm
  - Several stages due to the low mass of absorbent gels used in each stage



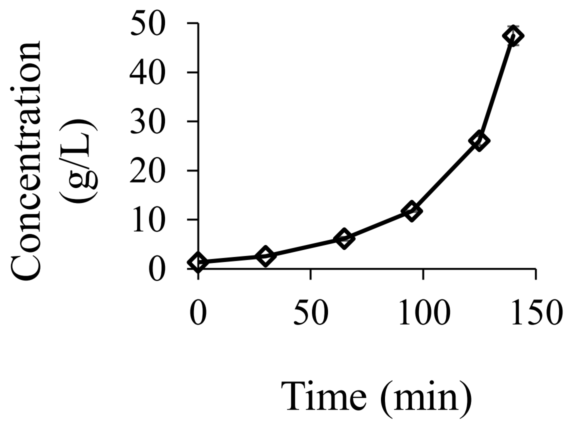
Improvements in performance of temperature-sensitive gels

- Semi-IPN 10 gels (10% PVA + 90% p-NIPAAm) showed more rapid swelling and deswelling
- Gels retain performance over multiple cycles
- Semi-IPN gels have greater mechanical strength

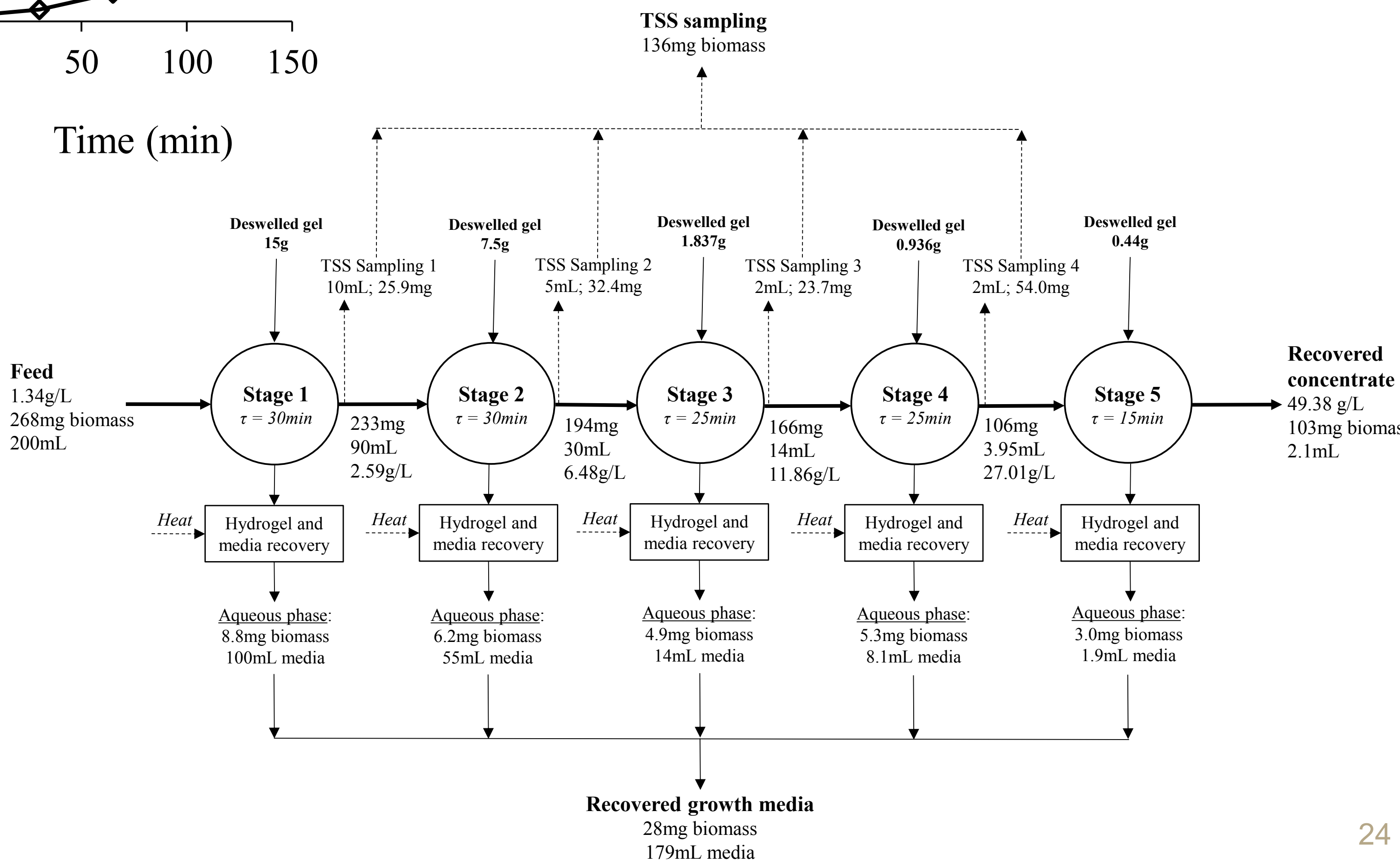




Stage-wise concentration of microalgae cultures using semi-IPN10 hydrogels



- Total process time reduced to ~2.5h.
- Final culture concentration = 50g/L



Conclusions for hydrogel-based harvesting

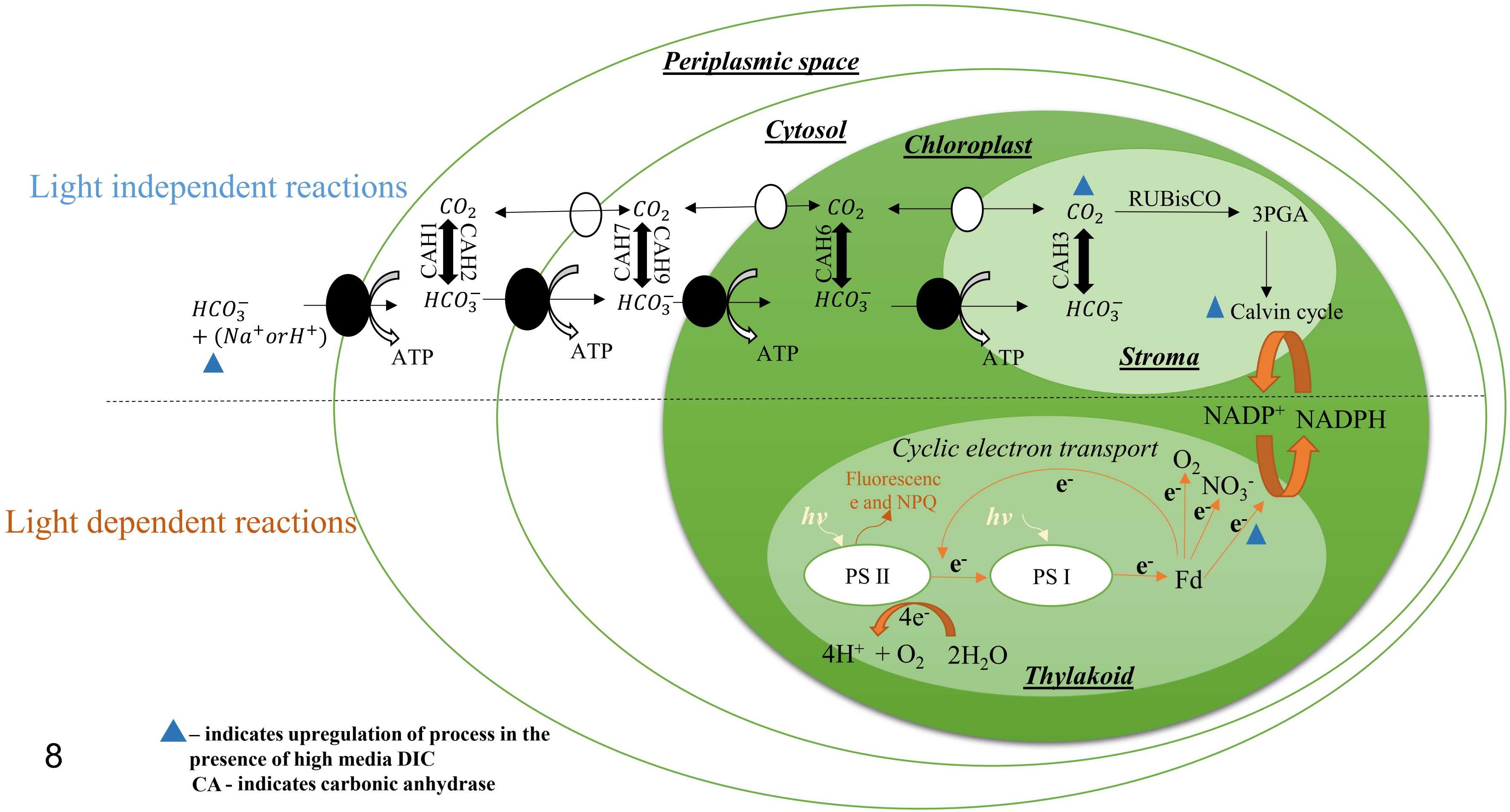
- With the hydrogel dewatering method, concentrations of up to ~100 g/L can be achieved.
- Gels can be re-used over multiple cycles without loss of gel functionality
