Algae for Wastewater Treatment Workshop Proceedings

October 23rd, 2016
Renaissance Glendale Hotel & Spa
Glendale, AZ

The Water Environment Federation (WEF), AZ Water Association (AZ Water), and the Algae Biomass Organization (ABO) Presented this Knowledge Development Forum in Conjunction with the 10th Annual Algae Biomass Summit

WSEC-2016-PD-001

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Moderator John Benemann

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Moderator Noah Mundt

ALGAE BIOMASS ORGANIZATION

Water Environment Federation
the water quality people™

AZ Water ASSOCIATION
Professionals Dedicated To Arizona's Water

Algae for Wastewater Treatment

Opportunities in Operational Energy Efficiency, Product Recovery and Low Cost Systems

Renaissance Glendale Hotel & Spa, AZ, October 23, 2016 12:30-4:00pm

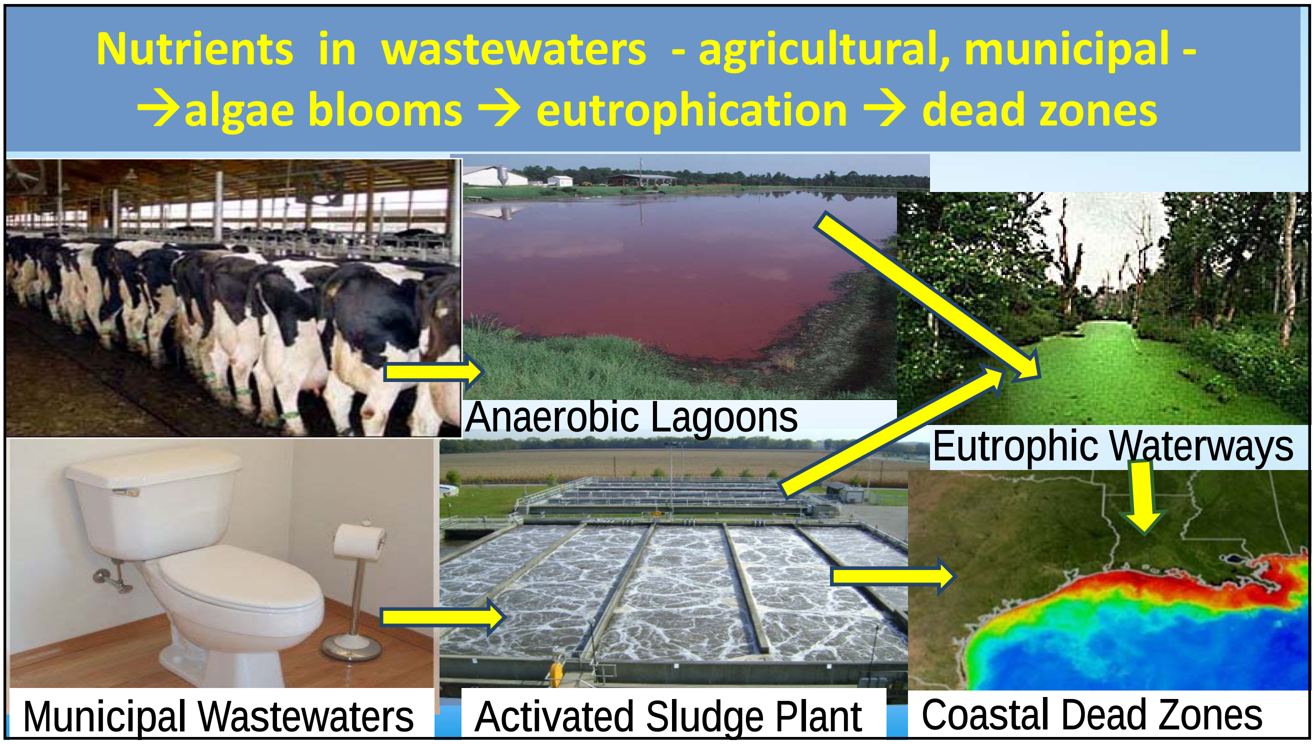
PANEL 1 – Algae Biotechnology for Wastewater Treatment: An Introduction

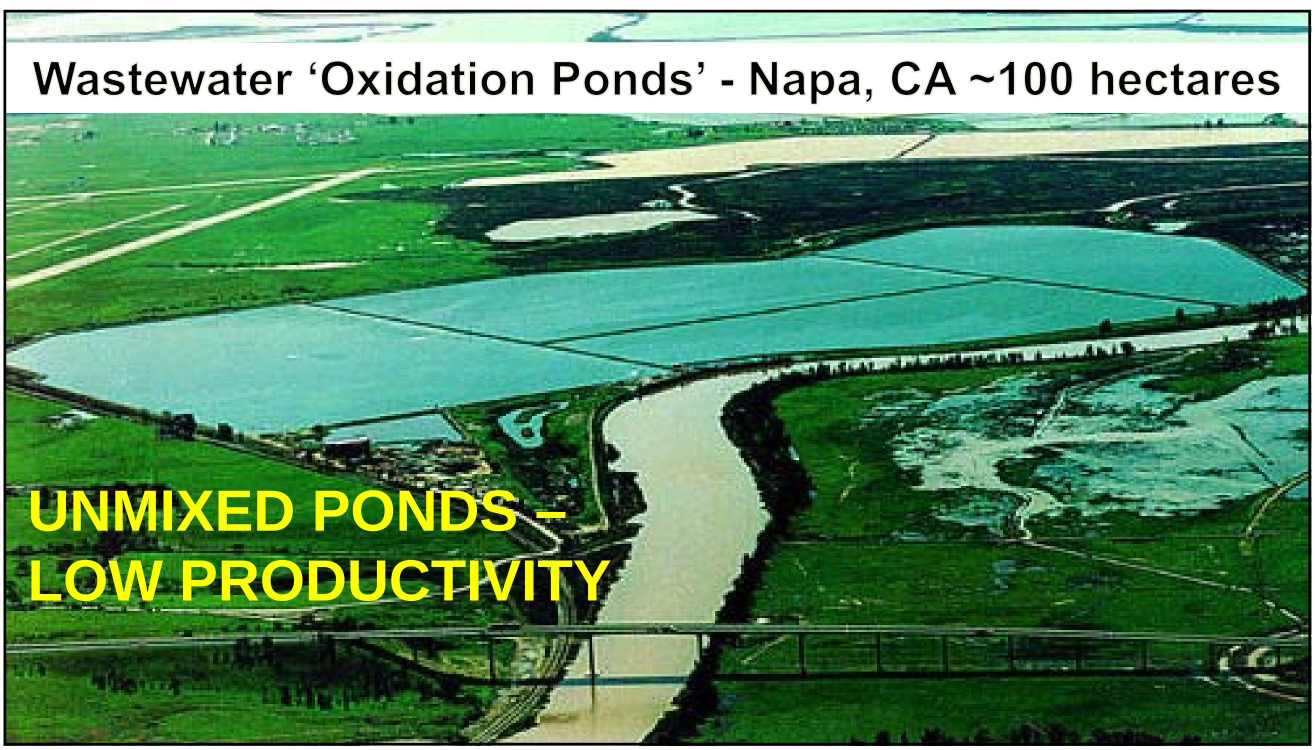
Moderator: John Benemann, MicroBio Engineering Inc.

