Development of Algae-Based Nitrogen Removal Technologies

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HRSD
Cleaning wastewater every day for a better Bay.

WERF

Outline of talk

- Phycoremediation –
  - – pros and cons, state of technology, potential solutions
- Approach & Experimental design
- Results
- Conclusions
- Future Work

Current technologies for low TN in WWTP effluent commonly involve biological nutrient removal (BNR) using bacteria

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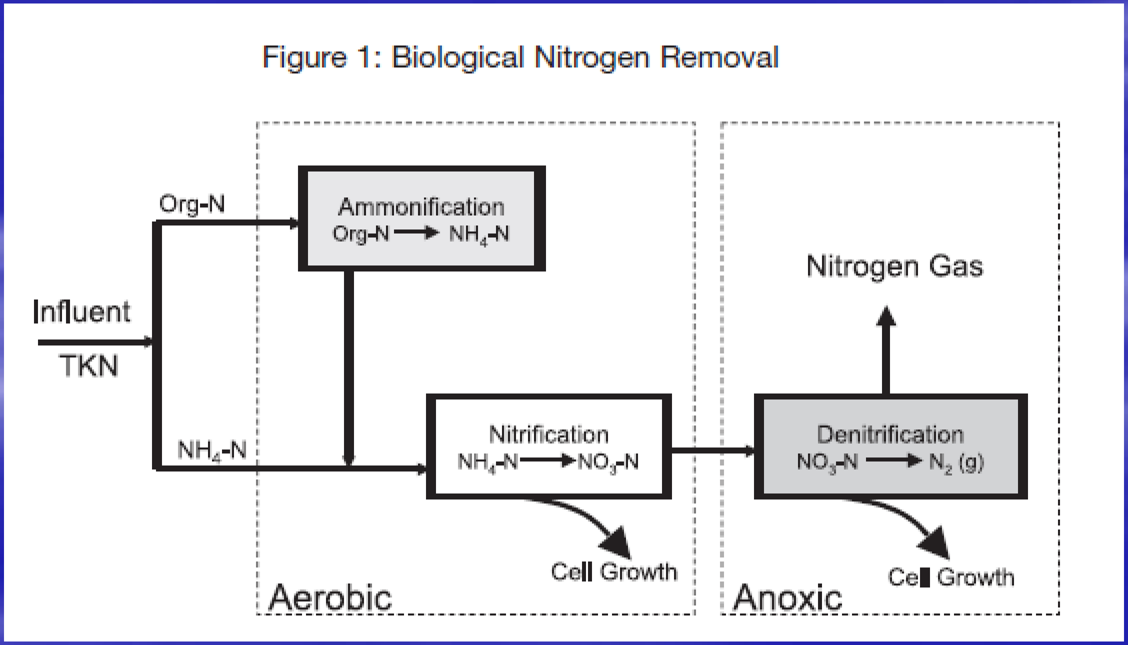


(Jeyanayagam 2005)

Algae-based Nitrogen Removal

- Phycoremediation – the use of algae to remove or reduce nutrients
- Potential replacement for BNR or post-BNR polishing
- Certain sectors have already capitalized on the ability of algae to take up a diverse suite of N:
  - Aquaculture, agriculture, livestock, and small community wastewater facilities
  - There are many bioreactor designs that achieve nutrient removal using algae

Phycoremediation - Pros

- N rapidly converted to biomass that can be removed and used
- No need for supplemental carbon (C) additions (e.g. methanol) – need to control pH/aerate
- Algae also remove phosphorus (P) during their growth – could reduce P removal costs
- No gaseous N intermediates (e.g., N_2O)
- Inexpensive, simple, and environmentally friendly

$$106\ CO_2 + 16\ HNO_3 + H_3PO_4 + 78\ H_20 \rightleftharpoons C_{106}H_{175}O_{42}N_{16}P + 150\ O_2$$

Phycoremediation - Cons

- Requires light
- Separation of algae from treated wastewater stream
- Continuous flow – chemostat reactors
  - Short in-plant hydraulic residence times (HRTs) and high flow rates – need fast-growing algae!
  - Balance conversion of N to biomass and wash out
- Space – large surface area required to provide access to “free” light
  - Requires large footprint
  - Existing WWTP reactors use less space

Current state of technology

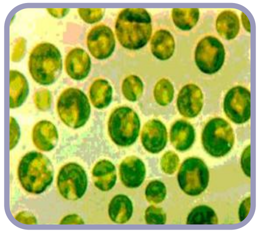
- Phycoremediation technologies using algae have been developed, primarily outside of the US or where space is not limiting
- While various phycoremediation techniques have been described, none have been designed for use in large WWTP applications (>1-3 MGD) for plants with short HRTs (< 4-8 hours)
- Algal nutrient removal has focused on dissolved inorganic P (DIP) as PO_4^{3-} and N primarily as ammonium (NH_4^+)

Potential solutions

- Separation problem - Immobilize algae so they can be easily removed
  – Natural polymers – sodium alginate
  – Embed or apply as a biofilm
- Light problem - Increase light penetration
  – Submerged light sources
  – Side-emitting fiber optics
  – Solar/light collectors
  – Wavelength specific light sources

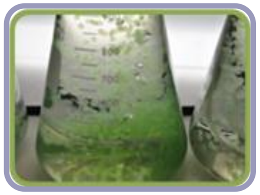
Our approach

Algal Selection



- Mixed algal suspension from WWTP
- *Chlorella* spp.
- *Desmodesmus* spp.

Algal Immobilization



- Embed as beads, strands, or layers in sodium alginate
- Attach to biofilm carriers

Nutrient Removal

- Polishing step for final effluent from wastewater treatment process
- N removal: NO_3^-, NH_4^+, DON
- Evaluate P requirements for algae and P removal

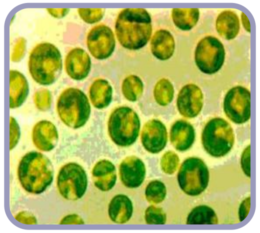
Optimization

- Temperature - 15, 20, 25, 30˚C
- Light supply – surface, surround, side-emitting fiber optics
- Mixing/aeration
- CO_2 concentrations

• Biological endpoints – Chl *a*, fluorescence, cell counts, productivity
• Nutrient concentrations – TDN, NOx-N, NH_4^+, DON, PO_4^{3-}
• pH, DIC

Measurements

Our approach



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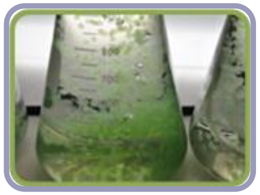
- *Chlorella* spp
- *Desmodesmu*



Algal I

- Embed as be
  alginate
- Attach to biof

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- Polishing ste
  treatment pro
- N removal: N
- Evaluate P re