  - High mechanical strength and elasticity
- Overall processing time could be <3h – comparable with residence times of other conventional processes
- The energy costs associated with the hydrogel-dewatering could be minimized by integration with low-grade waste heat

Additional Slides

(Not a template slide – for information purposes only)

- *The following slides are to be included in your submission for Peer Evaluation purposes, but* <u>*will **not** be part of your oral presentation*</u> *–*
- *You may refer to them during the Q&A period if they are helpful to you in explaining certain points.*

Cellular DIC transport and fixation mechanisms in alkaline media



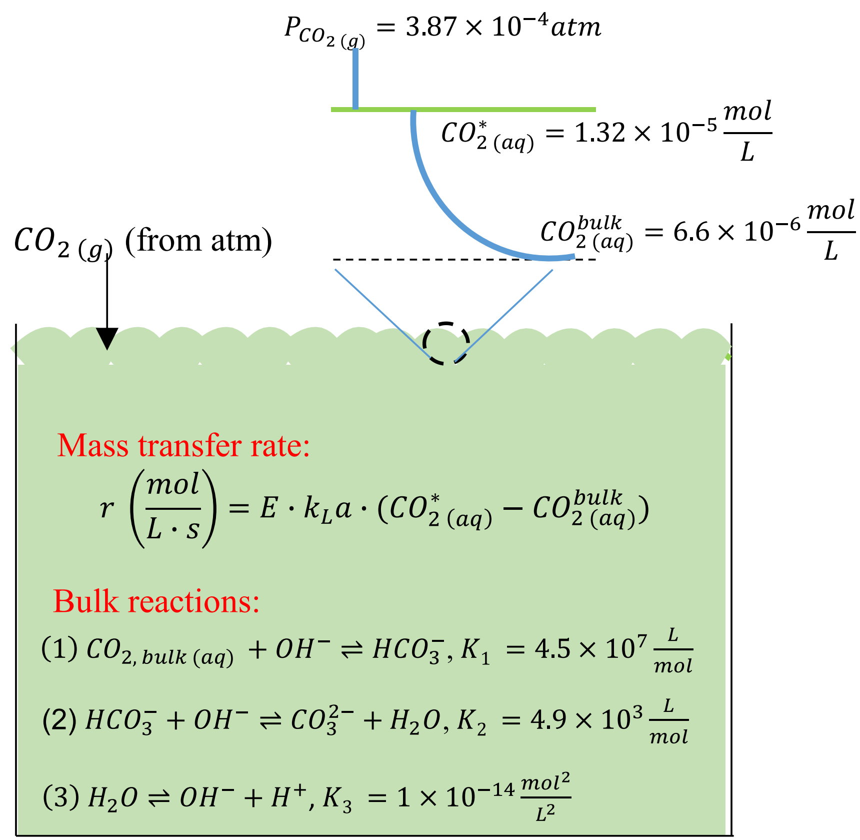
– indicates upregulation of process in the presence of high media DIC
CA - indicates carbonic anhydrase