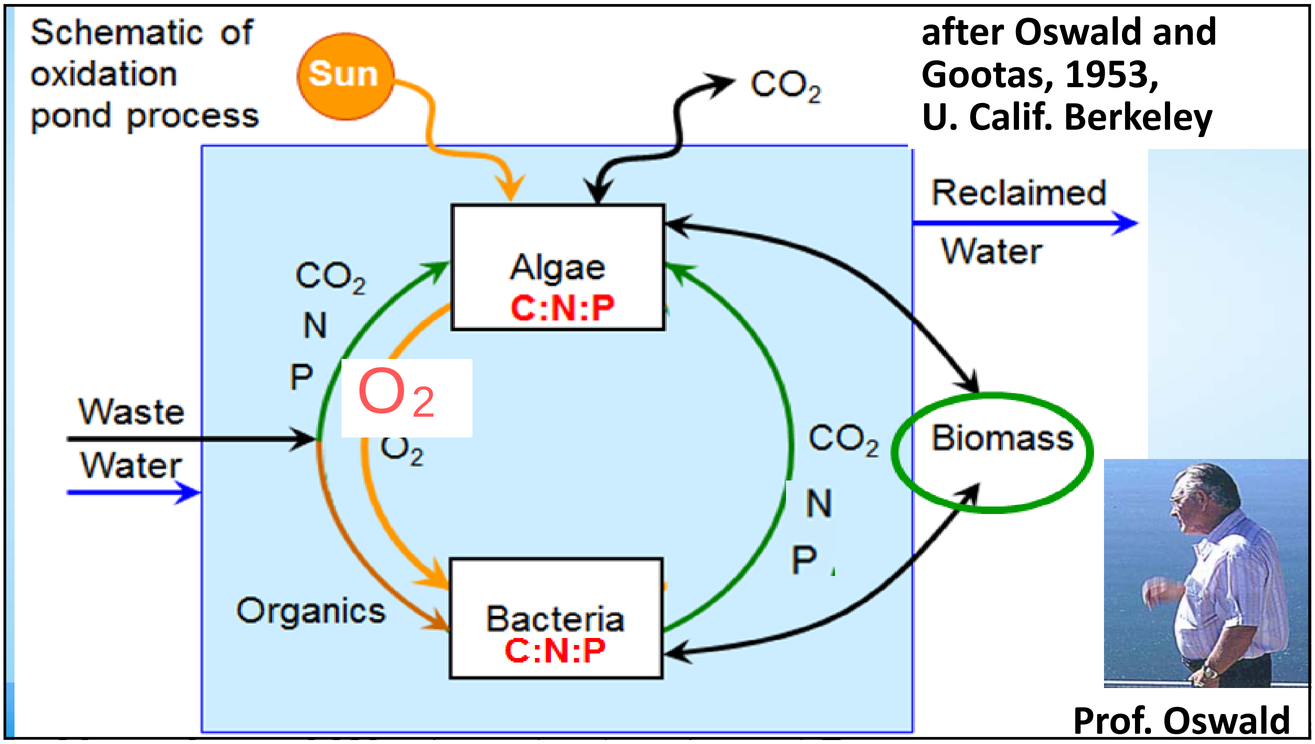
Ron Sims, Utah State University

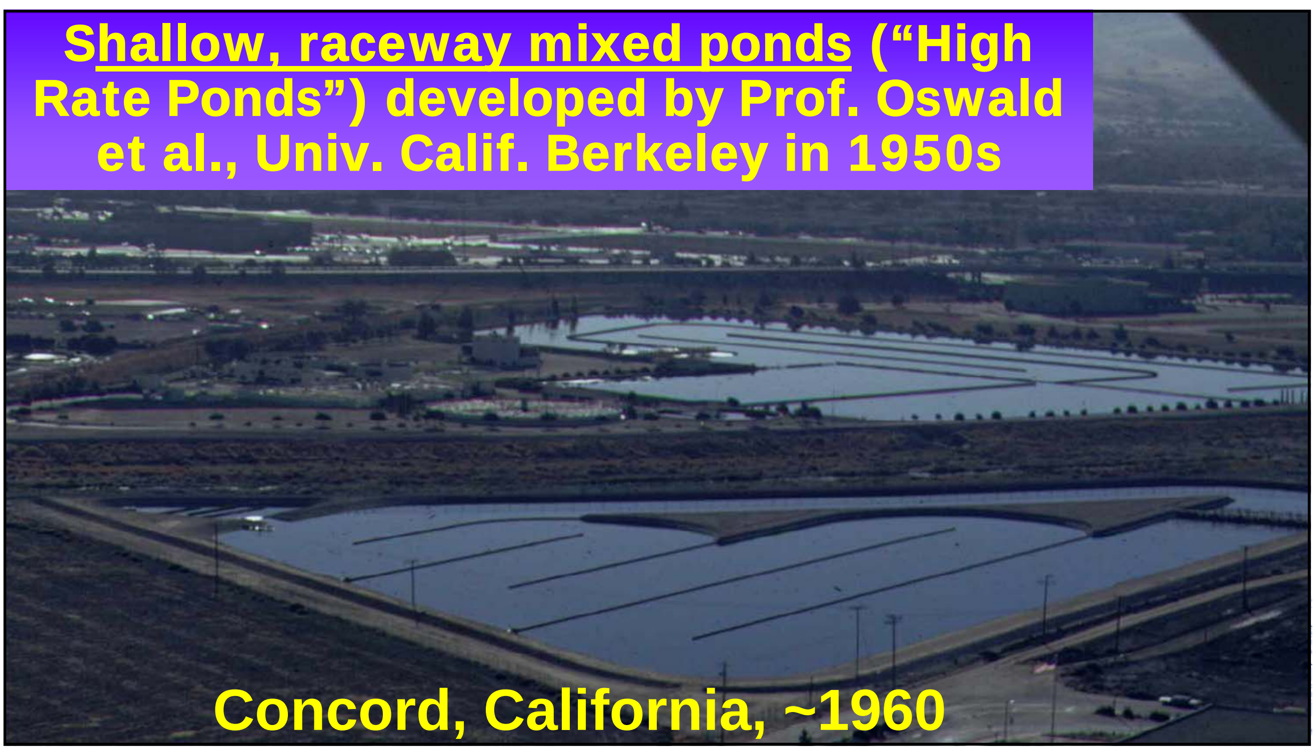
Tryg Lundquist, Cal Poly, California

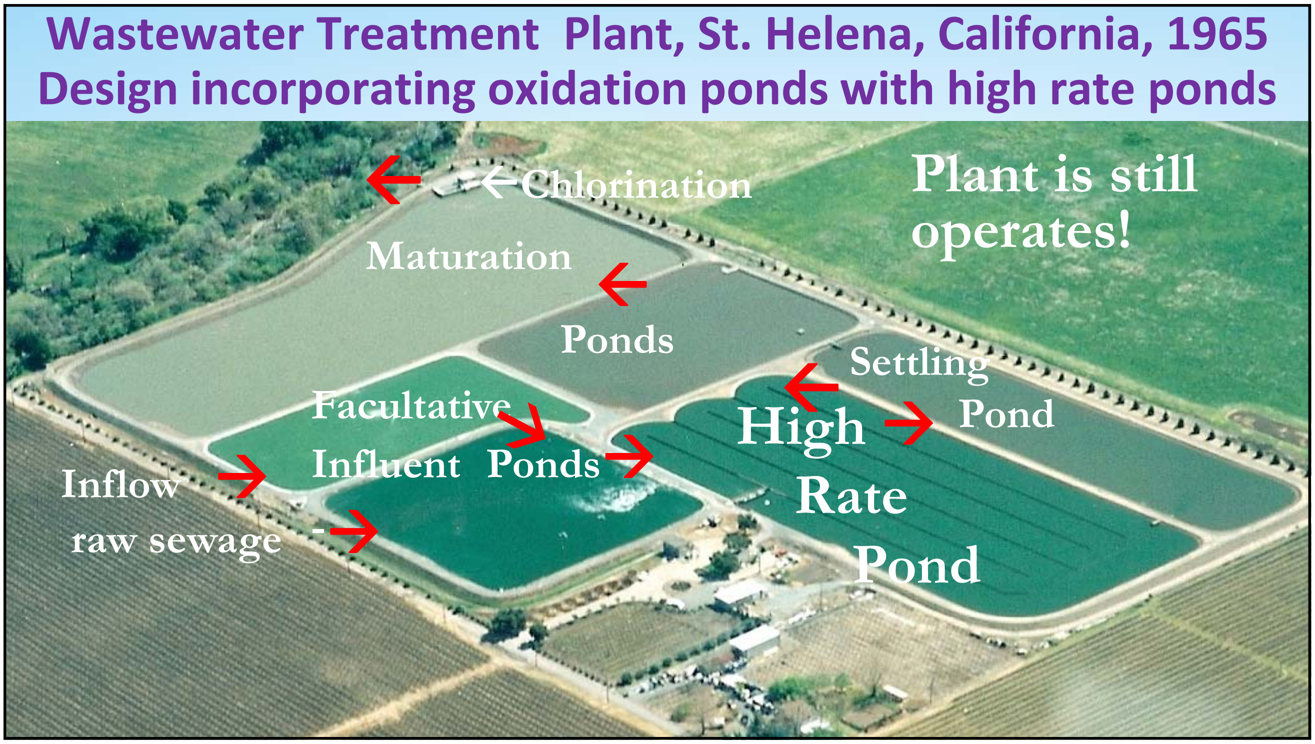
Frank Rogalla, Aqualia / FCC, Spain

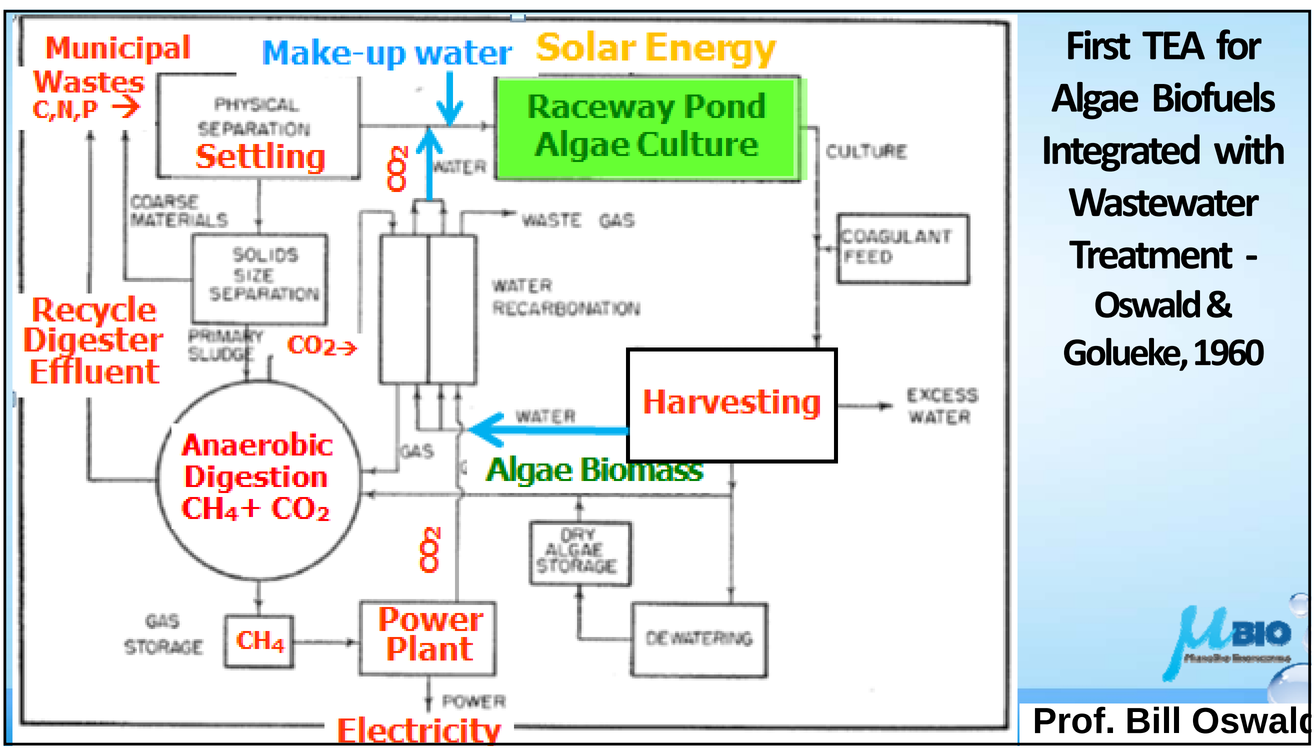

Nutrients in wastewaters - agricultural, municipal -
→algae blooms → eutrophication → dead zones
Anaerobic Lagoons
Eutrophic Waterways
Municipal Wastewaters
Activated Sludge Plant
Coastal Dead Zones


Wastewater 'Oxidation Ponds' - Napa, CA ~100 hectares
UNMIXED PONDS –
LOW PRODUCTIVITY

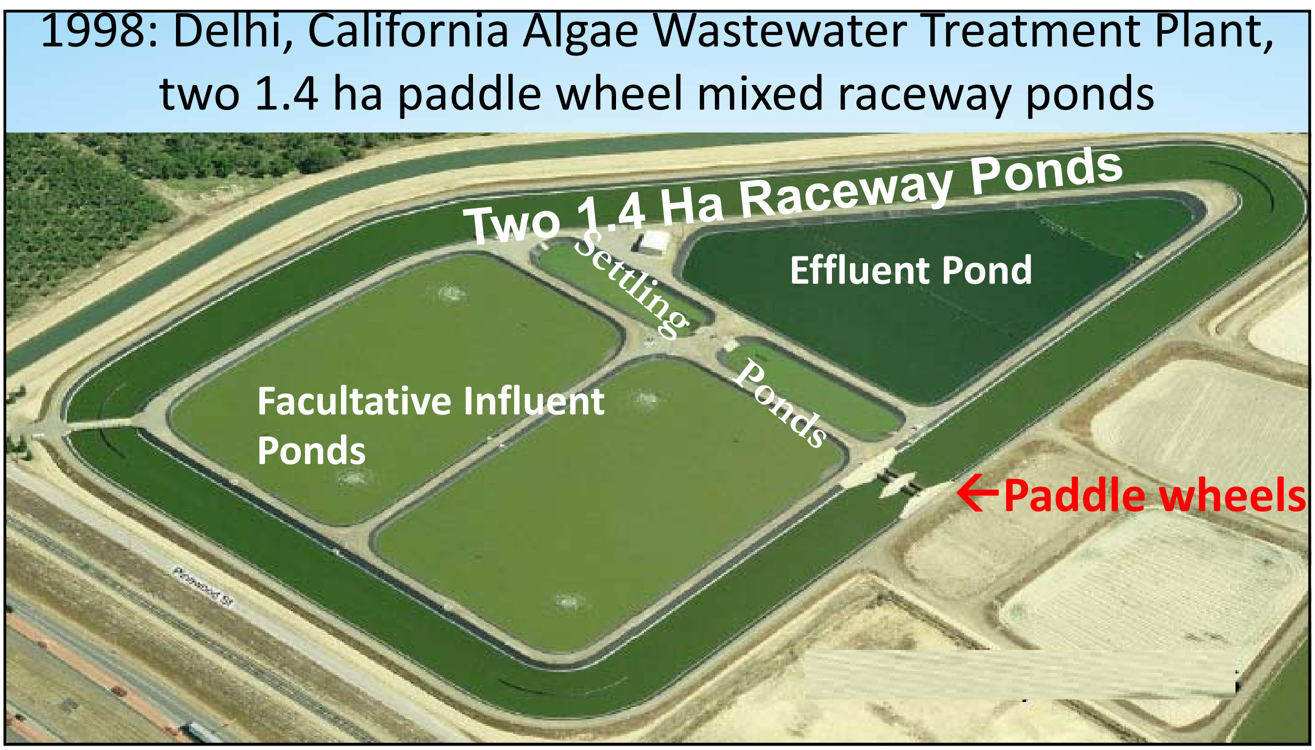

Schematic of oxidation pond process
Sun
CO_2
after Oswald and Gootas, 1953, U. Calif. Berkeley
Reclaimed Water
Algae
C:N:P
CO_2
N
P
O_2
Waste Water
Organics
Bacteria
C:N:P
CO_2
N
P
Biomass
Prof. Oswald


Shallow, raceway mixed ponds ("High Rate Ponds") developed by Prof. Oswald et al., Univ. Calif. Berkeley in 1950s
Concord, California, ~1960


Wastewater Treatment Plant, St. Helena, California, 1965
Design incorporating oxidation ponds with high rate ponds
Chlorination
Plant is still operates!
Maturation
Ponds
Settling
Pond
Facultative
High
Rate
Pond
Influent Ponds
Inflow
raw sewage


Municipal Wastes C,N,P
Make-up water
Solar Energy
PHYSICAL SEPARATION
Settling
Raceway Pond Algae Culture
CO2
WATER
CULTURE
COARSE MATERIALS
WASTE GAS
SOLIDS SIZE SEPARATION
COAGULANT FEED
WATER RECARBONATION
Recycle Digester Effluent
PRIMARY SLUDGE
CO2
Harvesting
EXCESS WATER
WATER
Anaerobic Digestion CH4+ CO2
GAS
Algae Biomass
CO2
DRY ALGAE STORAGE
GAS STORAGE
CH4
Power Plant
DEWATERING
POWER
Electricity
First TEA for Algae Biofuels Integrated with Wastewater Treatment - Oswald & Golueke, 1960
Prof. Bill Oswald


U.C. Berkeley, Richmond Field Station,
Sanitary Engineering Research Lab
First use of paddle-wheels for
mixing wastewater treatment raceway
ponds (Two x 0.1 ha) receiving settled sewage.
Demonstrated algae settling (“bioflocculation”), for
harvesting, CO2 fertilization for nutrient removal and


1998: Delhi, California Algae Wastewater Treatment Plant,
two 1.4 ha paddle wheel mixed raceway ponds
Two 1.4 Ha Raceway Ponds
Settling
Ponds
Effluent Pond
Facultative Influent
Ponds
←Paddle wheels


High Rate Ponds with Paddle Wheels, Hilmar, California
Facultative
Influent Ponds
Raceway Ponds


Will we ever invent anything this useful again?
The growing debate about dwindling innovation
The Economist
January 12-18 2013

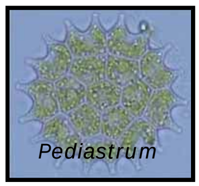
Algae Biotechnology for Wastewater Treatment

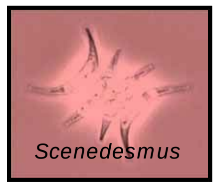
Ron Sims, Utah State University

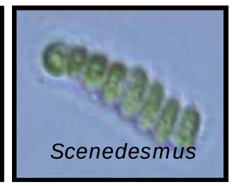
Microalgae-based approaches

Algae-based tertiary wastewater treatment

Suspended







Algae Farming for Nutrient Removal and Bioproduct Production

- Nutrient removal – phosphorus and nitrogen through production of algae biomass for wastewater bioremediation
- Cultivate and Harvest algae biomass and transform to biofuels and bioproducts

Microalgae for Wastewater Treatment

- Nutrients from nitrogen and phosphorus
- Capture carbon as CO_2
- Energy from sunlight
- Produce oxygen as a waste product
- Typically mixed culture (as occurs in nature)
- Tolerate wide range in environments (temperature, salinity, water quality)

Types of Microalgae in Wastewater

- Photosynthetic – use CO_2 and sunlight
  (1) Cyanobacteria (blue green algae) are bacteria
    - Pigment: phycocyanin (blue-green color)
    - Toxins: microcystins (algae blooms in lakes)

  (2) Algae are eucaryotes (green, brown, red)
- Heterotrophic – use organic chemicals for carbon and energy

Ron Sims – Utah State University
Sustainable Waste to Bioproducts Engineering Center <swbec.usu.edu>
Algae Biotechnology for Wastewater Treatment:

Microalgae Wastewater Processes and Stoichiometry

- Suspended growth - Raceways
- Attached growth – Biofilms
- Stoichiometry:
- $106\ CO_2 + 16\ NO_3{}_{-} + HPO_4{}_{-2} + 18H_{+} \rightarrow$

$C_{106}H_{263}O_{110}N_{16}P_1 + 138\ O_2$

(Microalgae)

Note the P:N ratio of 1:16

Raceway Configuration

- Paddles keep microalgae suspended for sunlight
- Shallow depth for light penetration