Opt

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Experimental Design

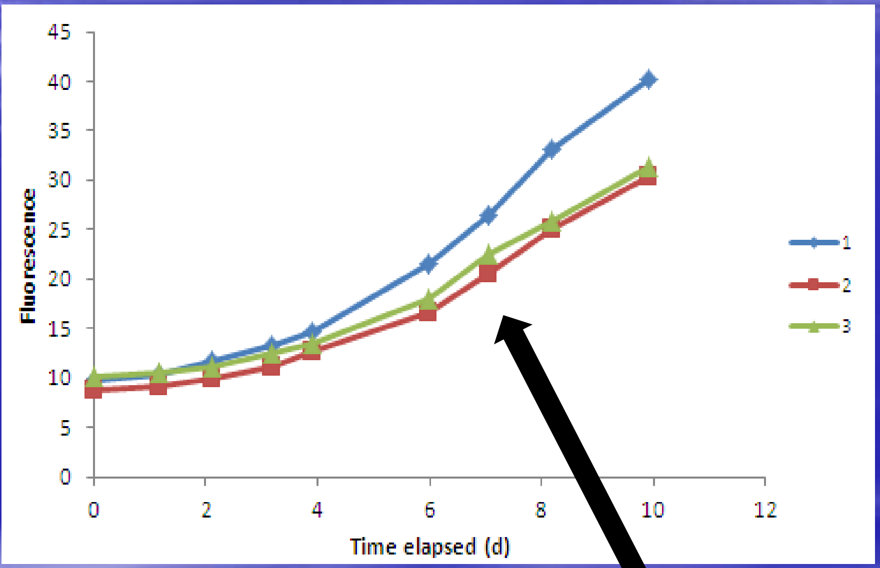
1. Free-floating algal growth in effluent amended with P
2. Small-scale (<1L) encapsulation (alginate beads) in batch mode, light penetration from all sides
   a) Altered aeration/mixing
   b) Altered temperature
3. Larger scale (5L) encapsulation
   a) Batch vs continuous flow
   b) pH effects
   c) Varied light source

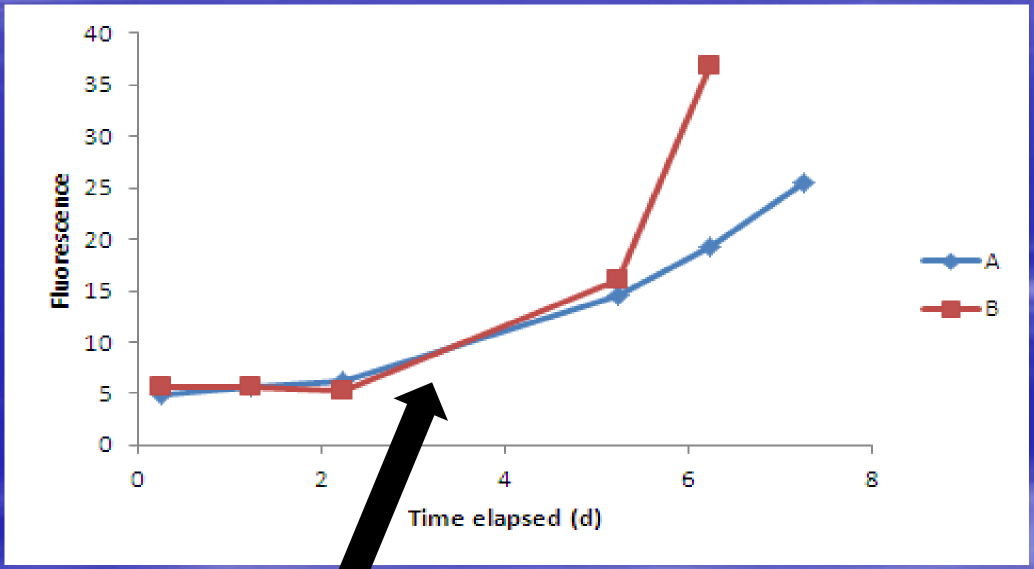
Experimental constants

- All experiments start with HRSD's Virginia Initiative Plant treated effluent (fully nitrifying/partially denitrifying)
  - $NH_4^+ < 1$ mg/L
  - NOx-N = 5 -7 mg/L
  - OP < 0.1 – 0.3 mg/L
  - TP < 0.5 mg/L
- All experiments conducted using 24 h light
- P always added as 16 N:1 P (algal molar N:P requirement)
- All bioreactors either mixed or aerated
- Growth rates calculated as doubling times

Results - Free algae

- Algae like to grow in wastewater





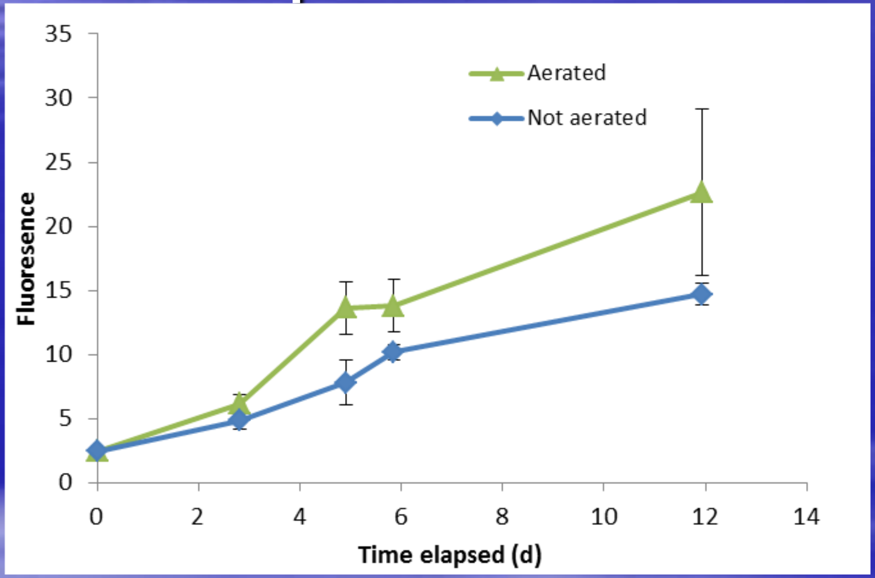
Desmodesmus sp. **and** ***Chlorella v.*** **– common freshwater algae, grow well in effluent**

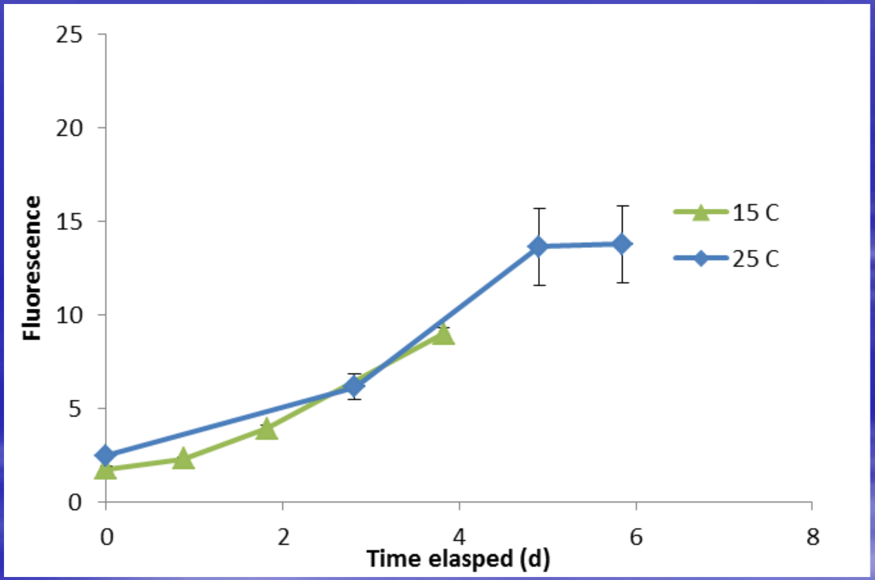
Algal Immobilization - embedding

- Sodium alginate
  - Simple and cost-effective natural polymers, derived from algae, form rigid beads when dropped into an ionic solution.
  - When mixed with suspended algae, beads encapsulate algae that can grow within the polymer, allowing nutrients from effluent to diffuse into the beads