CO_2 transfer from the atmosphere into alkaline media

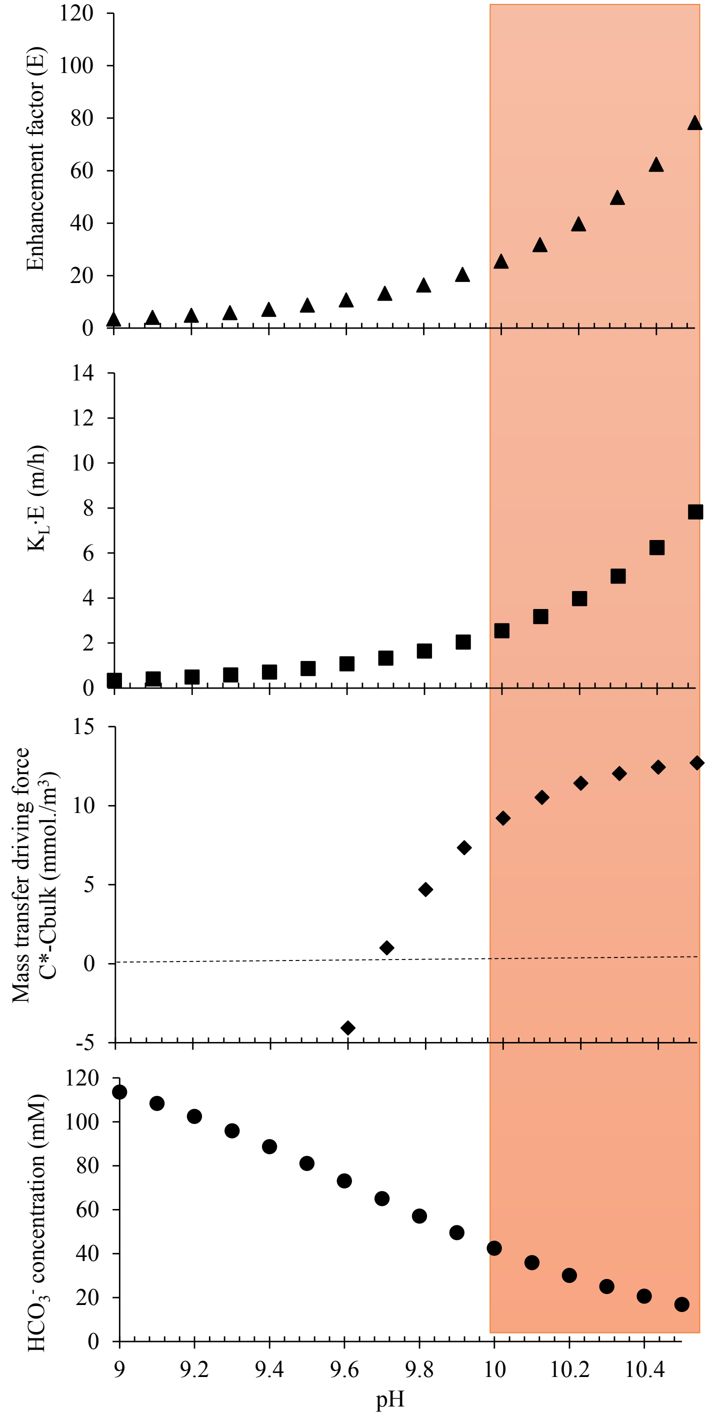
- During microalgae growth, HCO_3^- is taken up and CO_2 is fixed resulting in a net release of OH^-

$$HCO_3^- \xrightarrow{microalgae} CO_{2,\,cellular} + OH^-$$

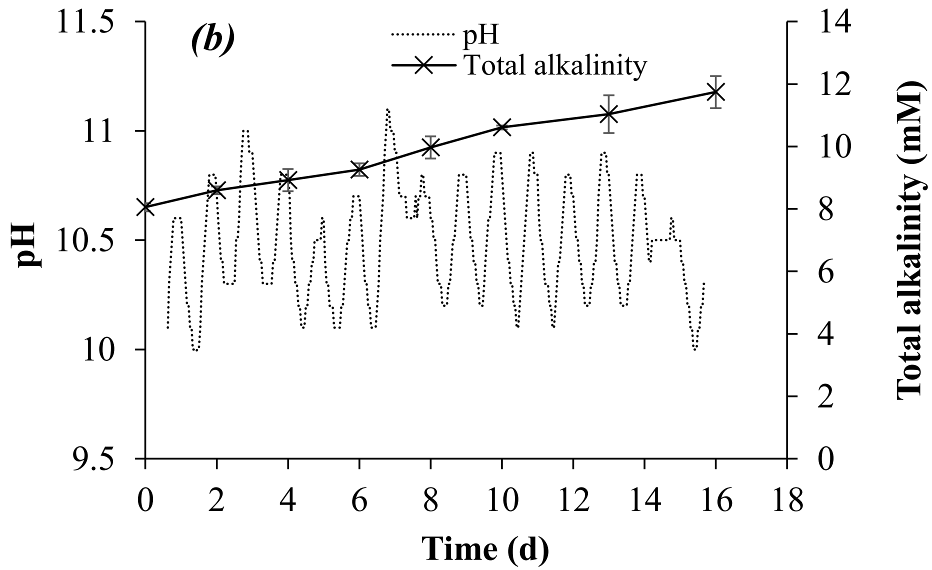
- Shifts the inorganic carbon equilibrium towards CO_3^{2-} (Eq. 2); <u>microalgae are unable to uptake or utilize CO_3^{2-}</u>
- Depletion of HCO_3^- can be mitigated by
  - Maintaining high alkalinity in media (i.e. high buffer concentration) and
  - Replenishment from the atmosphere,



$$E = 1 + \frac{D_{OH^-} \cdot D_{HCO_3^-} \cdot K_1 \cdot [OH^-]}{D_{CO_2} \cdot (K_1 \cdot CO^*_{2\,(aq)} \cdot D_{HCO_3^-} + D_{OH^-})}$$



Enhancement factor (E)
0
20
40
60
80
100
120
$K_L \cdot E$ (m/h)
0
2
4
6
8
10
12
14
Mass transfer driving force
C*-Cbulk (mmol./m³)
-5
0
5
10
15
HCO_3^- concentration (mM)
0
20
40
60
80
100
120
9
9.2
9.4
9.6
9.8
10
10.2
10.4
pH



(b)
pH
Total alkalinity
11.5
11
10.5
10
9.5
14
12
10
8
6
4
2
0
0
2
4
6
8
10
12
14
16
18
pH
Total alkalinity (mM)
Time (d)

Detailed calculations for mass transfer rates of DIC (shown as ΔDIC).