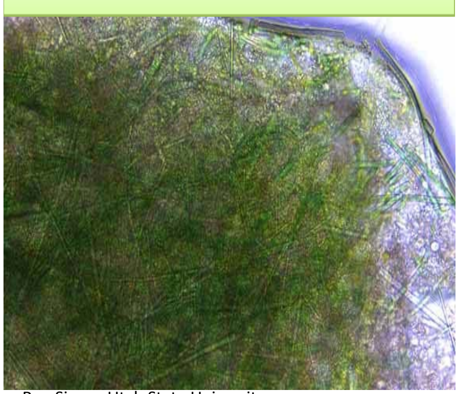
Biofilm Configuration
Rotating Algae Biofilm Reactor (RABR)

Substratum rotates alternatively through wastewater(nutrients) and atmosphere (sunlight, CO_2)

Testing Applications
- Colored water
- Turbid water
- Deeper water
- "Drop In" retrofit
- "Add On" retrofit

Biofilm Microalgae – Cyanobacteria

Great Salt Lake | **Logan Lagoons**



Wastewaters Applicable

- Produced Water from Oil & Gas Extraction
- Petroleum Refining wastewater
- Dairy farm lagoon wastewater
- Municipal wastewater
  - Logan City Lagoons System (dilute)
  - Central Valley Water Reclamation Facility (strong)
- Swine wastewater

Bioproducts from Wastewater Microalgae

- Biogas (methane and CO_2)
- Biocrude
- Biodiesel
- Bioplastics
- Acetone, Butanol, Ethanol
- Feed (protein for aquaculture and agriculture)
- Phycocyanin products (pigments, antioxidants)

Microalgae Cultivation in Produced Water for Conversion into Bio-crude (Ben Peterson & Jay Barlow)

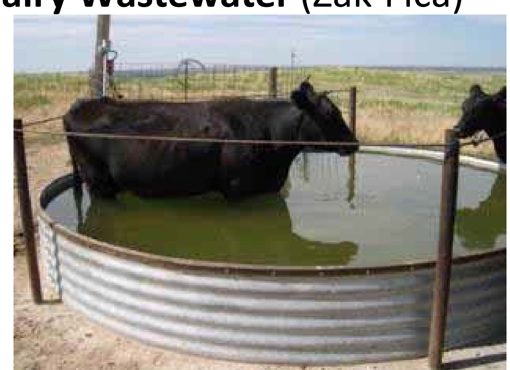
- Produced water contains high levels of salts and hydrocarbons, and variable concentrations of nitrogen and phosphorus.
- Two strains of microalgae were grown in mixed culture using a Rotating Algal Biofilm Reactor (RABR), which was rotated in produced water from the Uinta Basin in Utah.

A Rotating Algal Biofilm Reactor (RABR) was used as a platform to grow microalgae on produced water

Ron Sims – Utah State University
Sustainable Waste to Bioproducts Engineering Center <swbec.usu.edu>

RABR Treatment of Dairy Wastewater (Zak Fica)

- Turbid waste streams
- Seasonal temperature
- Caine Dairy Farm

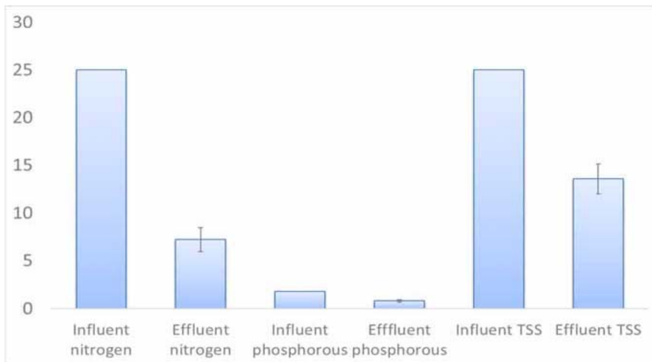


http://goldenplains.colostate.edu/agri/agri_docs/2011_stock_tank_algae_control.shtml

Cyanobacterial Dominated Biofilm Cultivation in Wastewater derived from Petroleum Refining (Alan Hodges)

- Treatment and methane production

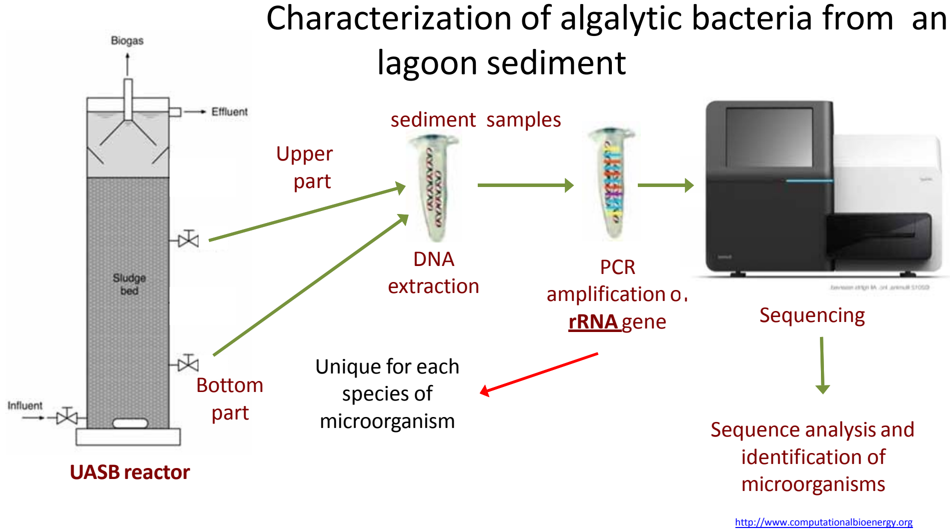
Concentration (mg/L)



Anaerobic Digestion of Microalgae Biomass in Upflow Anaerobic Sludge Blanket (UASB) Reactors

(Anna Doloman)

Characterization of algalytic bacteria from anaerobic lagoon sediment



Biomethane from Algae

- Two 1,000 gallon Anaerobic Digesters
- Mix algae with food wastes and municipal wastewater biosolids to generate more methane for CHP

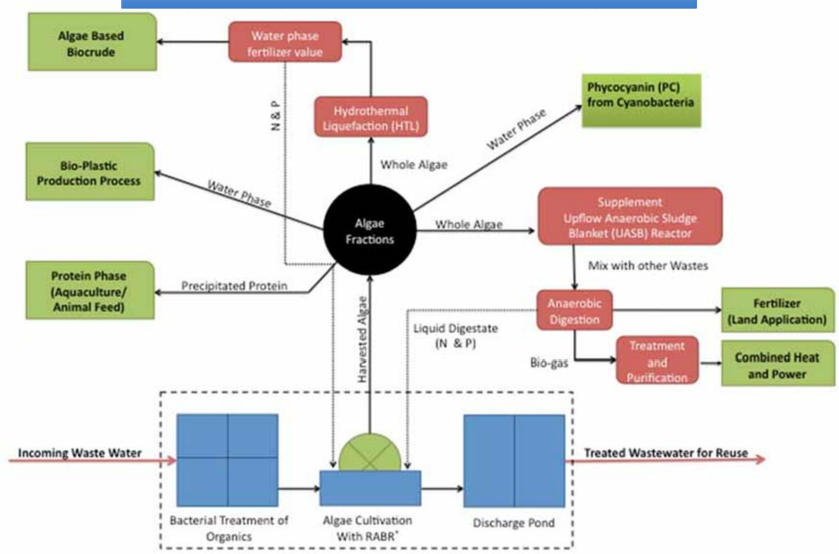
Pretreatment & Bioproduct Production

100 Liter reactors at Algae Processing & Products (APP) facility for

Pretreatment

Fermenter Bioplastics Materials

Wastewater Microalgae-Based Biorefinery



Wastewater Treatment with Rotating Algae Biofilm Reactor

Ron Sims – Utah State University
Sustainable Waste to Bioproducts Engineering Center <swbec.usu.edu>

Algae Biotechnology for Wastewater Treatment:
ABO/ WEF Workshop 10/23/2016

The RNEW® Process: Recycled Water, Fertilizer, and Power from Wastewater

Tryg Lundquist, Ph.D., P.E.[1,2], *Presenter*
R. Spierling[1], L. Parker[1], C. Pittner[1], L. Medina, T. Steffen, J. Alvarez, N. Adler[2], J. Benemann[2]

CAL POLY SAN LUIS OBISPO

[1]*California Polytechnic State University San Luis Obispo, California*

μBIO MICROBIO ENGINEERING

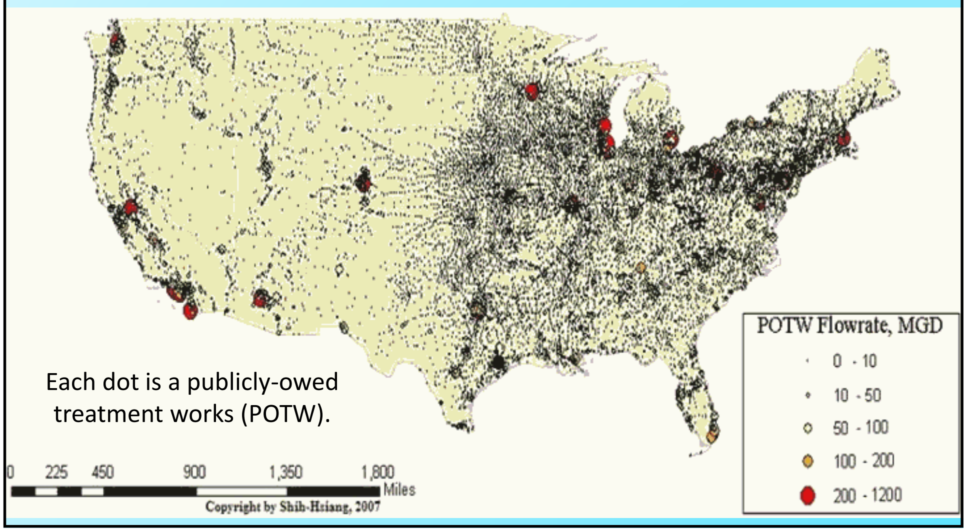
[2]*MicroBio Engineering Inc. San Luis Obispo, California*

ABO-WEF Water Forum | October 23, 2016 | Glendale

Outline

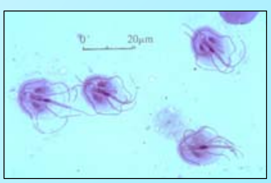
- WW scene, recycle, high costs energy
- Biofuels scene, need for feedstock graph, gal/ac-yr targets show later
- Oswald raceway ponds since 1967 for 2o; professor not much happened., then 1998 Delhi.
- Nutri limits; add CO2, seasonal geogr limits
- Overcome w mech supplement
- Biomass disposition, hi prod targets, biofuels, dig, HTL
- OUC future, small communities now, then large

The US wastewater treatment industry deals with 33,000 million gallons per day of sewage (publicly-owned only).



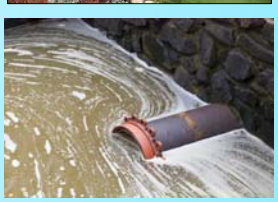
Each dot is a publicly-owed treatment works (POTW).

The wastewater treatment industry focuses on these problems:



Pathogens, which might reach drinking water supplies

Nutrients causing excess algae growth



Organic matter causing low dissolved oxygen

Solving the problems affordably means recognizing the value of wastewater:

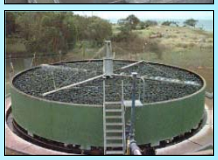
Recycle water

Recover nutrients

Produce biofuels

Typical activated sludge treatment plant

Treatment is performed using three major technologies

	Technology	Number of Facilities	Total Flow MGD*	Energy Intensity MWh/MG
	Activated Sludge	6,800	25,000	1.3 - 2.5
	Biofilm Systems	2,500	6,000	0.8 -1.8
	Traditional Ponds	5,100	2,000	0.4 – 1.4

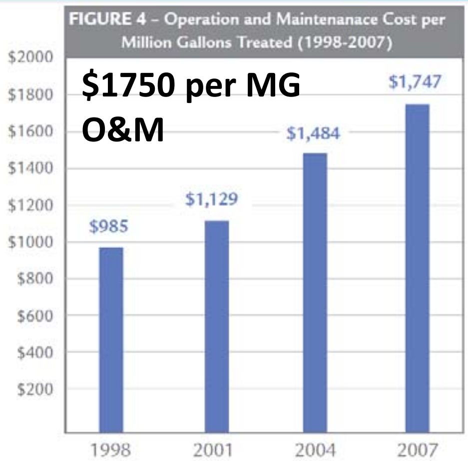
* MGD = million gallons per day (~10,000 persons)

Providing oxygen to bacteria is expensive and energy intensive.

Activated Sludge Process per 10,000 population.
1.3 – 2.5 MWh per day
$5 - $12 million capital cost and higher

Wastewater treatment costs: high & rising

Machinery and complexity require more personnel, which is the highest cost factor.



Expenditures	2007
Personnel	45.1%
Private sector services	16.6%
Electric power	10.3%
Service provided by other departments	7.1%
Supplies and materials	6.4%
Chemicals	4.7%
Other utilities	3.5%
Utility management	1.0%
Other	4.9%
Total	100%

45% personnel

10% power

TABLE 2 – Operation and maintenance cost category breakdown (2007)

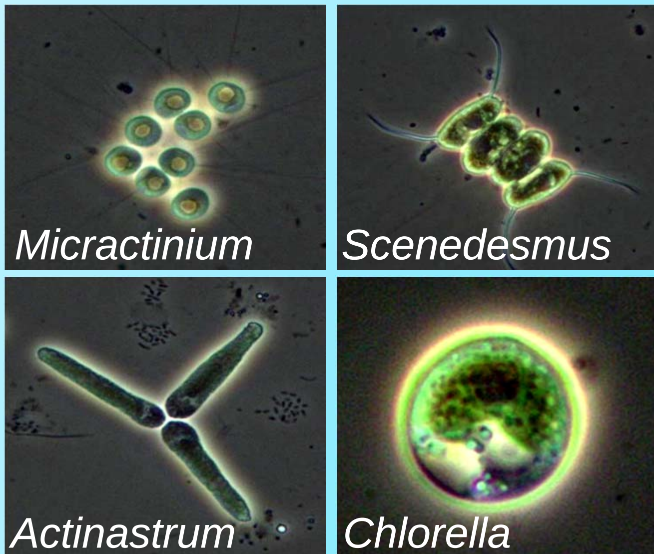
2008 NACWA Financial Survey Summary

WWT facility replacement & rehab need is huge.