Results – encapsulated algae

- Algae like to grow in wastewater while encapsulated





Chlorella v. **doubling time greater in aerated bioreactor**

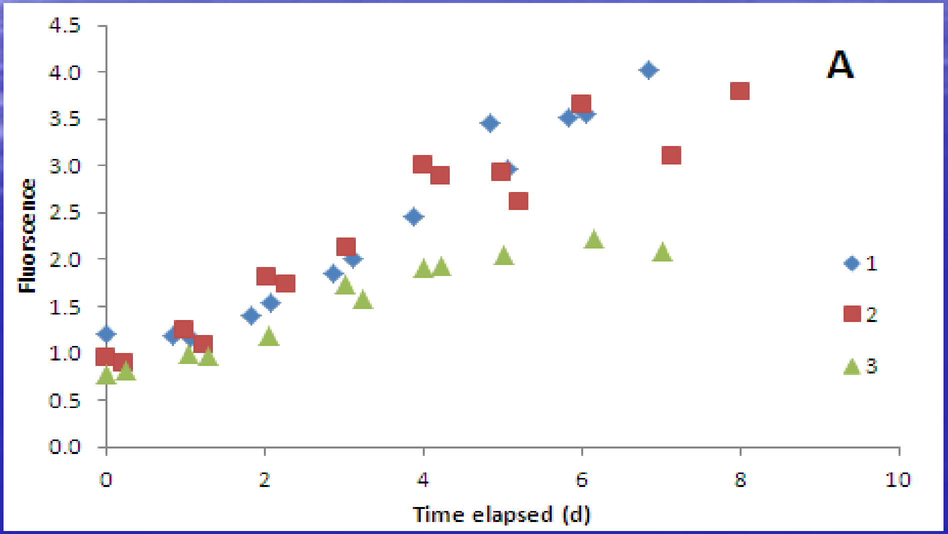
Chlorella v. **doubling times similar in different temperature bioreactors**

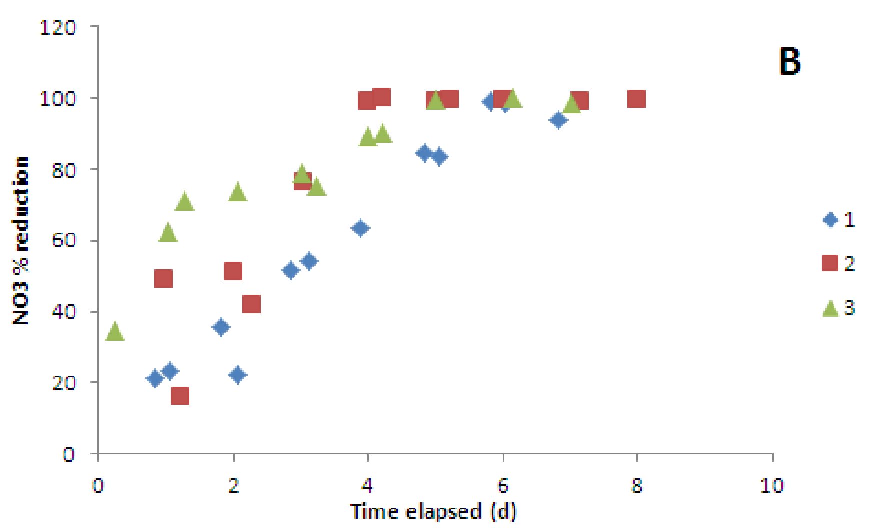
Results – Nutrient reduction

- Algae can remove N and P

Exp. #	Type of algae/ free or embedded	Batch or flow through	Doubling time (d)	NOx-N removal efficiency	P removal efficiency
1	Desmodesmus/free	Batch	5.1 ± 0.6	N/A	N/A
2	Desmodesmus/free	FT[1] (0.2 mL/min)	0	20%	N/A
3	Desmodesmus/free	Batch	4.9 ± 0.5	<40%	N/A
4	Synechococcus/free	Batch	0	N/A	N/A
5	Chlorella/free	Batch	2.5 ± 0.4	N/A	N/A
6	Chlorella/embedded	Batch	4.7 ± 0.3	N/A	N/A
7	Chlorella/embedded	Batch	4.0 ± 0.5	N/A	N/A
8	Chlorella/embedded	Batch	1.6 ± 0.1	100% in 4d	90% in 4d
9	Chlorella/embedded	Batch	4.0 ± 0.5	100% in 6d	90% in 12d