		Time (d)	pH	Temperature (º C)	Ionic strenght (I)	pK_1	pK_2	TA (mM)	HCO_3^- (mM)	CO_3^{2-} (mM)	DIC (mM)	ΔDIC (mM)	ΔDIC ($mmol.\cdot m^{-2}\cdot d^{-1}$)[c]	ΔDIC ($g\text{-}C\cdot m^{-2}\cdot d^{-1}$)
Set 1[a]	Day 1	1.21	10.2	17.8	0.024	6.33	10.15	8.1	2.4	2.7	5.2	0.23	688.1	8.3
		1.25	10.1	17.3		6.33	10.15		2.9	2.5	5.4			
	Day 4	4.33	10.2	24.0		6.29	10.09		2.2	2.9	5.0	0.22	635.3	7.6
		4.38	10.1	23.8		6.29	10.09		2.6	2.7	5.3			
	Day 5	5.25	10.2	21.8		6.30	10.11		2.3	2.8	5.1	0.22	641.1	7.7
		5.29	10.1	21.7		6.30	10.11		2.7	2.6	5.3			
	Day 6	6.29	10.2	20.9		6.31	10.12		2.3	2.8	5.1	0.22	657.6	7.9
		6.33	10.1	20.6		6.31	10.12		2.7	2.6	5.3			
	Day 10	10.38	10.2	16.6		6.34	10.16		2.5	2.7	5.2	0.23	681.7	8.2
		10.42	10.1	16.3		6.34	10.16		2.9	2.5	5.4			
	Day 11	11.38	10.2	15.1		6.35	10.18		2.5	2.7	5.2	0.24	690.1	8.3
		11.42	10.1	14.8		6.35	10.18		3.0	2.5	5.5			
	Day 15	15.25	10.2	23.2		6.29	10.09		2.2	2.8	5.1	0.22	645.0	7.7
		15.29	10.1	22.9		6.30	10.10		2.6	2.6	5.3			
Set 2[b]	Day 1	0.99	10.2	17.8	0.020	6.33	10.16	4.5	1.4	1.5	2.9	0.14	548.3	6.6
		1.03	10.1	17.5		6.34	10.17		1.6	1.4	3.0			
	Day 2	1.97	10.2	18.9		6.33	10.15		1.3	1.5	2.8	0.14	617.0	7.4
		2.00	10.1	18.5		6.33	10.16		1.6	1.4	3.0			
	Day 3	2.95	10.2	19.7		6.32	10.14		1.3	1.5	2.8	0.14	618.3	7.4
		2.98	10.1	19.2		6.32	10.15		1.6	1.4	3.0			
	Day 4	3.97	10.2	19.2		6.32	10.15		1.3	1.5	2.8	0.14	615.5	7.4
		3.99	10.1	18.8		6.33	10.15		1.6	1.4	3.0			
	Day 5	4.77	10.2	20.2		6.32	10.14		1.3	1.5	2.8	0.14	547.4	6.6
		4.80	10.1	19.7		6.32	10.14		1.6	1.4	3.0			
	Day 6	5.77	10.2	20.2		6.32	10.14		1.3	1.5	2.8	0.14	492.7	5.9
		5.80	10.1	19.7		6.32	10.14		1.6	1.4	3.0			
	Day 7	6.72	10.2	20.8		6.31	10.13		1.3	1.5	2.8	0.14	558.4	6.7
		6.75	10.1	20.0		6.32	10.14		1.5	1.4	3.0			

[a] Data obtained from the experiments carried out during December 2013

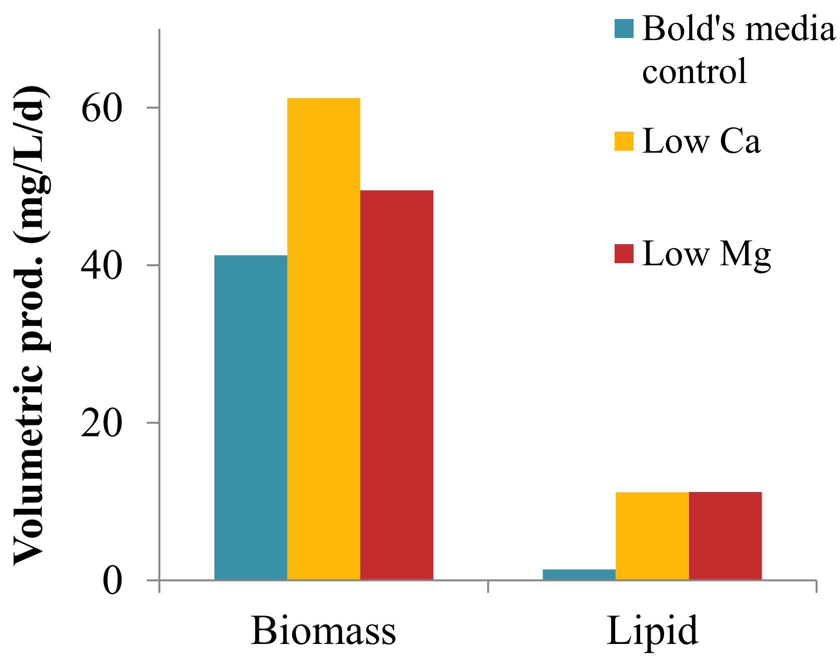
[b] Data obtained from the experiments carried out during September 2013

[c] Cultivations were carried out in small raceway ponds (surface area = 0.18 m^2) and the rate of increase in DIC was calculated using this surface area.