5-year need is $3-5 billion*
Am. Society of Civil Engineers rates US infrastructure:

*** National Association of Clean Water Agencies, 2011**

Green algae typically found in wastewater pond polycultures.



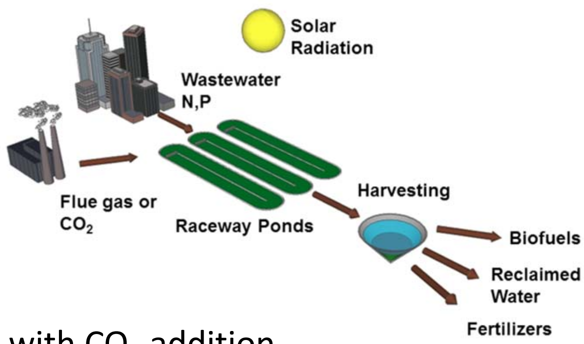
Add CO_2 to balance C:N:P ratio and achieve completed nutrient assimilation.

CO_2 Enhanced
600 mg/L Algae
<1 mg/L NH_4^+-N
<0.3 mg/L PO_4^{3-}-P

Air Sparged
130 mg/L Algae
25 mg/L NH_4^+-N
3 mg/L PO_4^{3-}-P

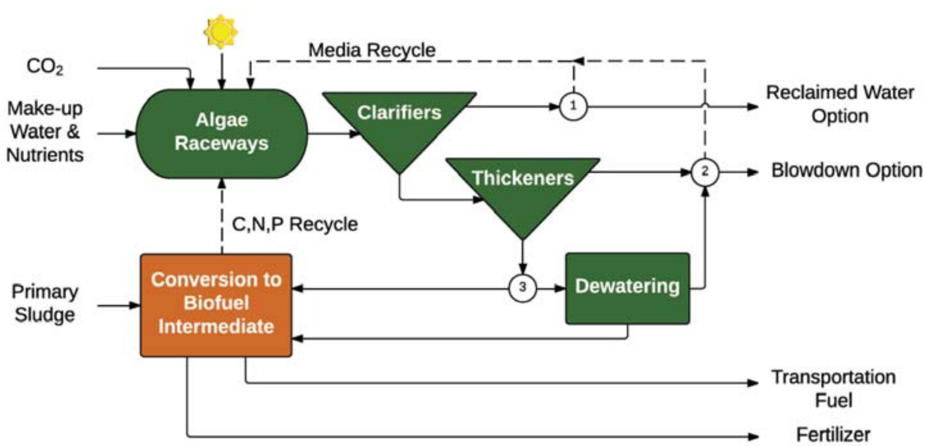
RNEW® Technology

Recycle
Nutrients
Energy
Water



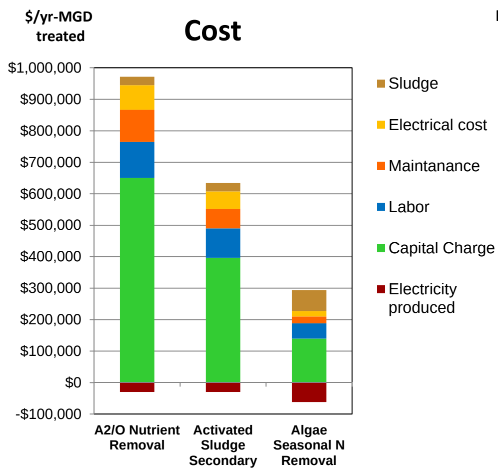
- Nutrient removal with CO_2 addition
- Low energy intensity vs. conventional treatment
- Biofuel via digestion or hydrothermal liquefaction
- Harvesting by bioflocculation
- Low cost for treatment; biofuel still pricey

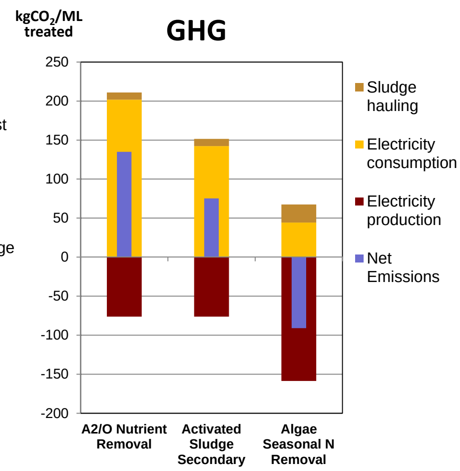
Wastewater reclamation for irrigation or for biofuel productions.



Algae wastewater treatment is low cost and energy efficient. But algae nutrient removal is seasonal.

Save 50% total cost. Save 67% electricity (w/out biogas)





- Consulting Engineers
- Facilities Designs
- Algae Equipment
- R&D Consulting
- Business Consulting
- Techno-Economic Analyses
- Life Cycle Assessments

μBIO
MicroBio Engineering

Applications

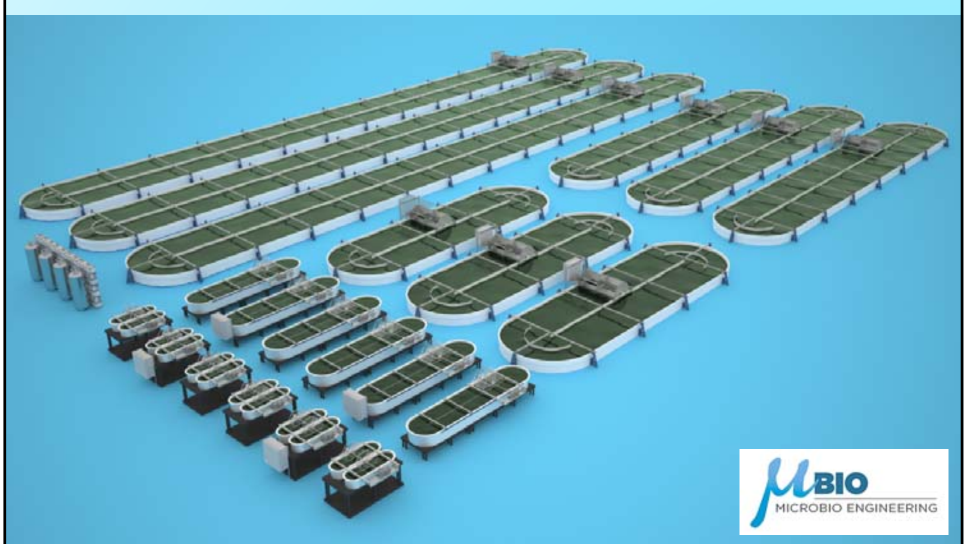
Wastewater Reclamation

Nutraceuticals

Aquafeeds

Cal Poly State University and MicroBio Engineering built and operate the Algae Field Station in SLO.

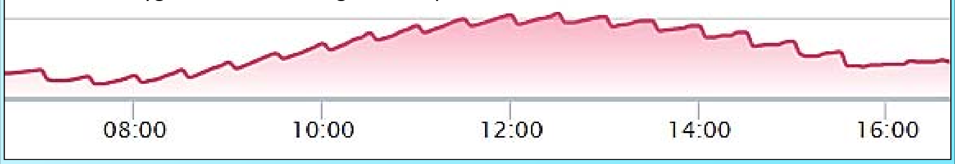
Scale-up cultures with a raceway cascade. Complete pilot facility designs.

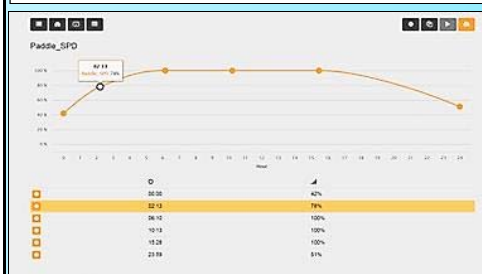


Remote control and data logging capabilities

Feed rates, CO_2 dosing, paddle speeds, etc. can be changed on timer basis or remotely.

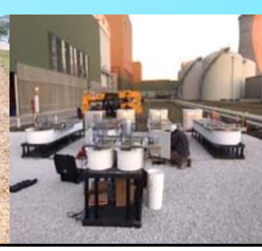
Dissolved oxygen conc. indicating influent pulses.

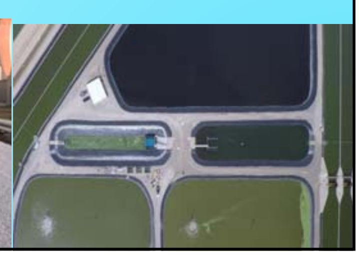




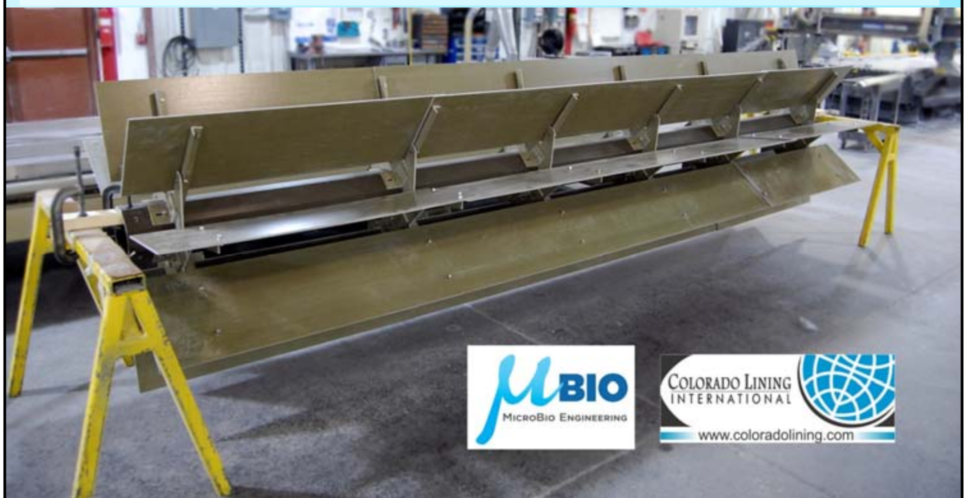
Current MicroBio Engineering Inc. U.S. DOE R&D Projects Algae Biofuels and Wastewater Treatment

- 2011 -2014 Cal Energy Com. Algae WWT Biodiesel (w. Cal Poly)
- 2015 -2017 Algae Culture Air CO_2 (w. PNNL & Cal Poly)
- 2013 -2016 Water & Nutrient Recycling (w. Cal Poly)
- 2015 - 2017 Microalgae CO_2 Use at Coal-Fired Power Plant (FE - NETL)
- 2015 -2018 Algae Harvesting by Bioflocculation (w. Cal Poly)
- 2016 Culture of Filamentous Algae on Wastewater (SBIR, sub CP)
- 2014 - 2020 Algae Biomass Yield (w. CP, Heliae, PNNL, SNL)





Fiberglass paddle wheels are available.



Existing full-scale raceway systems are retrofit candidates: add CO_2 for nutrient removal & biofuels.

Delhi, Calif. plant designed for secondary treatment, but now total nitrogen removal will be required.

Two 14,000-m^2 (3.4-acre) raceways

- **The two 3.5-acre raceways treat the WW of 10,000 people.**
- **Flow is driven by two 20-ft long paddle wheels that turn slowly.**

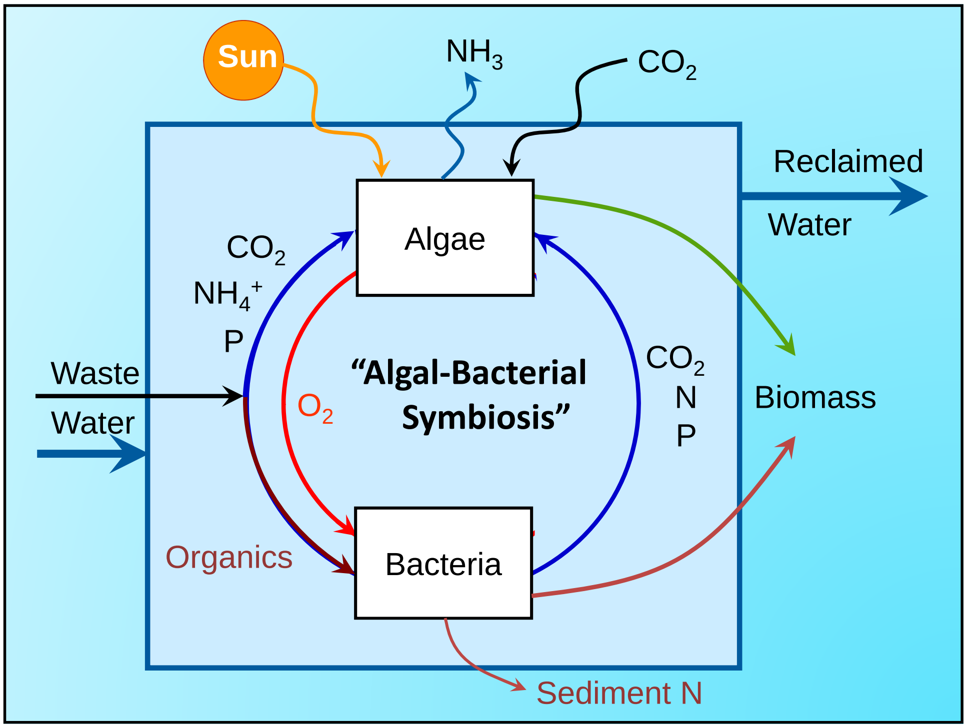
At full-scale, algae are coagulated, settled, and solar dried.

~100,000 gallons of 3% solids algae in decanted settling basin

Solar dried algae

Concrete drying pad

A covered lagoon digester for long residence time digestion of algae and other wastes.