Results – large- scale encapsulated algae



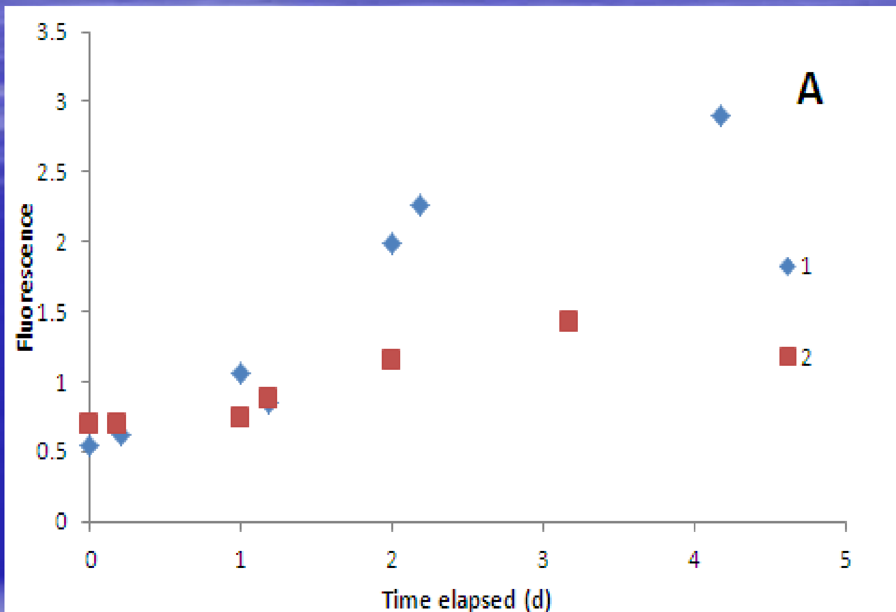


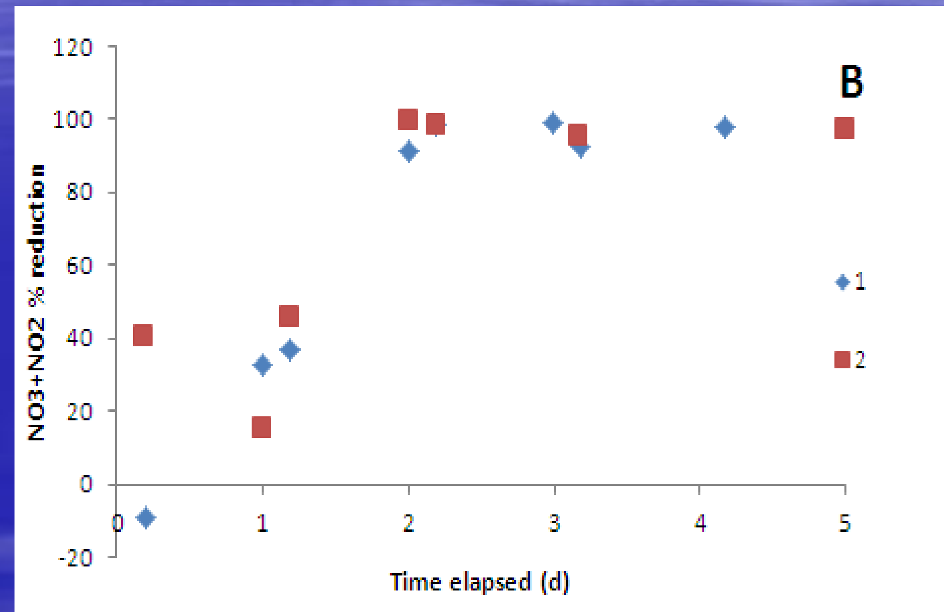
Doubling time: 3.8 ± 0.5 d

100% NOx-N reduction in 4 days

* 30° C bioreactor,
overhead fluorescent light

Results – Increased light





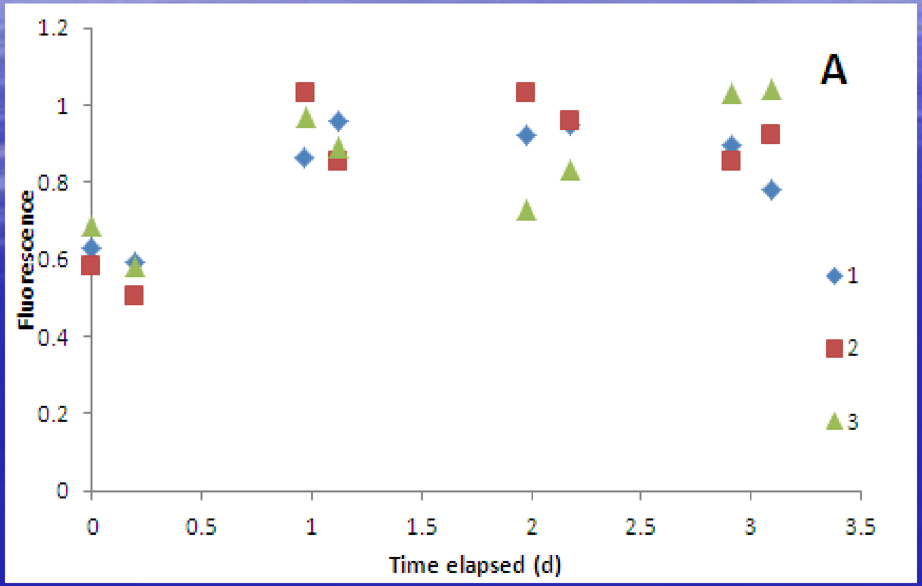
Doubling time: 2.2 ± 0.8 d

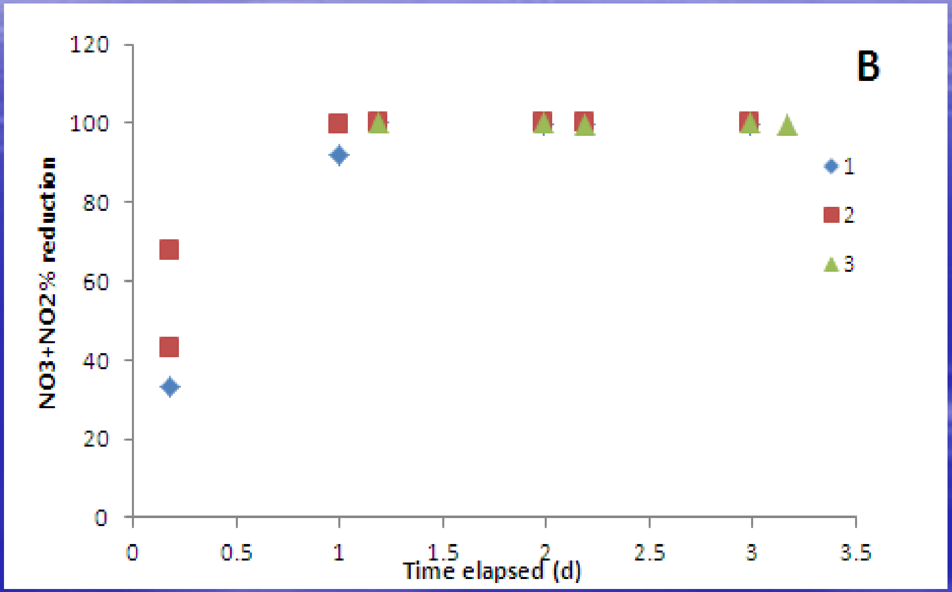
100% NOx-N reduction in 2 days

* 30° C bioreactor, increased light by 23%

Results – Controlled pH

Prevent C limitation





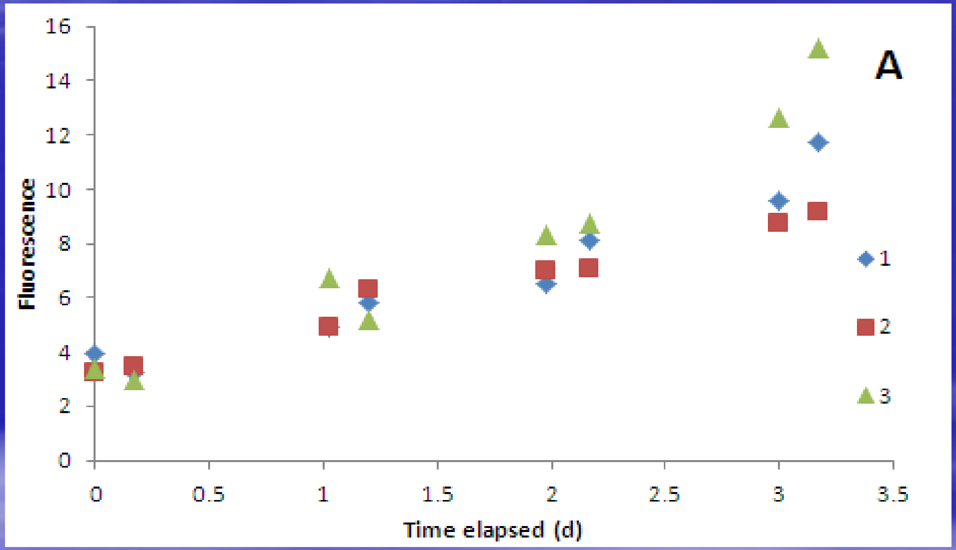
Doubling time : 1.4 ± 0.3 d