Mass transfer coefficients calculated using the mass transfer rates

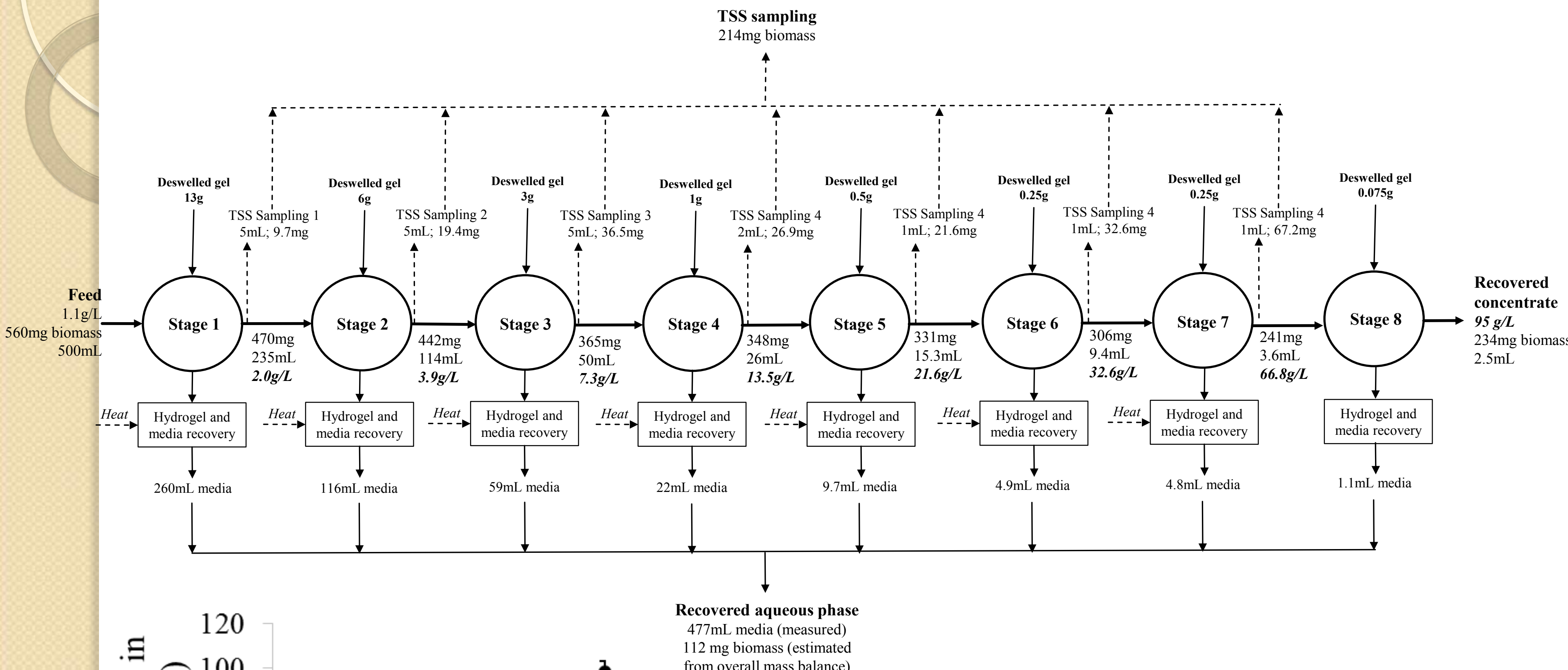
ΔDIC (mmol.·m^{-2}·d^{-1})	Mass transfer driving force			KL·E ($m·h^{-1}$)	K_L ($m·h^{-1}$)
	CO_2^{*} $_{(aq)}$ (mmol.·m^{-3})	CO_2^{bulk} $_{(aq)}$ (mmol.·m^{-3})	CO_2^{*} $_{(aq)}$ - CO_2^{bulk} $_{(aq)}$ (mmol.·m^{-3})		
688.1	13.2	0.23	12.97	2.21	0.06
635.3		0.18	13.02	2.03	0.05
641.1		0.20	13.00	2.05	0.05
657.6		0.21	12.99	2.11	0.05
681.7		0.24	12.96	2.19	0.06
690.1		0.26	12.94	2.22	0.06
645.0		0.19	13.01	2.07	0.05
548.3		0.20	13.00	1.76	0.04
617.0		0.19	13.01	1.98	0.05
618.3		0.19	13.01	1.98	0.05
615.5		0.19	13.01	1.97	0.05
547.4		0.19	13.01	1.75	0.04
492.7		0.19	13.01	1.58	0.04
558.4		0.18	13.02	1.79	0.04

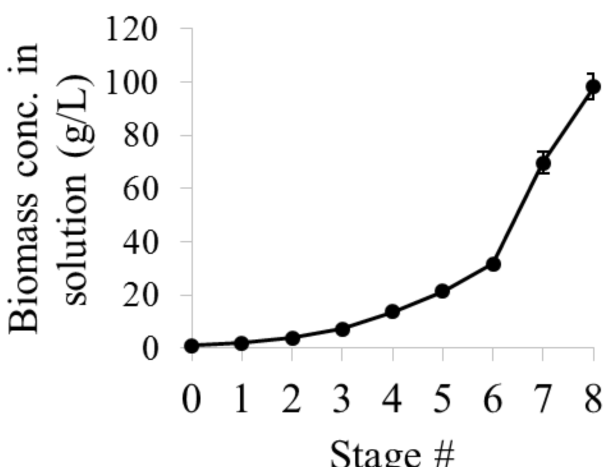
Results – Micro nutrient utilization



- Biomass and lipid productivities are improved (up to 33%) in low-Ca (1.5 mg/L and low-Mg (0.5mg/L) media
- Standard media have 10× higher Ca and Mg concentrations