Add CO_2 to balance C:N:P ratio and achieve completed nutrient assimilation.

CO_2 Enhanced
600 mg/L Algae
<1 mg/L NH_4^+-N
<0.3 mg/L PO_4^{3-}-P

Air Sparged
130 mg/L Algae
25 mg/L NH_4^+-N
3 mg/L PO_4^{3-}-P

Lundquist et al., Cal Poly

Heterotrophic growth represents a portion of the productivity in ponds operated with primary wastewater.

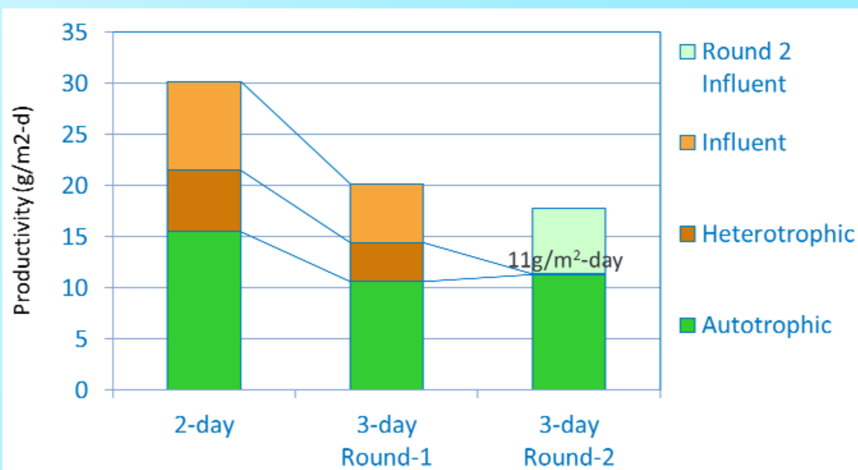
Autotrophic VSS = $(VSS_{Pond}-VSS_{Inf}) - (Y_{obs} \times BOD_{consumed})$

$$Y_{obs} = \frac{Y}{1+(k_d)SRT} + \frac{(f_d)(k_d)(Y)SRT}{1+(k_d)SRT}$$

Yield considering cell decay — Non-biodegradable cell residual

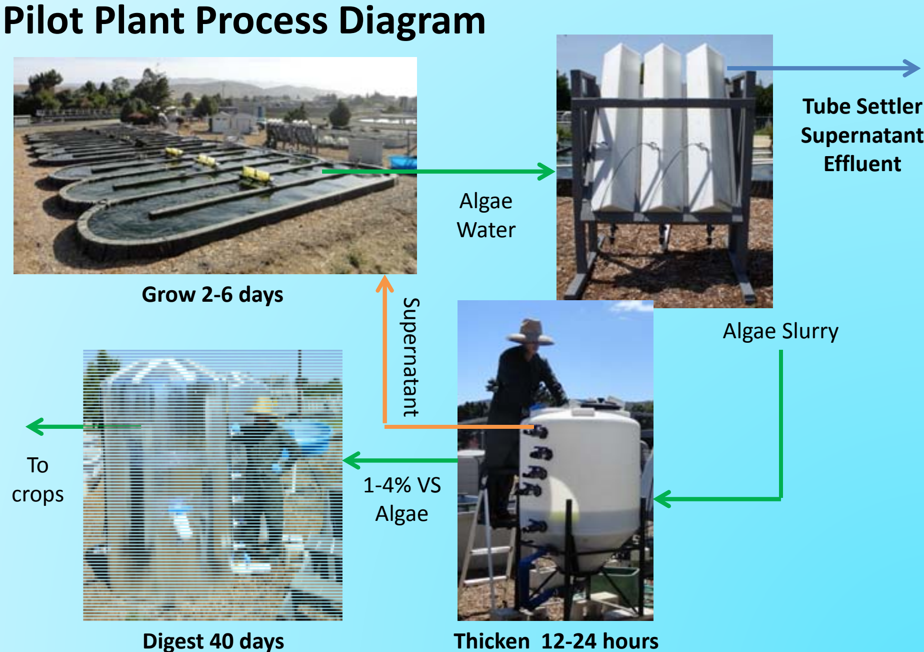
Y_{obs} = observed heterotrophic yield (g VSS/g $scBOD_5$)
Y = theoretical biomass yield (g VSS/g $scBOD_5$)
k_d = endogenous decay coefficient (g VSS/g VSS-day)
SRT = solids residence time (day)
f_d= fraction degraded biomass remaining as cell debris (g VSS/g VSS)

Heterotrophic growth can be algal or bacterial at ~50% of gross productivity at 2-day residence time.

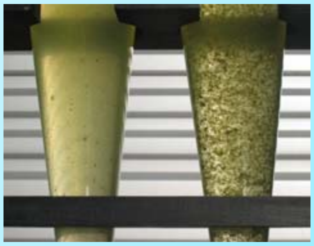


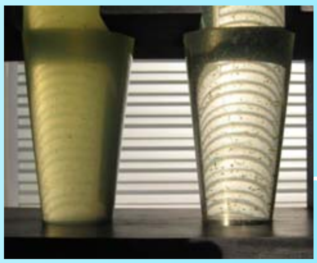
CO_2 addition to integrate wastewater treatment & biofuels at San Luis Obispo, Calif.

Pilot Plant Process Diagram



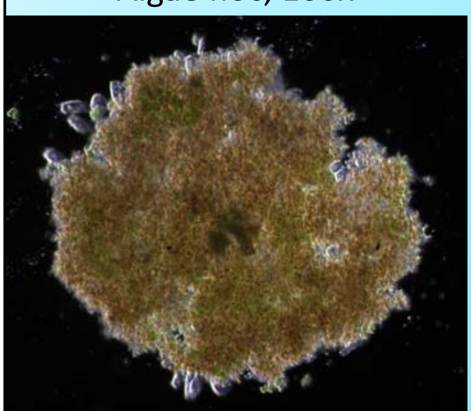
Bioflocculation and settling are low cost harvesting. Chemical coagulants for backup only.





Bioflocculation and settling process is similar to activated sludge.

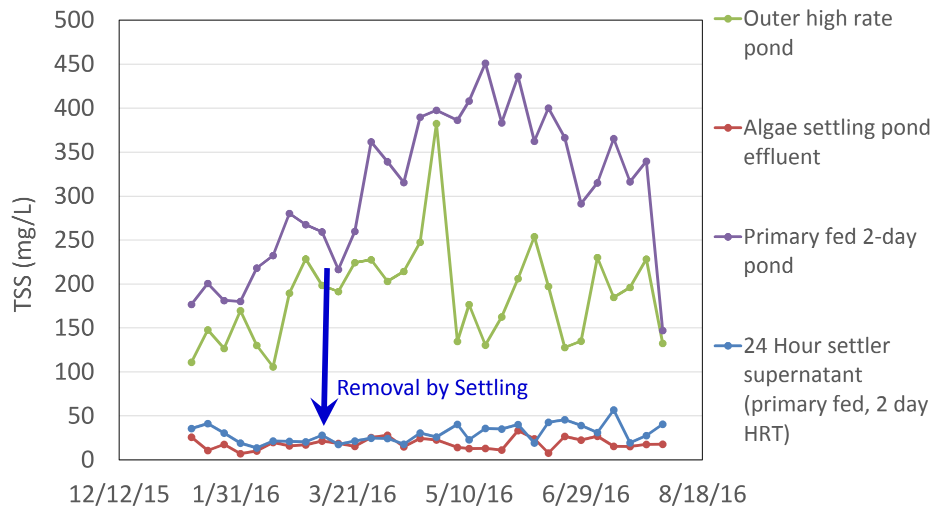
Algae floc, 100x



Algae floc, 1000x

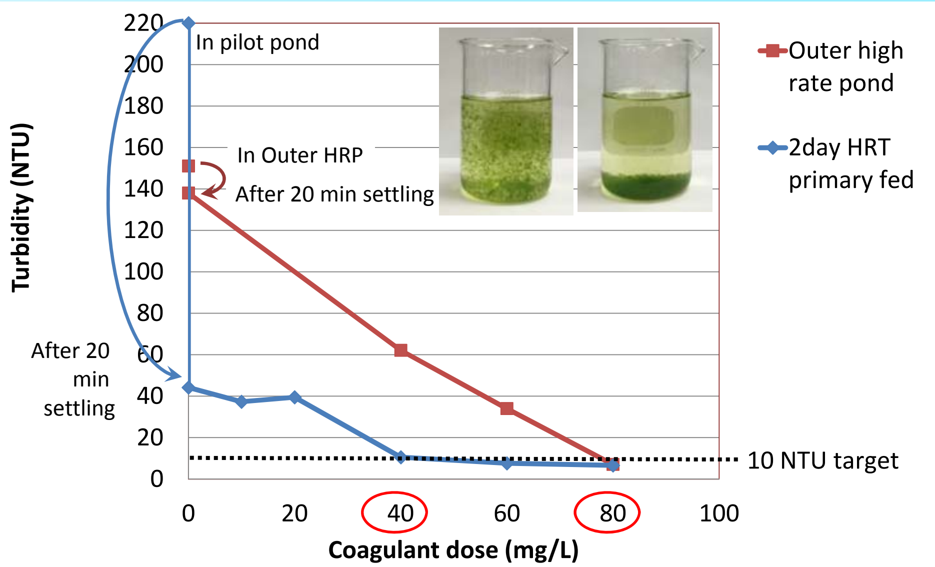
Bioflocculation alone is nearly as effective as chemical coagulation in promoting algae settling.

24-hr Imhoff cone settling used to assess bioflocculation.

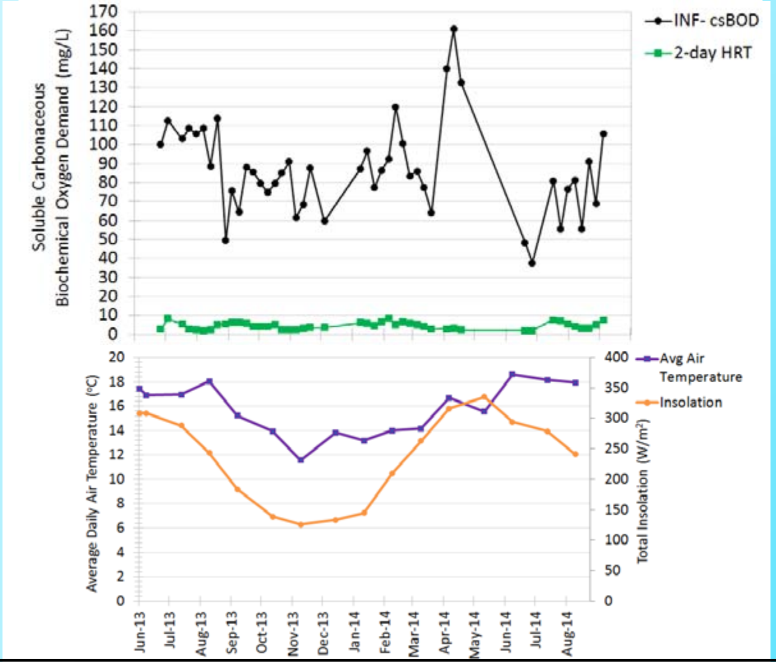


Bioflocculation lowers needed coagulant dose.

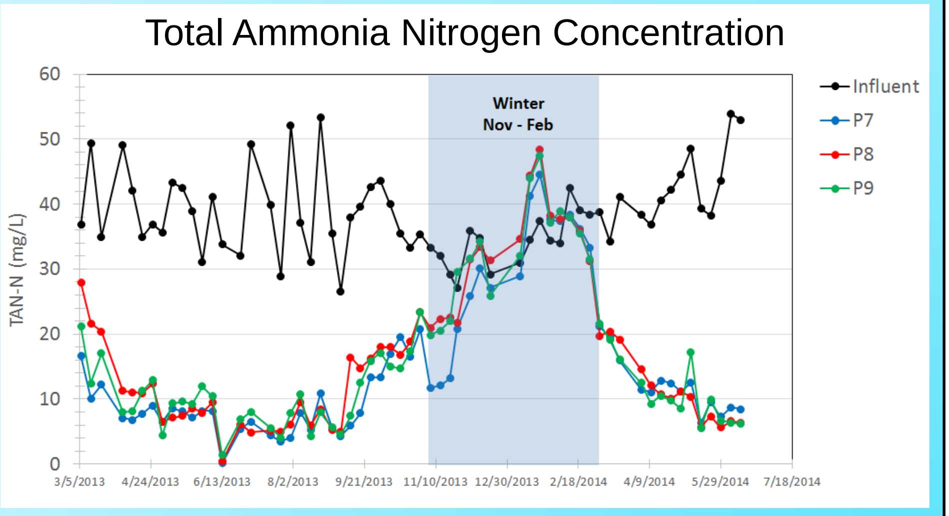
Colloidal algae pond compared to bioflocculated pilot.



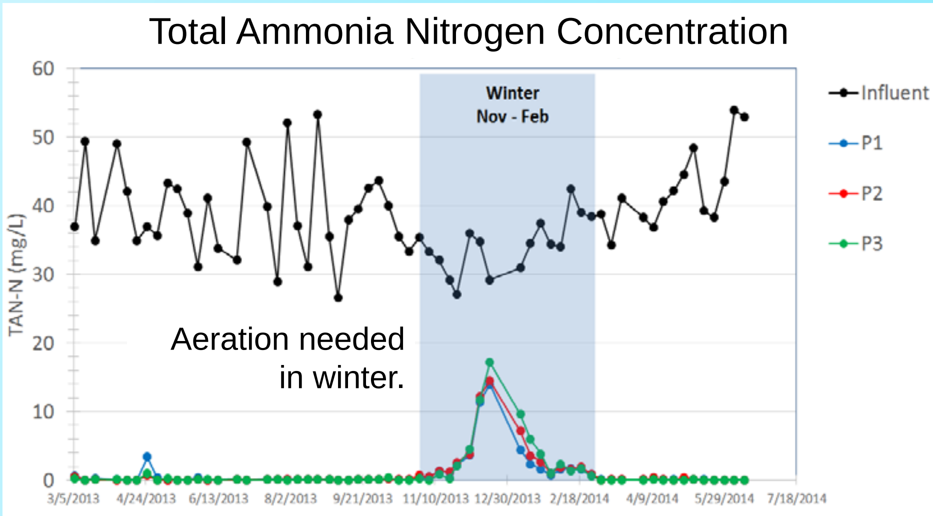
cBOD removal is good all year (in San Luis Obispo).