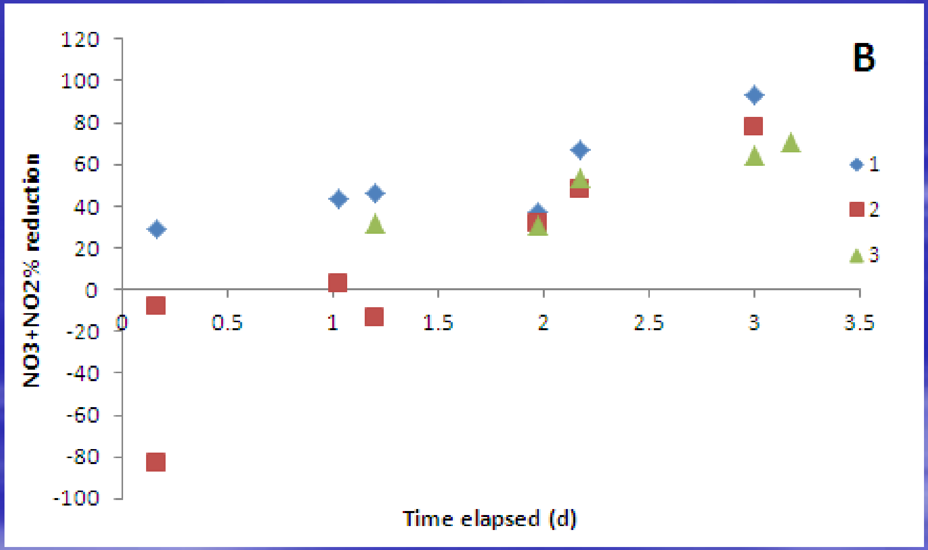
100% NOx-N reduction in 1 day

* 30° C bioreactor, increased light by 23%, pH = 7-7.5

Results – Flow through system

- 5L bioreactors (3.6L effluent), stirred, 30°C, 23% increased light, 5 mL/min (12 h HRT)





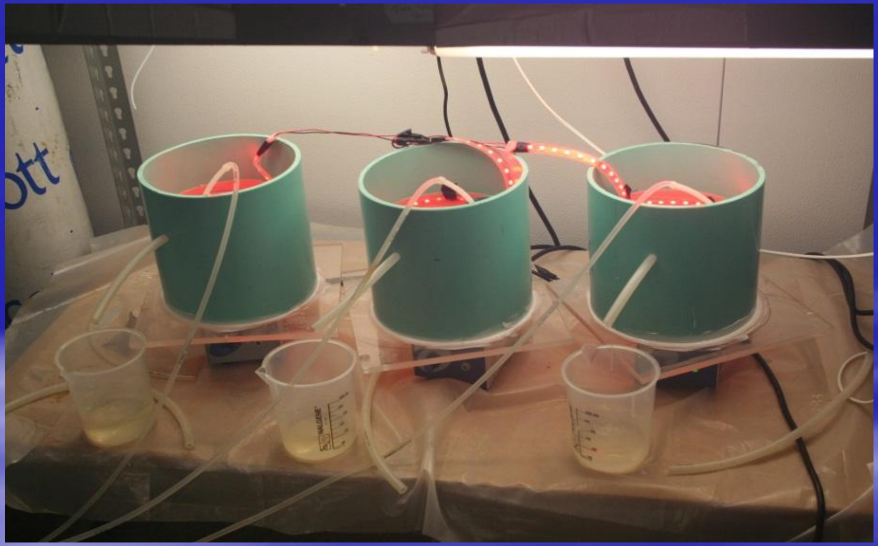
Doubling time : 1.8 ± 0.4 d

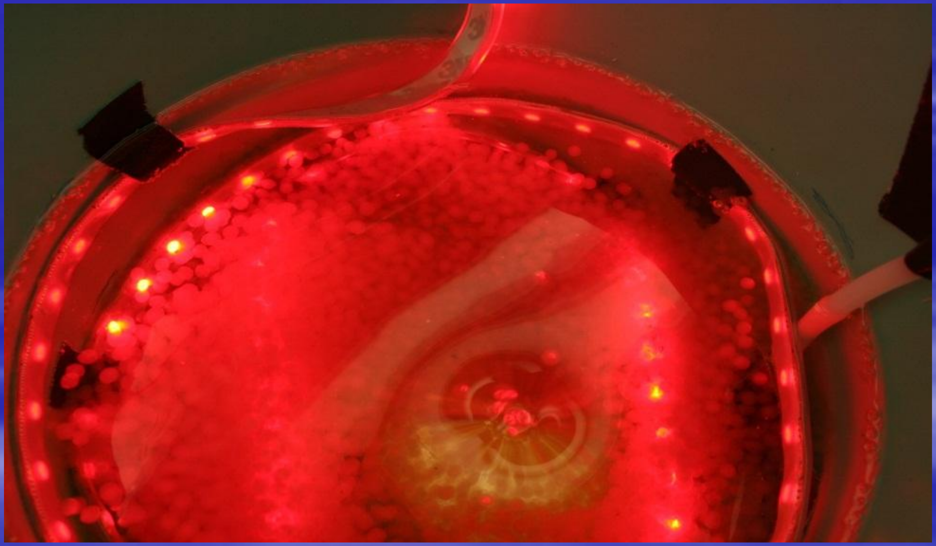
DT > HRT

<100% NOx-N reduction in 3 days

Results – Flow through system

- 5L bioreactors, stirred, 30°C, 23% increased light, 5 mL/min (12 h HRT), **submersible wavelength specific LEDs (623 nm)**