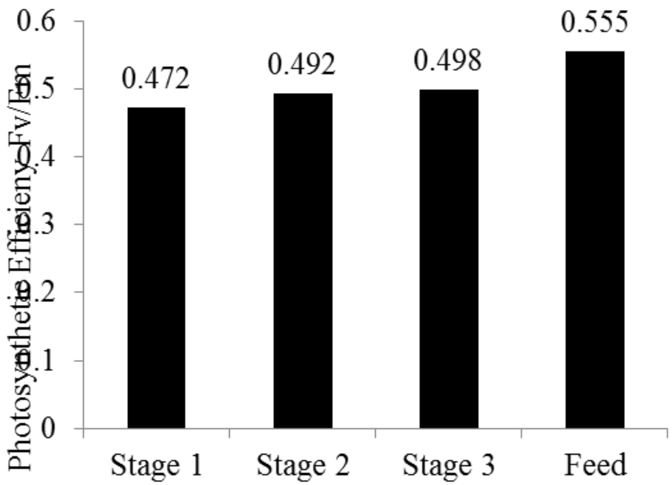
Stage-wise concentration of microalgae cultures using PNIPAAm hydrogels



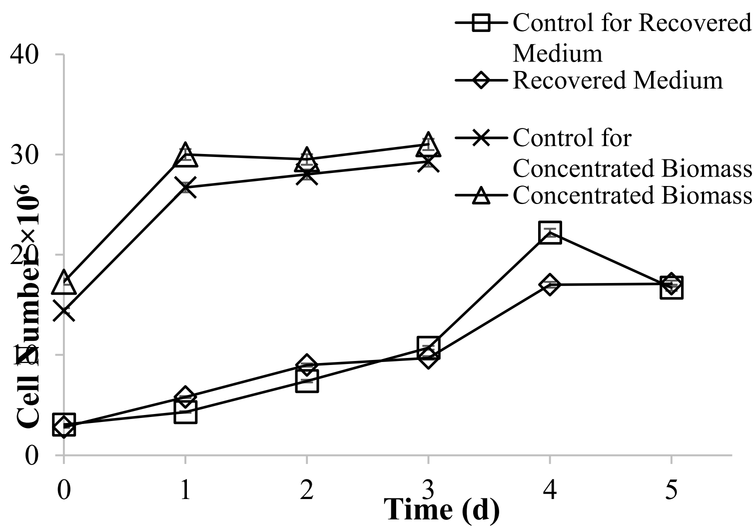


- Concentration was increased from 1g/L to 100 g/L <u>BUT</u> 2h duration per stage (lengthy process time)
  - Slow swelling of PNIPAAm
  - Several stages due to the low mass of absorbent gels used in each stage