In secondary treatment mode (2 day retention time), NH_3 removed in summer. High biomass.

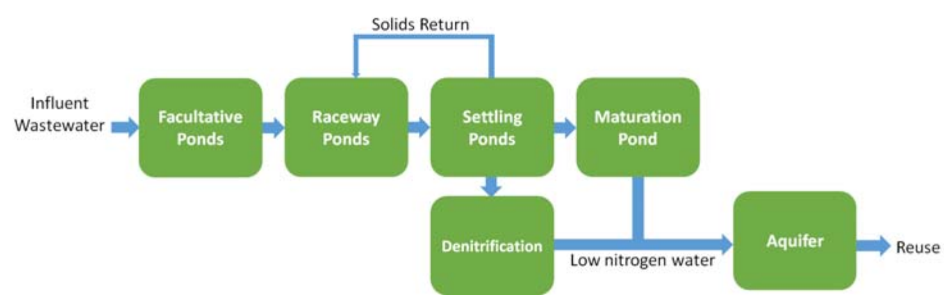


In nutrient removal mode (6-d HRT), TAN removal nearly complete 8 mo per year. Nitrification-denitrification polish needed in winter.



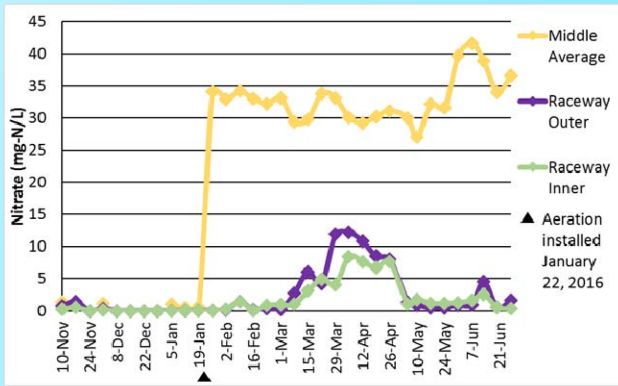
Cool winters require nitrification-denitrification with relatively minor additional equipment.

Night aeration of raceways and denitrification basins.



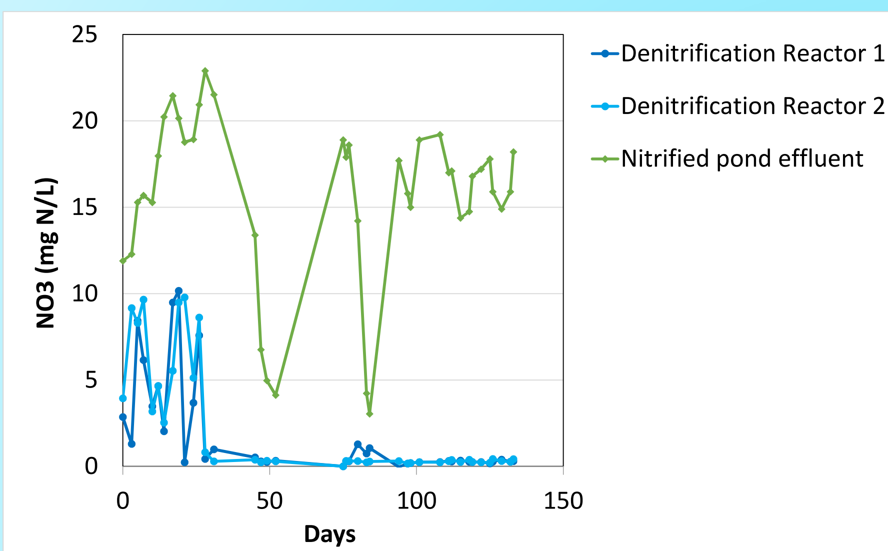
Night aeration converted most ammonia to nitrate, which can then be removed by denitrification.

Aerators operated 6 pm to 6 am in Middle pilot raceways.



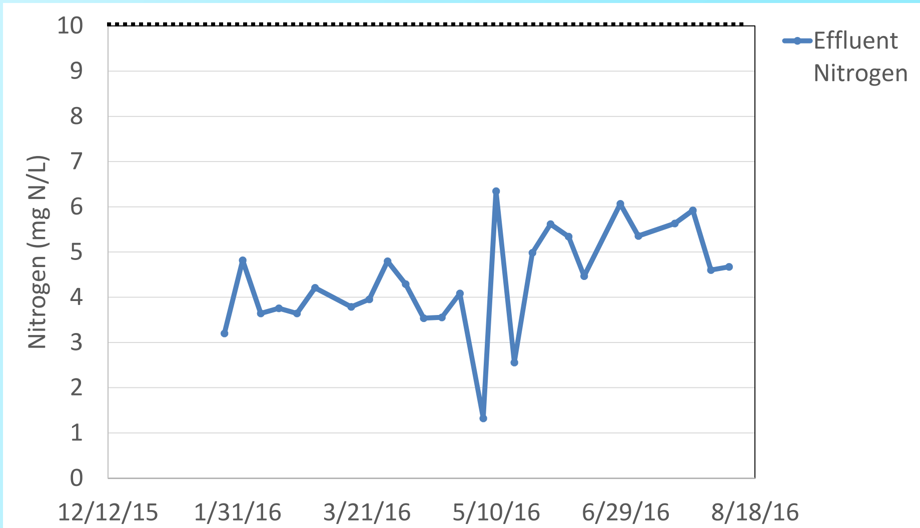
Denitrification can remove 99% of nitrate and nitrite, completing removal of total nitrogen.

Data from pilot systems at San Luis Obispo.



Meeting 10 mg/L total N limit seems possible with night aeration, denitrification & good TSS removal.

Full duration of winter has not yet been tested.



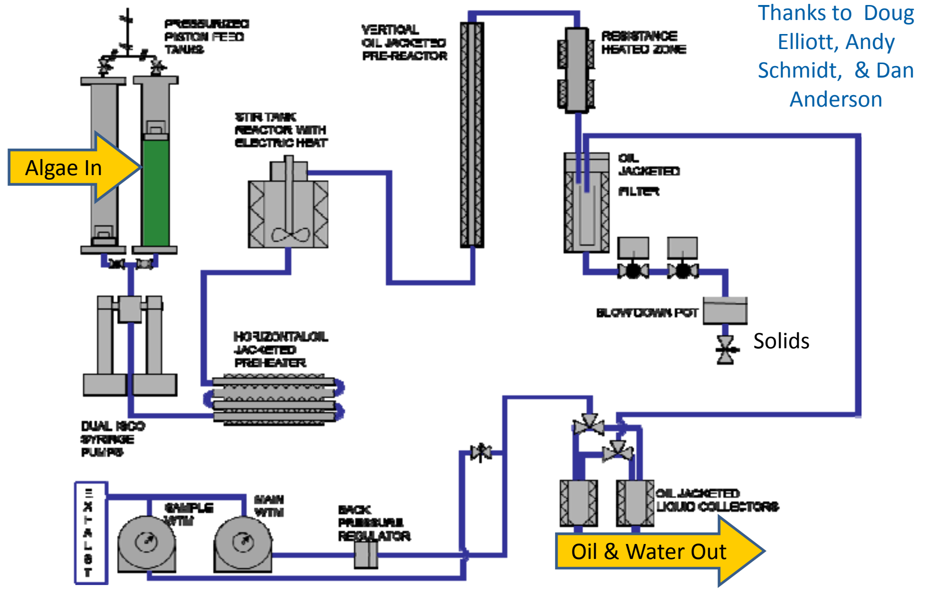
Biofuels is one option for using the biomass.

~100,000 gallons of 3% solids algae in decanted settling basin

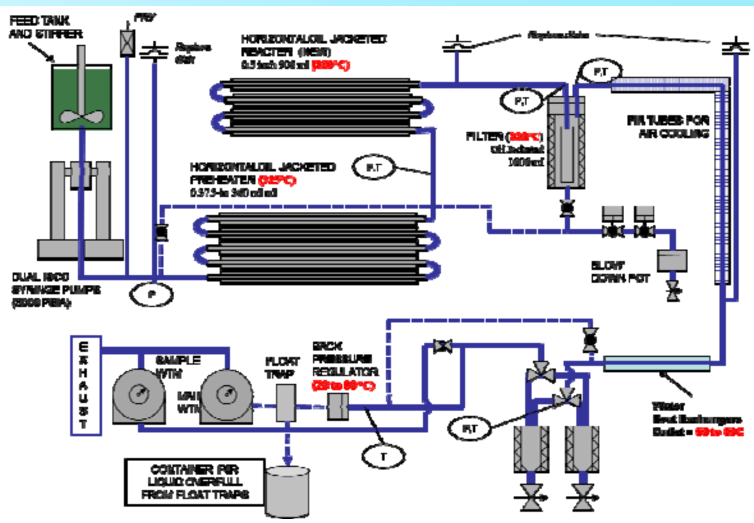
Solar dried algae

"Pressure cooking" (hydrothermal liquefaction) converts algae to biocrude oil.

Thanks to Doug Elliott, Andy Schmidt, & Dan Anderson



PNNL Continuous Bench Scale HTL Systems



Plug flow configuration being use for Algae Testing

Biocrude yield is most sensitive to solids content of the feed. 20% is ideal.

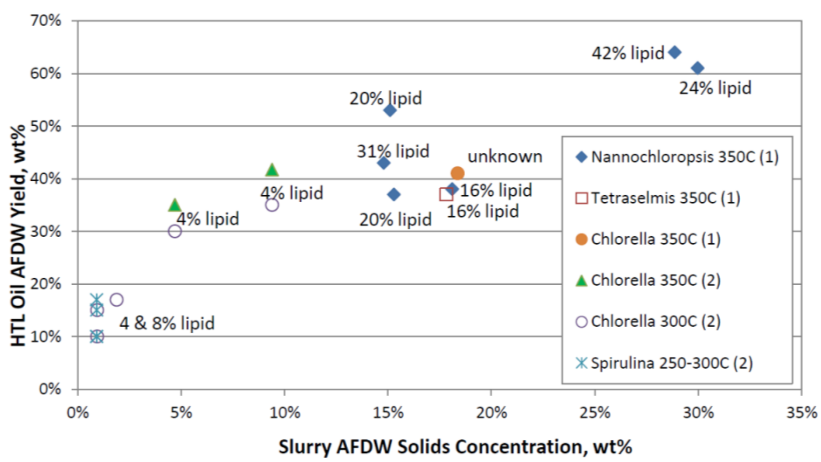
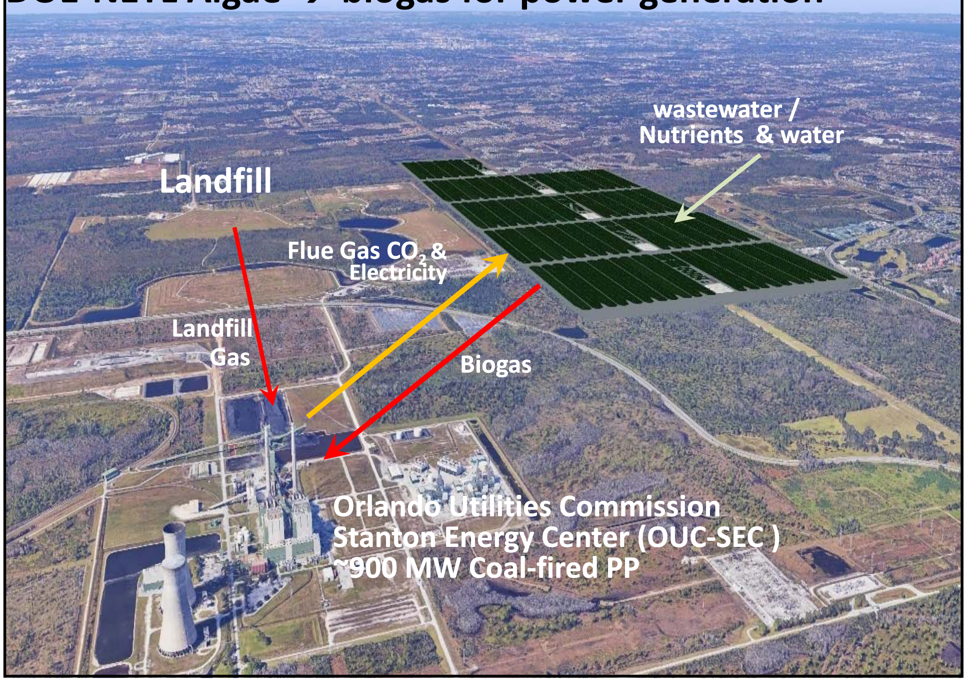
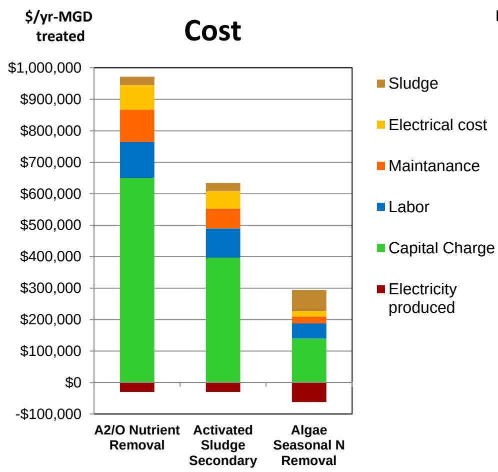