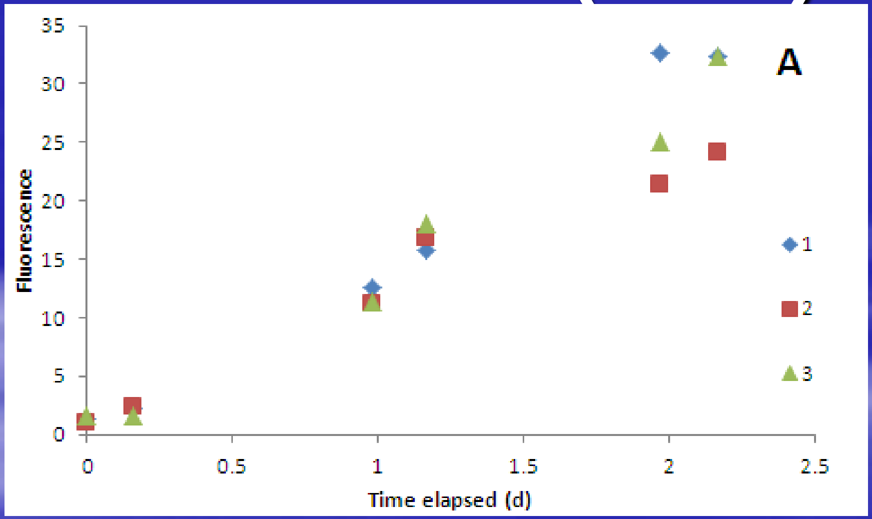
Doubling time : 0.89 ± 0.04 d

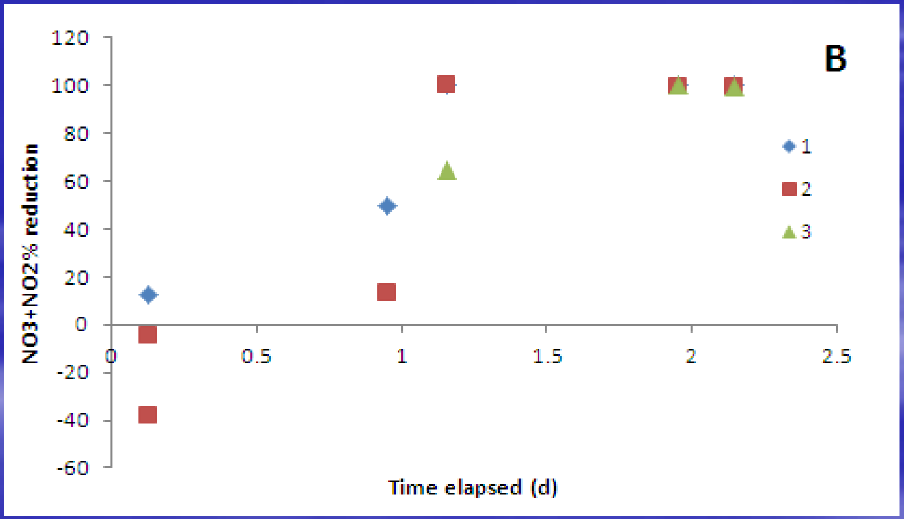
DT > HRT

Only 50% NOx-N reduction in 3 days

Results – Flow through system

- 5L bioreactors, stirred, 30°C, 23% increased light, 5 mL/min (12 h HRT), submersible wavelength specific LEDs (red; 623 nm), **pH maintained (7-7.5)**



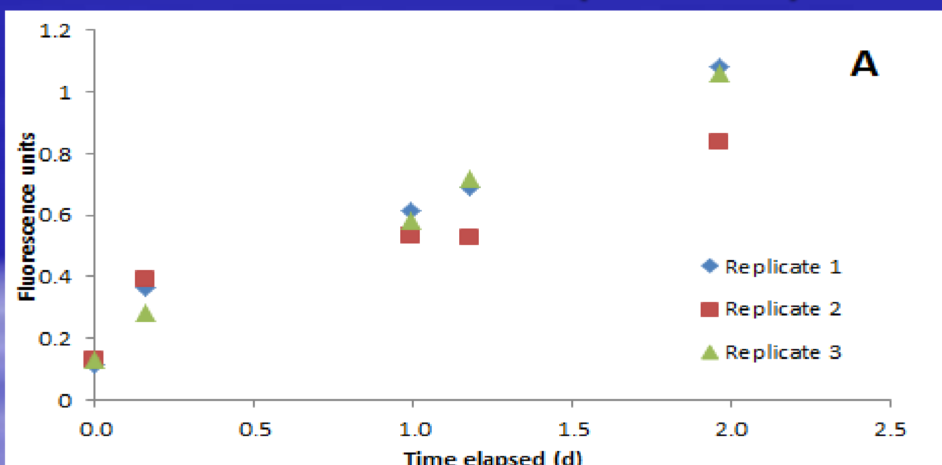


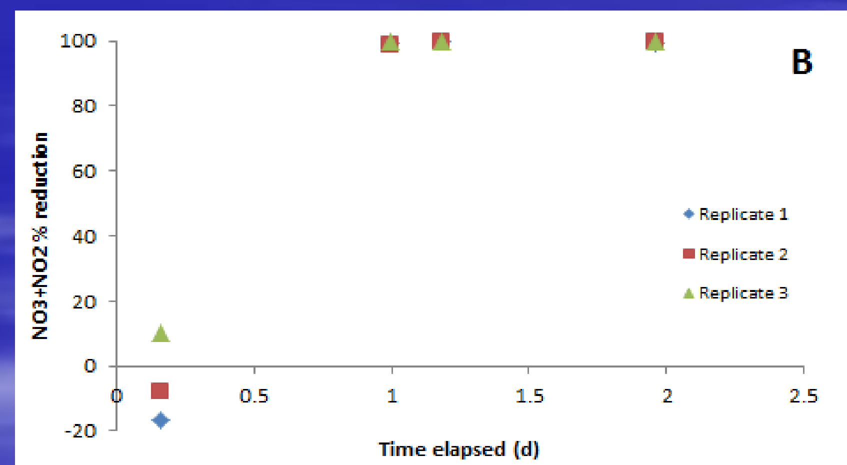
Doubling time : 0.48 ± 0.01 d
Now about equal to HRT!

100% NOx-N reduction in 1 day (2/3 replicates)

Results – Flow through system

- 5L bioreactors, stirred, 30°C, 23% increased light, **8.5 mL/min (6.5 h HRT)**, submersible wavelength specific LEDs (red; 623 nm), pH maintained (7-7.5)



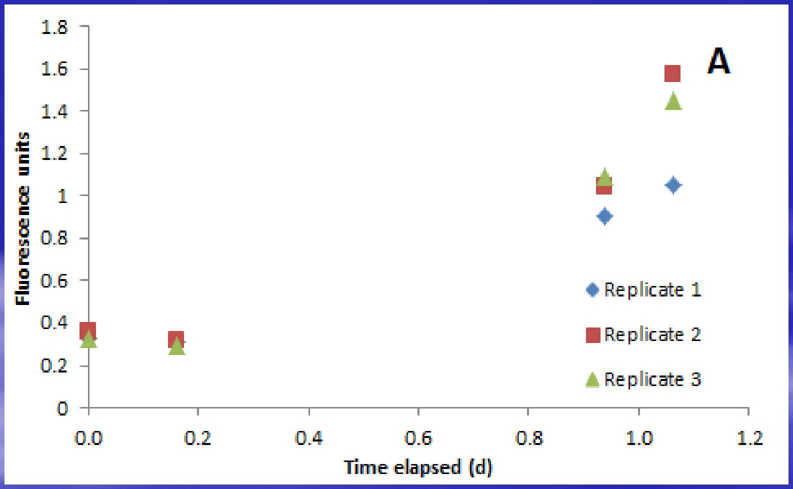


Doubling time : 0.72 ± 0.01 d

100% NOx-N reduction in 1 day

Results – Flow through system

- 5L bioreactors, stirred, **20°C**, 23% increased light, 8.5 mL/min (6.5 h HRT), submersible wavelength specific LEDs (red; 623 nm), pH maintained (7-7.5)