Viability of harvested biomass and unrecovered cells

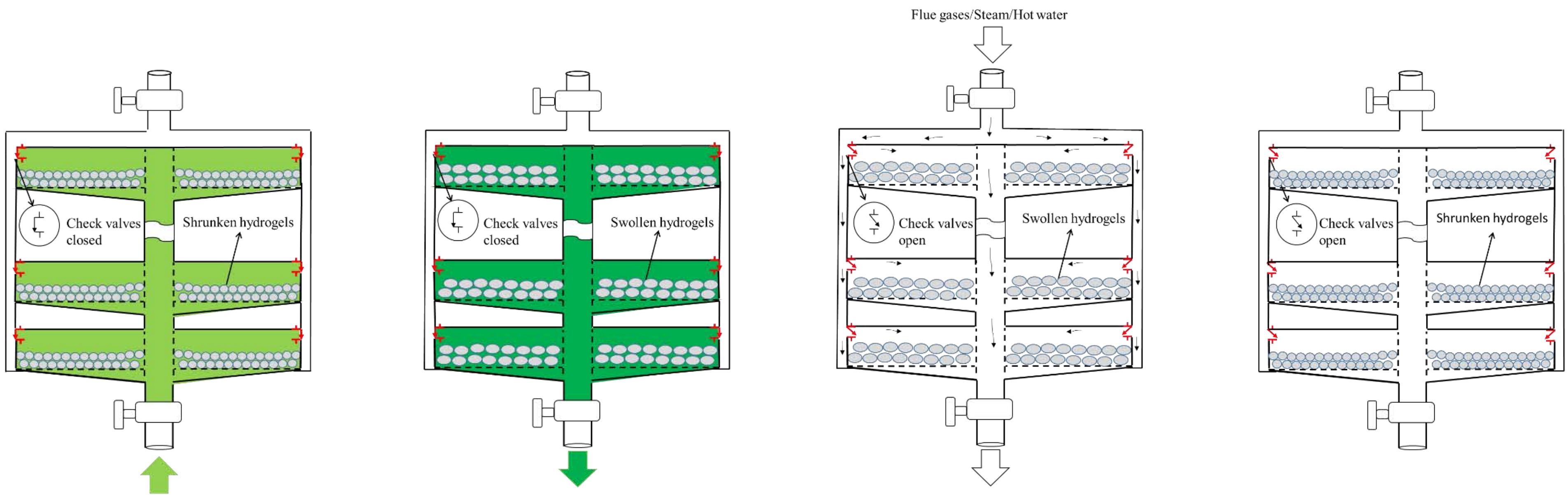


Photosynthetic efficiencies of feed and concentrated cultures



Growth of harvested biomass and unrecovered cells

Design of a harvesting device



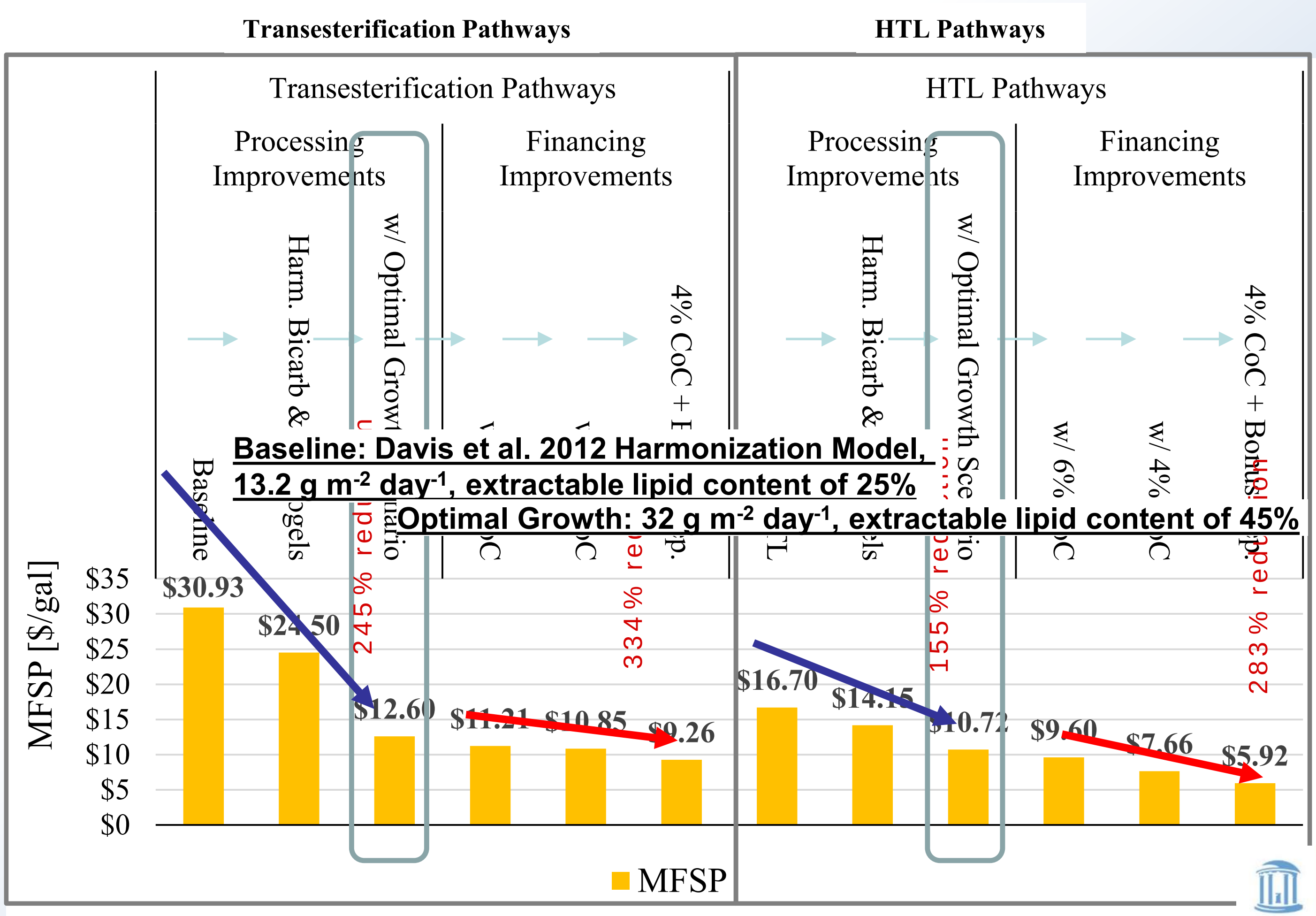
Step 1: Dilute algae solution introduced into inner chamber through the bottom valve. Check valves connected to jacket are kept closed to prevent leakage of algae slurry into jacket.

Step 2: Concentrated algae solution removed from inner chamber leaving behind swollen hydrogels containing absorbed growth media. Check valves connected to jacket remain closed.

Step 3: Heat or CO_2 is introduced into the jacket through the top valve. Check valves on the jacket are forced open allowing the heat/ CO_2 to enter into the inner chamber. These stimuli cause deswelling of the swollen hydrogels. The desorbed growth media is drained though the bottom valve.

Step 4: Hydrogels are fully shrunken and top valve is closed. Inner chamber has been fully drained and is ready for re-introduction of dilute algae feed.

Impact of Technical Improvements and Financing Incentives



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THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

Responses to Previous Reviewers' Comments

- Reviewers suggested that we focus on hydrogel harvesting task and we have improved the method significantly since the previous review
- Reviewers suggested we pivot towards scale-up of cultivation. Since the last peer review we have focused on outdoor cultivation and scale-up.

Note: This slide is for the use of the Peer Reviewers only – it is not to be presented as part of your oral presentation. These Additional Slides will be included in the copy of your presentation that will be made available to the Reviewers.

Publications and Presentations

Publications:

1. Lohman, E. J.; Gardner, R.D.; Halverson, L.; Macur, R.; Peyton, B.M.; Gerlach, R. An Efficient and Scalable Extraction and Quantification Method for Algal Derived Biofuel. *Journal of Microbiological Methods*. Accepted. June 04, 2013. MIMET-D-13-00177. DOI: 10.1016/j.mimet.2013.06.007
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- Lohman, E.J.; Gardner, R.D.; Halverson, L.; Peyton, B.M.; Gerlach, R. (2013): Lipid profiling of *Chlamydomonas reinhardtii* grown under three different inorganic carbon regimes. Platform Presentation. Montana Biofilm Meeting, Bozeman, MT, July 14-16, 2013
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Publications and Presentations

Presentations (cont.):