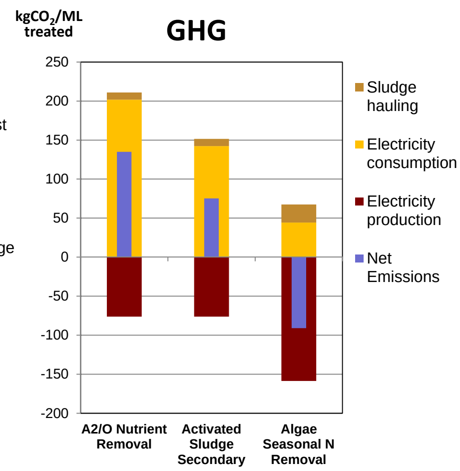
Figure 5 Continuous flow reactor parameter effects on HTL oil yield
(1) PNNL, oil recovery by gravity separation
(2) Jazwari et al. [2013], oil recovery by solvent extraction

DOE-NETL Algae → biogas for power generation



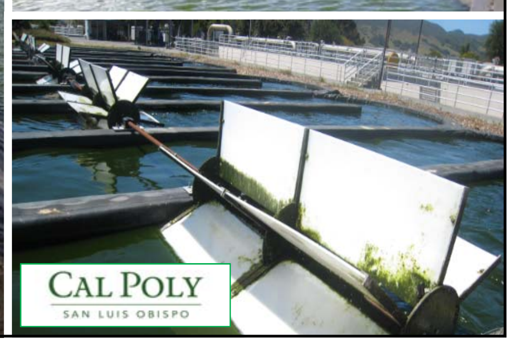
Conclusion on algae wastewater treatment





Thank you for your attention

TrygLundquist@MicroBioEngineering.com



WASTEWATER TREATMENT AND ENERGY RECOVERY WITH CULTIVATION OF MICROALGAE

Ignacio de Godos, Zouhayr Arbib, Enrique Lara and Frank Rogalla

FCC Aqualia

EU Algae Cluster

Three large scale demonstration projects started in 2011 for biofuel production from algae with ambitious, but achievable targets:

- ❑ Industrial scale of up to **10 ha**
- ❑ Annual productivity: **90 Tons / ha year**

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www.All-gas.eu :

Partners and main objectives

1

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All-gas project: From Wastewater to Bio-energy

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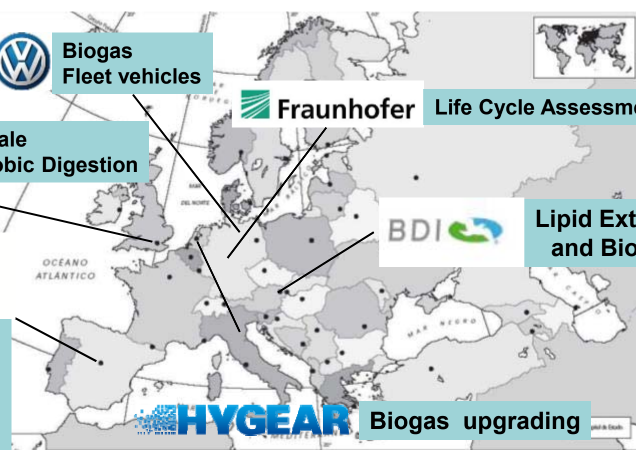
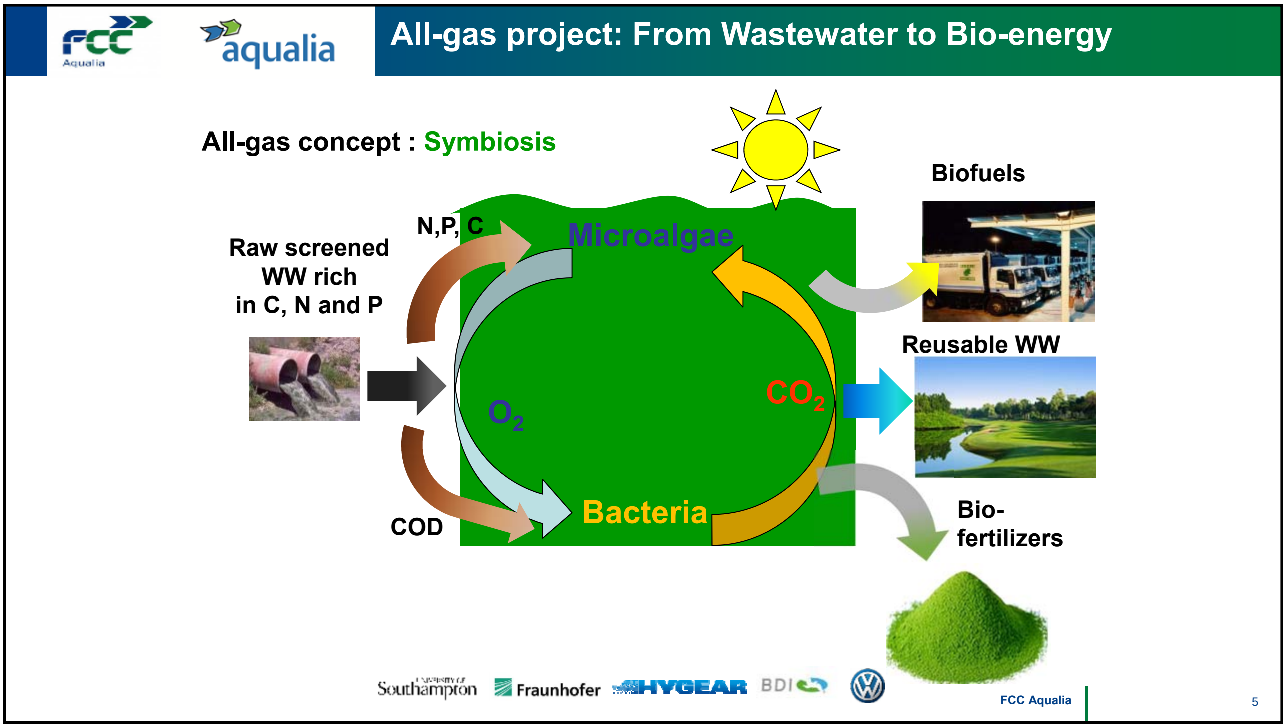
Partners

All-gas

SEVENTH FRAMEWORK PROGRAMME




All-gas project: From Wastewater to Bio-energy
All-gas concept : Symbiosis
Raw screened WW rich in C, N and P
N,P, C
Microalgae
O_2
CO_2
Bacteria
COD
Biofuels
Reusable WW
Bio-fertilizers
Fraunhofer
HYGEAR
BDI
FCC Aqualia
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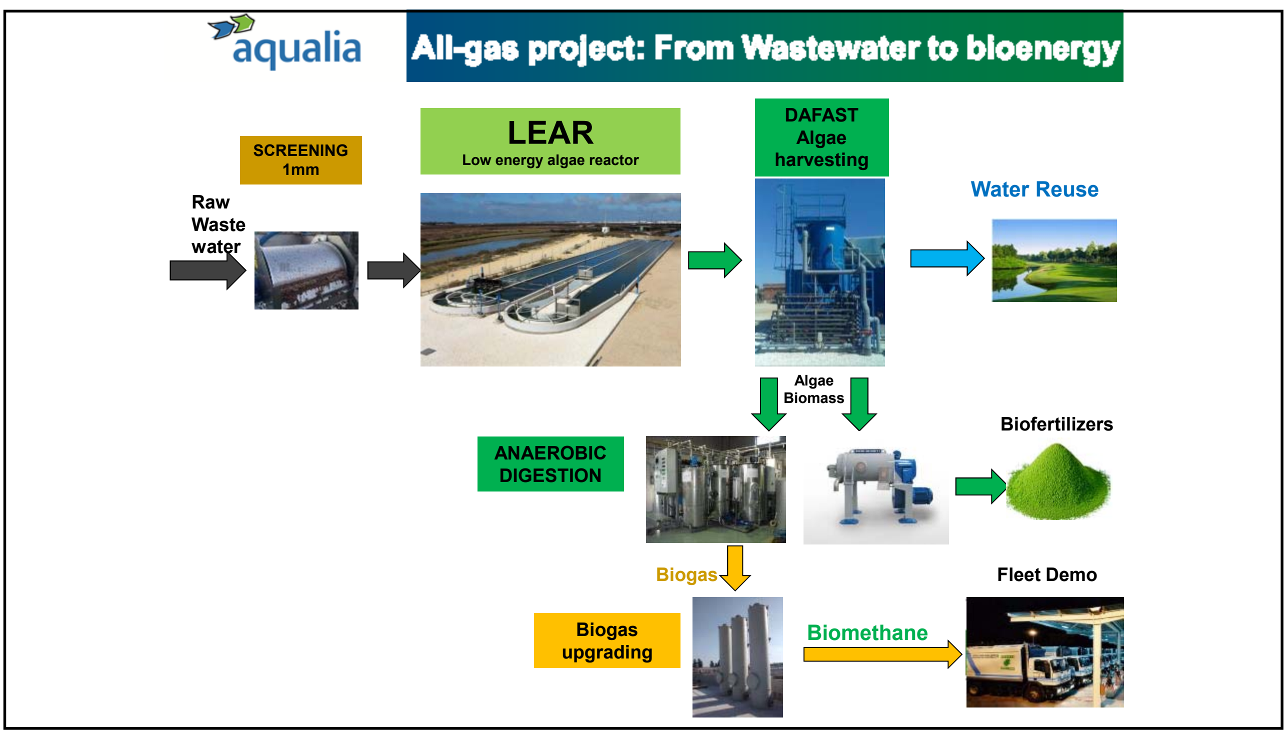
All-gas project: From Wastewater to bioenergy
SCREENING 1mm
Raw Waste water
LEAR
Low energy algae reactor
DAFAST Algae harvesting
Water Reuse
Algae Biomass
Biofertilizers
ANAEROBIC DIGESTION
Biogas
Fleet Demo
Biogas upgrading
Biomethane

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2

Installations:

From pilot plant to demo scale

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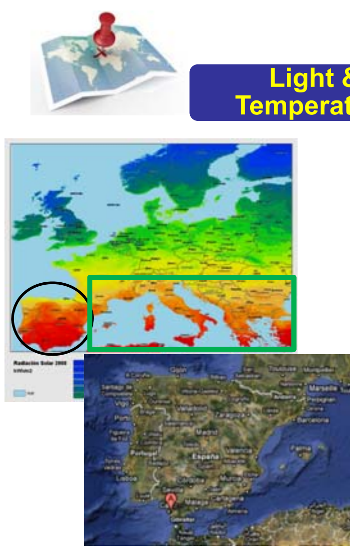
All-gas FROM WASTEWATER TO BIOENERGY

Light & Temperature | Water | Space



No arable Land: unused salt ponds

No Freshwater

El Torno WWTP 10 000 m3/d

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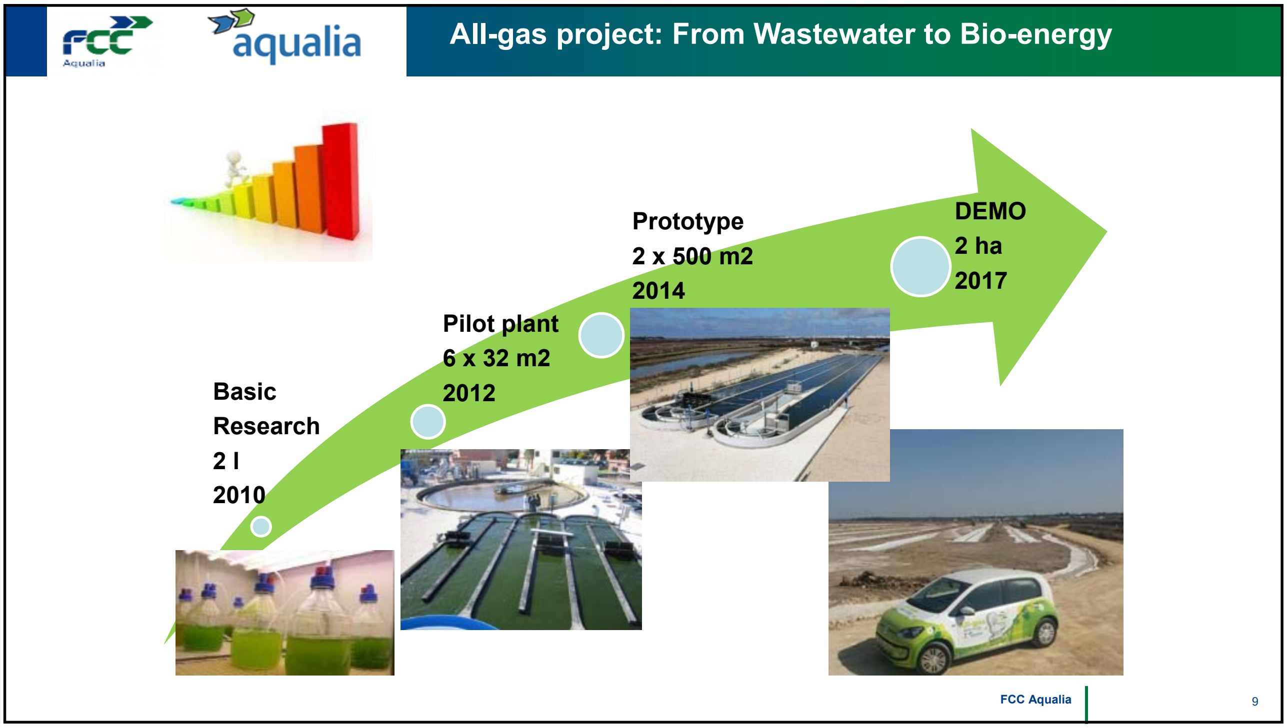
aqualia
All-gas project: From Wastewater to Bio-energy
Basic
Research
2 l
2010
Pilot plant
6 x 32 m2
2012
Prototype
2 x 500 m2
2014
DEMO
2 ha
2017
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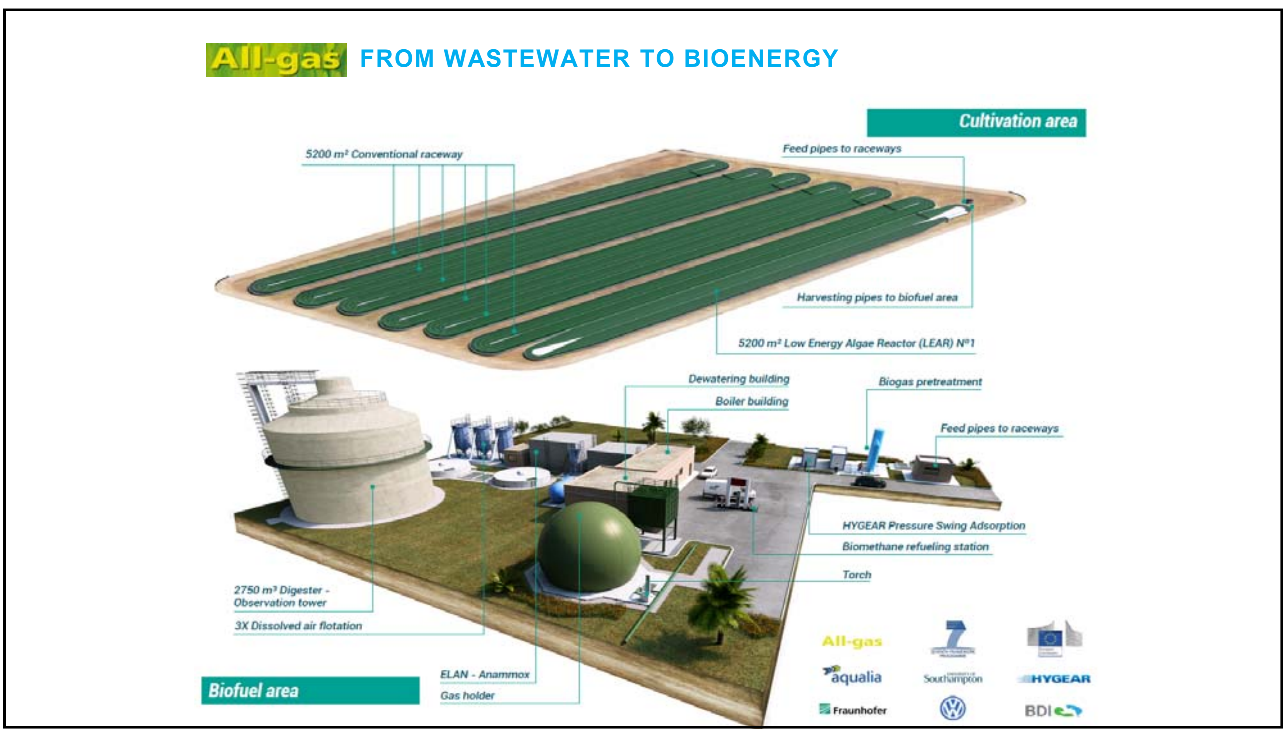
9