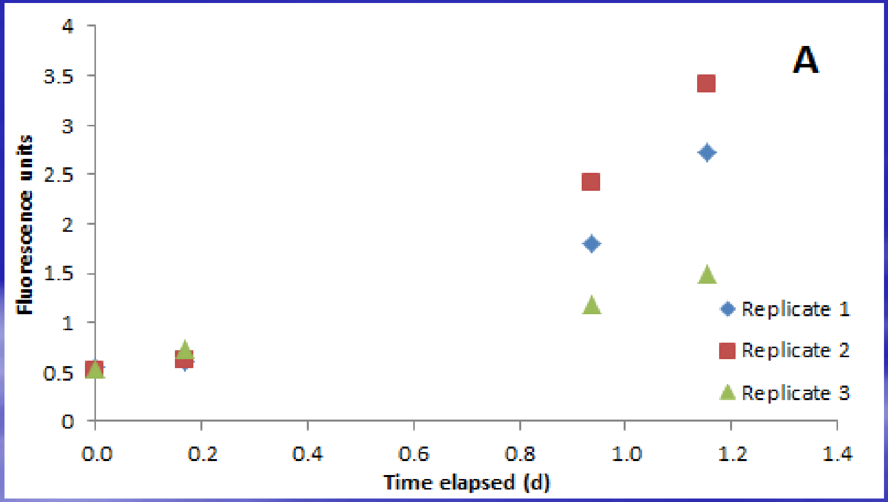


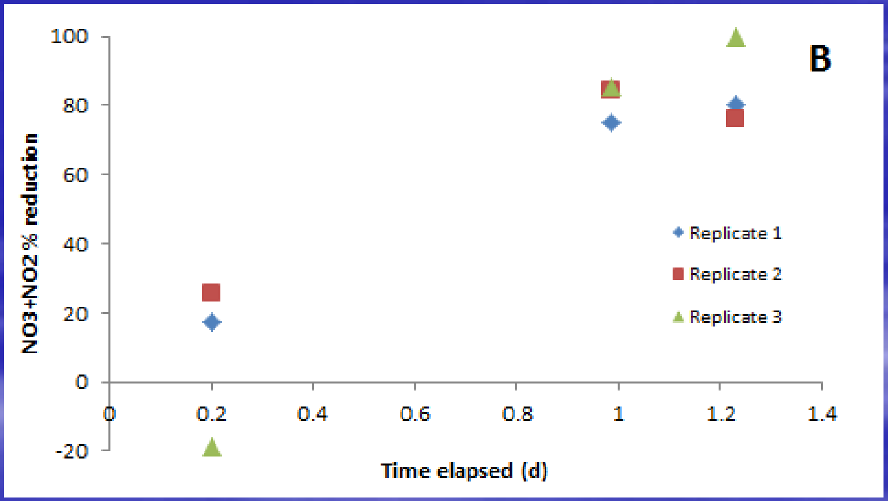
NOx-N produced but VIP effluent was uncharacteristically dominated by NH_4^+ which was depleted to 0 within 24 h

Doubling time : 0.52 ± 0.08 d

Results – Flow through system

- 5L bioreactors, stirred, 20°C, 23% increased light, 8.5 mL/min (6.5 h HRT), submersible wavelength specific LEDs (red; 623 nm), pH maintained (7-7.5), **bead/effluent = 10% (v/v)**



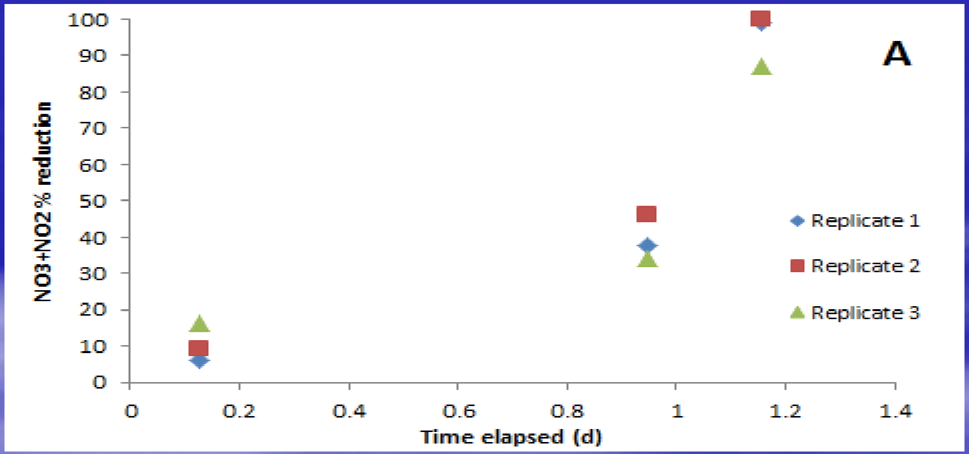


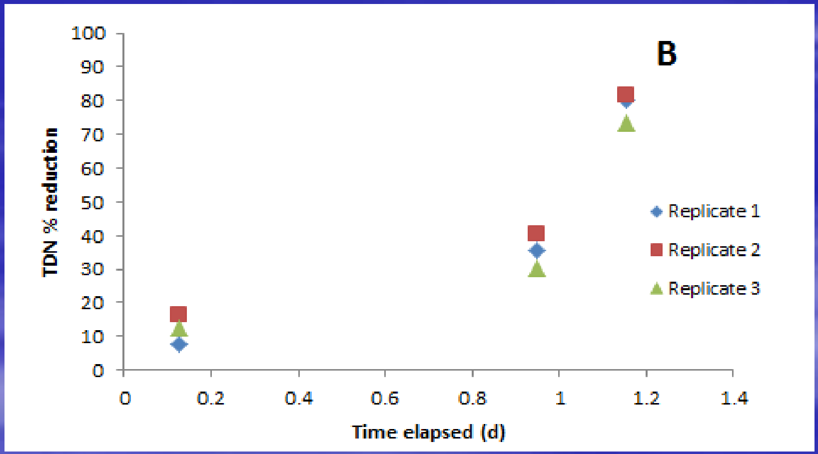
Doubling time : 0.68 ± 0.26 d

80% NOx-N reduction in 1 day

Results – Flow through system

- 5L bioreactors, stirred, **20°C**, 23% increased light, 5 mL/min (12 h HRT), submersible wavelength specific LEDs (red; 623 nm), pH maintained (7-7.5), **coated biofilm carriers**