- Jackson, M.C.; Pedersen, T.; Berninghaus, A.; Gardner, R.; Gerlach, R. (2015). *Promoting Lipid Accumulation in Chlorella vulgaris UTEX395 Using Nitrogen Limitation and Bicarbonate Amendment*. 2015 Montana Biofilm Meeting. Bozeman, MT.
- Shirazi Y, Maddi B, Urban B, Viamajala S, Varanasi S. (2014). *Pyrolytic fractionation of biomass lipids: catalyst-free production of hydrocarbons and fatty acids*. 2014 Annual AIChE conference. Atlanta GA.
- Berninghaus, A., Peyton, B., Gerlach, R. (2015). *Renewable biogas production from algal biomass using anaerobic digestate cultures acquired from municipal wastewater with varying carbon substrates*. 2015 Student Research Celebration, Montana State University. Bozeman, MT.
- Berninghaus, A., Peyton, B., Gerlach, R. (2015). *Renewable biogas production from algal biomass using anaerobic digestate cultures acquired from municipal wastewater with varying carbon substrates*. 2015 Student Research Celebration, Montana State University.. Bozeman, MT.
- Davis, K.J.; Hodgskiss, L. ; Schweitzer, H.D.; Corredor, L. ; Hiebert, R.; Barnhart, E.P. ; Cunningham, A.; Fields, M.W. (2015). *Sustainable Coalbed Methane (CBM) and Biofuel Production from Algae Grown in CBM Produced Water*. 2015 Montana Biofilm Meeting. Bozeman, MT.
- Davis, K.J.; Hodgskiss, L. ; Schweitzer, H.D.; Corredor, L. ; Hiebert, R.; Barnhart, E.P. ; Cunningham, A.; Fields, M.W. (2015). *Sustainable Coalbed Methane (CBM) and Biofuel Production from Algae Grown in CBM Produced Water.*. 2015 Montana Board of Research and Commercialization Technology meeting. Helena, MT.
- Hise A., Lohman E., Vadlamani A., Characklis G., Viamajala S. (2014). *Techno-economic analysis of bicarbonate triggered growth and hydrogel dewatering for algal biofuels*. 2014 Algae Biomass Summit. San Diego CA.
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- Shirazi Y, Viamajala S, Varanasi S (2016). *Catalytic pyrolysis of vegetable oil to fuels and chemicals in a novel continuous-flow reactor*. 20th Annual Green Chemistry & Engineering Conference. Portland OR.
- Moll, K.M.; Ramaraj, T.; Devitt, N.; Gerlach, R.; Peyton B.M. (2016). *Genomics of novel high biofuel-producing diatom*. Algal Biomass, Biofuels and Bioproducts. San Diego, CA.

Publications and Presentations

Presentations (cont.):

- Shirazi Y, Viamajala S, Varanasi S (2015). *High-yield production of fuels and oleochemical precursors from vegetable oils in a novel continuous-flow pyrolysis reactor*. Annual AIChE conference. Salt Lake City UT.
- Gardner, R.D.; Helms, G.L.; Hiscox, W.C.; Peyton, B.M.; Gerlach, R. (2015). *Insight into lipid biogenesis using stable isotope tracers coupled with NMR spectroscopy and mass spectrometry.*. AIChE Annual Meeting. Salt Lake City UT.
- Vadlamani A, Zhao X, Viamajala S, Varanasi S (2015). *Laboratory-scale demonstration of algae dewatering using fast-response temperature-sensitive hydrogels*. Algal Biomass Summit. Washington DC.
- Bell, T.A.S.; Doig, L.; Gerlach, R.; Peyton, B.M.; Fields, M.W. (2016). *Monitoring community ecology in wastewater treatment lagoons for the production of algal biodiesel*. Algal Biomass, Biofuels and Bioproducts. San Diego, CA.
- Abel G, Mudiyanselage A, Nguyen K, Viamajala S, Varanasi S, Yamamoto K (2016). *New approaches for efficient synthesis of precursors of industrial-nylons from oleic acid*. 20th Annual Green Chemistry & Engineering Conference. Portland OR.
- Rathore, M. S.; Moll, K. M., Gerlach, R.; Peyton, B. M. (2016). *Novel Algal Biofilm Reactor with Harvesting Mechanism for Enhanced Biomass Production*. 6th International Conference on Algal Biomass, Biofuels and Bioproducts. San Diego, CA.
- Rathore, M. S.; Moll, K. M., Gerlach, R.; Peyton, B. M. (2016). *Novel Algal Biofilm Reactor with Harvesting Mechanism for Enhanced Biomass Production*. Montana Biofilm Meeting. Bozeman, Montana.
- Shirazi Y, Viamajala S, Varanasi S (2015). *Production of hydrocarbons and fatty acids from vegetable oil pyrolysis in a continuous catalyst-free reactor*. TCBiomass conference. Chicago IL.
- Jackson, M.C., Pedersen, T.C.; Berninghaus, A.; Gardner, R.; Gerlach, R (2016). *Promoting Lipid Accumulation in Chlorella vulgaris UTEX395 Using Nitrogen Limitation and Bicarbonate Amendment*. Algal Biomass, Biofuels and Bioproducts. San Diego, CA.
- Jackson, M.C., Pedersen, T.C.; Berninghaus, A.; Gardner, R.; Gerlach, R (2015). *Promoting Lipid Accumulation in Chlorella vulgaris UTEX395 Using Nitrogen Limitation and Bicarbonate Amendment*. Algae Biomass Summit. Washington DC.
- Jackson, M.C., Pedersen, T.C.; Berninghaus, A.; Gardner, R.; Gerlach, R. (2016). *Promoting Lipid Accumulation in Chlorella vulgaris UTEX395 Using Nitrogen Limitation and Bicarbonate Amendment.*. Montana Biofilm Meeting. Bozeman, Montana.

Publications and Presentations

Presentations (cont.):

- Maddi B, Viamajala S, Varanasi S (2015). *Pyrolytic fractionation: A thermo-chemical technique for processing oleaginous algae*. Annual AIChE conference. Salt Lake City UT.
- Pendyala B, Vadlamani A, Viamajala S, Varanasi S (2015). *Role of dissolved inorganic carbon (DIC) speciation and availability on biomass productivity and photosynthesis in an alkaliphilic Chlorella sp.*. Algal Biomass Summit. Washington DC.
- Crawford, J.M.; Pedersen, T.; Peyton, B.M (2016). *Sodium bicarbonate supplementation for increased astaxanthin accumulation in chlorophyte Haematococcus pluvialis*. Montana State University Student Research Celebration. Bozeman, Montana.
- Crawford, J.M.; Pedersen, T.; Peyton, B.M. (2016). *Sodium bicarbonate supplementation for increased astaxanthin accumulation in chlorophyte Haematococcus pluvialis.*. National Conference on Undergraduate Research. Asheville, North Carolina.
- Yapa A, Viamajala S, Varanasi S, Yamamoto K (2015). *Synthesis of nylon precursors via cross-metathesis of methyl oleate and unsaturated alcohols*. Annual AIChE conference. Salt Lake City UT. Abel G, Yapa A, Viamajala S, Varanasi S, Yamamoto K (2015). *Towards Sustainable Synthesis of Nylon 11–13 Precursors Using Ring-Closing Olefin Metathesis Strategy*. Annual AIChE conference. Salt Lake City UT.