100% NOx-N reduction in 28 h

80 – 90% TDN reduction in 28 h

Results – Summary

Exp. #	Type of algae/ free or embedded	Batch or flow through	Light type	Temp. (°C)	pH regulated	Doubling time (d)	NOx-N removal efficiency	P removal efficiency
10	Chlorella/embedded	Batch + P	Fluor. 24h	25	N/A	3.8 ± 0.5	100% in 4d	70% in 8d
11	Chlorella/embedded	Batch + P	Fluor. 24h +23%	25	N/A	2.2 ± 0.8	100% in 2d	100% in 2d
12	Chlorella/embedded	Batch + P	Fluor. 24h +23%	25	7 – 7.5	1.4 ± 0.3	100% in 1d	100% in 1d
13	Chlorella/embedded	FT (5 mL/min) + P	Fluor. 24h +23%	30	N/A	1.8 ± 0.4	100% in 2d	100% in 2d
14	Chlorella/embedded	FT (5 mL/min) + P	Fluor. 24h + red LEDs	30	N/A	0.89 ± 0.4	50% in 1d	90% in 1d
15	Chlorella /embedded	FT (5 mL/min) + P	Fluor. 24h + red LEDs	30	7 – 7.5	0.48 ± 0.4	100% in 1d	100% in 1d
16	Chlorella /embedded	FT (8.5 mL/min) + P	Fluor. 24h + red LEDs	30	7 – 7.5	0.472± 0.01	100% in 1d	100% in 1d
17	Chlorella /embedded	FT (8.5 mL/min) - P	Fluor. 24h + red LEDs	30	7 – 7.5	1.25 ± 0.25	100% in 1d	N/A
18	Chlorella /embedded	FT (8.5 mL/min) - P	Fluor. 24h + red LEDs	20	7 – 7.5	0.52 ± 0.08	0	N/A
19	Chlorella /embedded (re-used)	FT (8.5 mL/min) - P	Fluor. 24h + red LEDs	20	7 – 7.5	1.3 ± 0.1	30-50% in 1d	N/A
20	Chlorella /embedded (10% v/v)	FT (8.5 mL/min) - P	Fluor. 24h + red LEDs	20	7 – 7.5	0.68 ± 0.26	80% in 1d	N/A
21	Chlorella /embedded (10% v/v)	FT (8.5 mL/min) - P	Fluor. 24h + blue LEDs	20	7 – 7.5	1.9 ± 0.9	30% in 2d	N/A
22	Chlorella /embedded (10% v/v; re-used)	FT (8.5 mL/min) - P	Fluor. 24h + blue LEDs	20	7 – 7.5	0.77 ± 0.13	30% in 2d	N/A
23	Chlorella /embedded (plastic carriers)	FT (5 mL/min) + P	Fluor. 24h + red LEDs	30	7 – 7.5	N/A	100% in 1.2d	0

Conclusions

- Phycoremediation strategies - successful at HRTs of 6.5 and 12 h
- 10% bead to effluent (v/v) efficient at N removal, reduce more?
- Coated biofilm carriers proved promising

Conclusions

- Effluent 'type' will effect results, NH_4^+ preferentially removed over NOx and organics
- Significant NOx-N removal was obtained, steady state within 24 h
- Wavelength specific submersible LEDs increase growth rates, red > blue
- Maintaining pH increases growth rates and N and P removal efficiencies because it alleviates C limitation of photosynthesis, could be a good use of plant CO_2

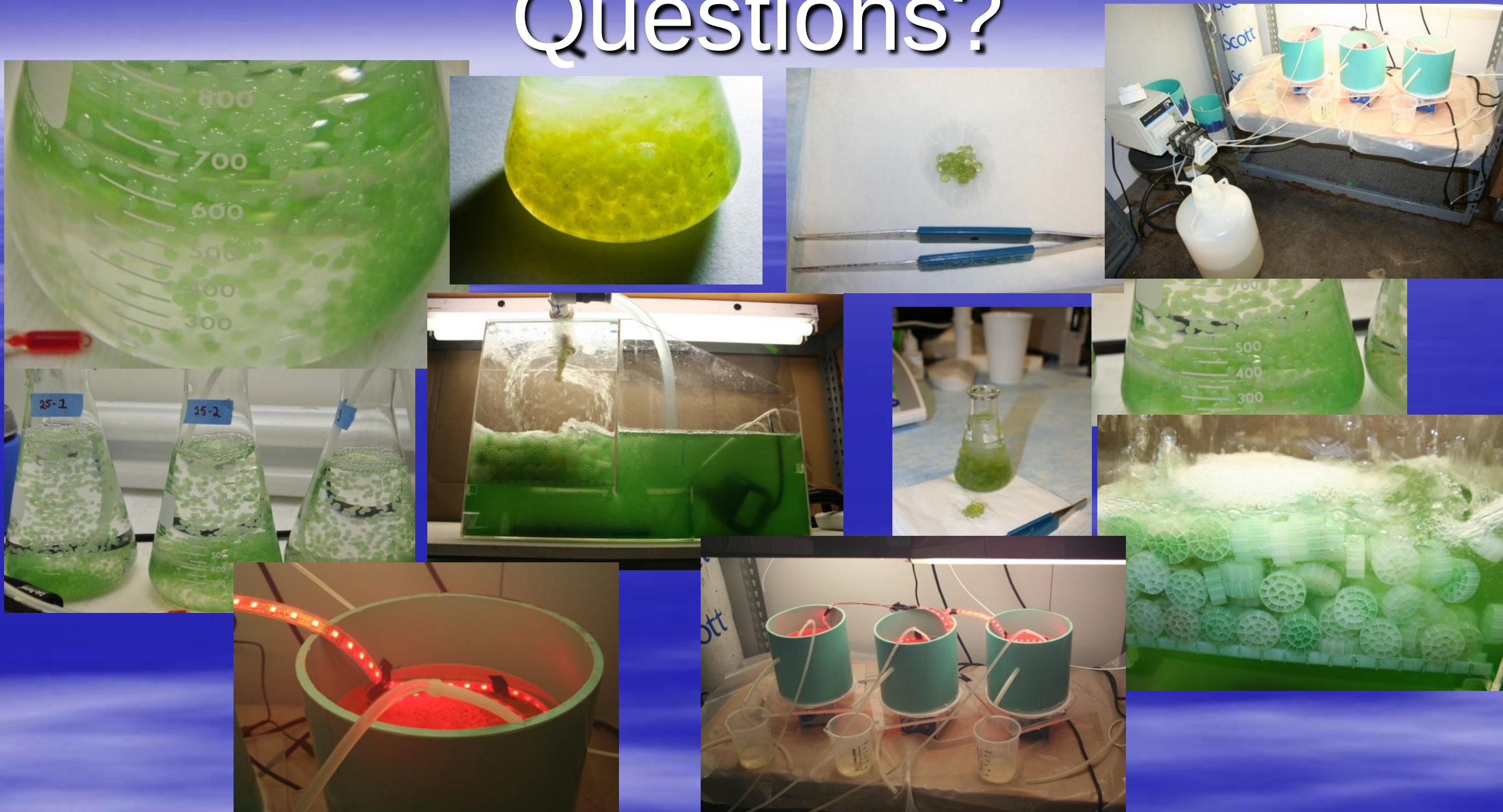
Reality check = Costs

- Lights and alginate are greatest expense
- Costs ~$0.03/m to use submersible red LEDs for 1 day - Need to scale down amount of lights used per L effluent
- Need to find cheaper source for large-scale alginate purchases, beads can be used for ~ 2 weeks and still maintain integrity and efficiency
- Other chemical costs – may be offset by recycling CO_2 and not removing PO_4^{3-}

Future work

- Decrease HRTs further
- Scale up
- Perform experiments in a series
- ID robust algal communities for plant setting
- Determine optimal N:P ratios
- More work into biofilm carriers like that used for bacteria in moving bed biofilm reactors (MBBR)
- Potential for algal and polymer recycle streams (However, algal beads dry rapidly)

Questions?



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