All-gas
FROM WASTEWATER TO BIOENERGY
Cultivation area
5200 m² Conventional raceway
Feed pipes to raceways
Harvesting pipes to biofuel area
5200 m² Low Energy Algae Reactor (LEAR) Nº1
Dewatering building
Boiler building
Biogas pretreatment
Feed pipes to raceways
HYGEAR Pressure Swing Adsorption
Biomethane refueling station
Torch
2750 m³ Digester -
Observation tower
3X Dissolved air flotation
ELAN - Anammox
Gas holder
Biofuel area
All-gas
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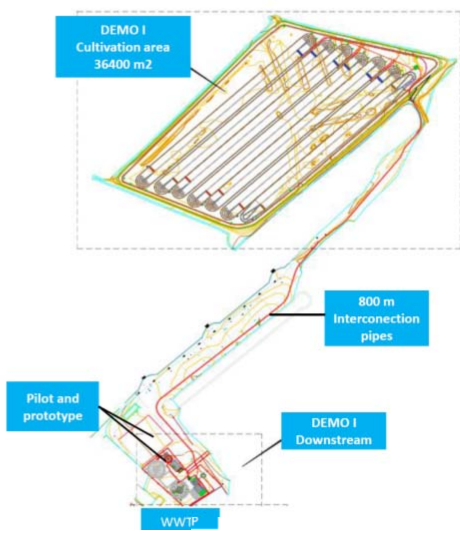
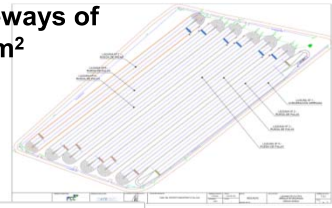
Southampton
HYGEAR
Fraunhofer
BDI

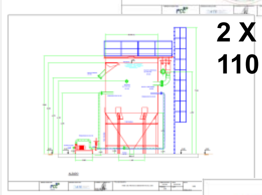
All-gas project: From Wastewater to Bio-energy

DEMO plant: Start construction March 2016



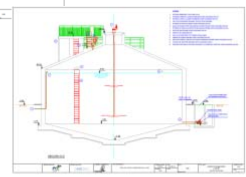
4 raceways of
5205 m^2





2 X
110 m^3/h DAF

1 X
2700 m^3
Anaerobic
Digestor



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SEVENTH FRAMEWORK PROGRAMME

3

Innovative design

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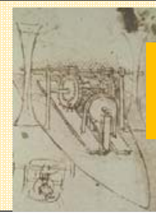
INNOVATIVE LOW ENERGY ALGAE REACTOR: LEAR

PADDLE WHEEL

Total energy efficiency:
~5% U. Florence
<17% Borowitza
~30% Weissmann



PADDLE BOAT – Leonardo da Vinci – Dateable to 1482.

SLOW SPEED SUBMERSIBLE BOOSTER

- -Mixing in many wastewater applications (carrousels)
- -High propeller efficiency (mixing power/power consumption) ~ 80%
- -Self cleaning properties
- -Can be raised for inspection
- -Gentle operation (<100 rpm)

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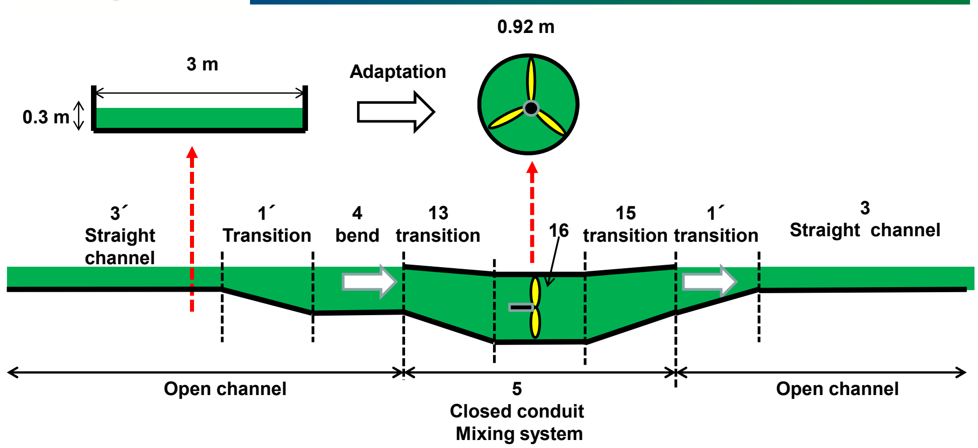
INNOVATIVE ALGAL POND: LEAR



HRAP Longitudinal section and two main cross sections

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INNOVATIVE ALGAL POND: LEAR

-Optimization by CFD analysis

Energy consumption determination by CFD analysis
Validation with 500 m2 raceways:
Paddle wheel and LEAR (Low Energy Algae Reactor) in parallel.

EP 2875724 "Open reactor for the cultivation of microalgae". 2013

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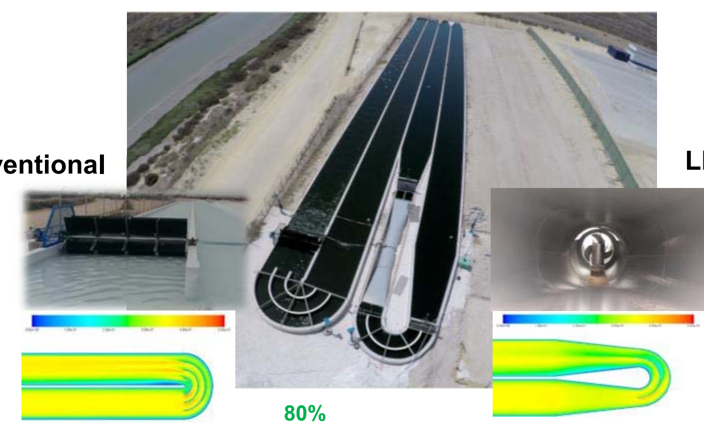
INNOVATIVE ALGAL POND: LEAR

Prototype : 1000 m^2 cultivation surface

Conventional

LEAR ®



Paddlewheel
0.5 W/m^2
0,12 kw/m^3 WW

80%
Energy savings

Propeller
0,1 W/m^2
0,02 W/m^3 WW

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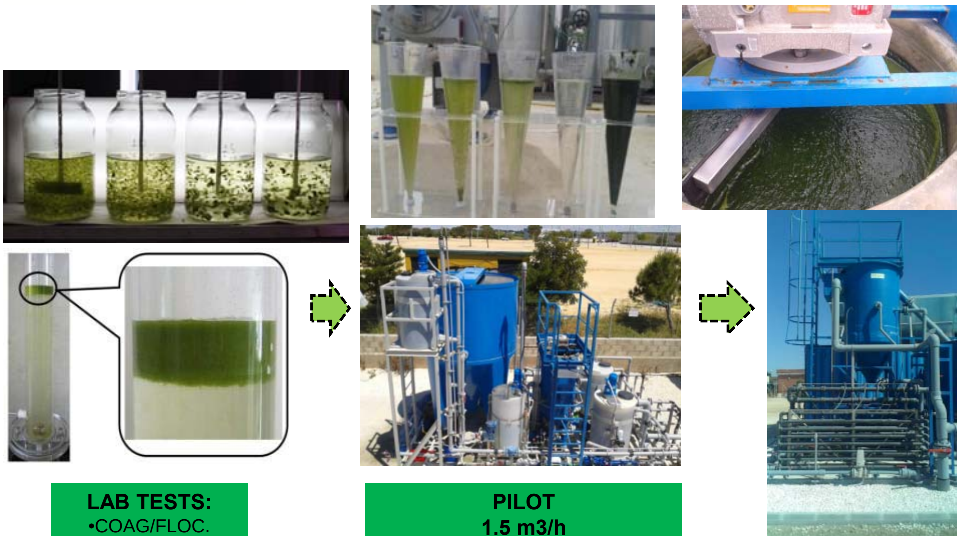
HARVESTING BY FLOTATION



LAB TESTS:
•COAG/FLOC.
•FLOTATEST

PILOT
1.5 m3/h
Comparison
- DAFAST
- SETTLER
- FILTER

PROTOTYPE
DAFAST
15 m3/h

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SEVENTH FRAMEWORK PROGRAMME

4

Most relevant results

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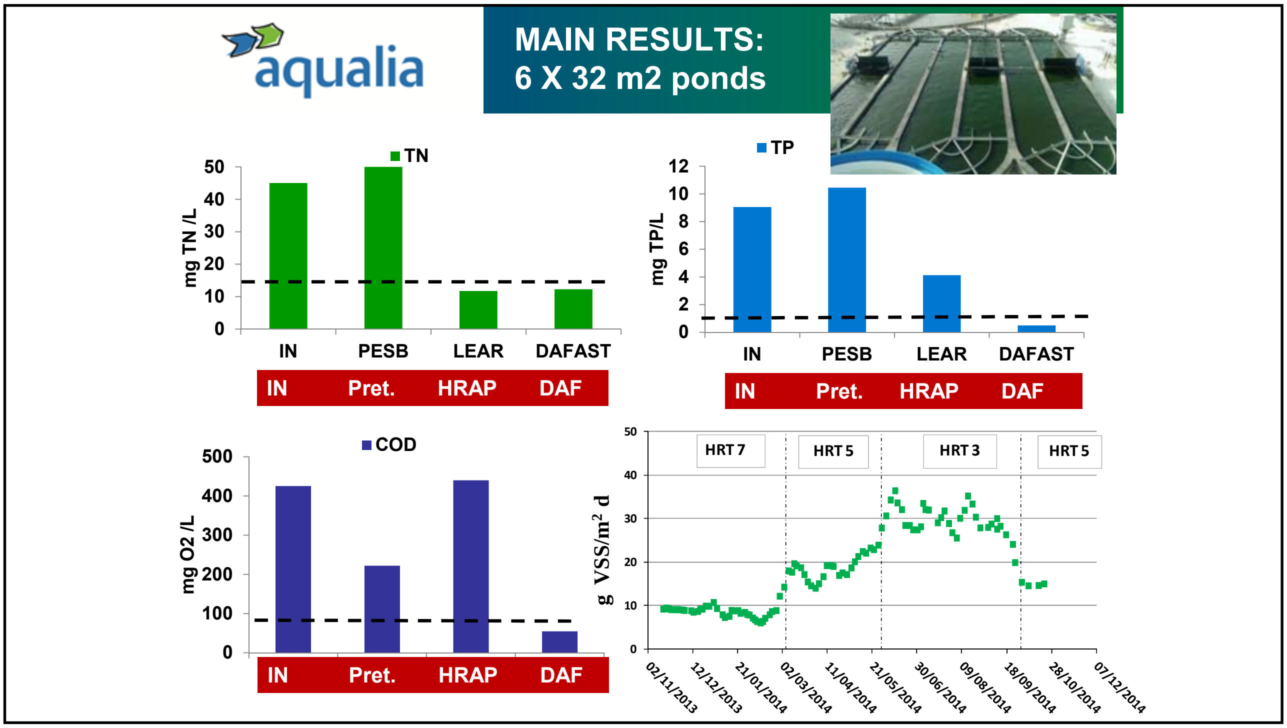
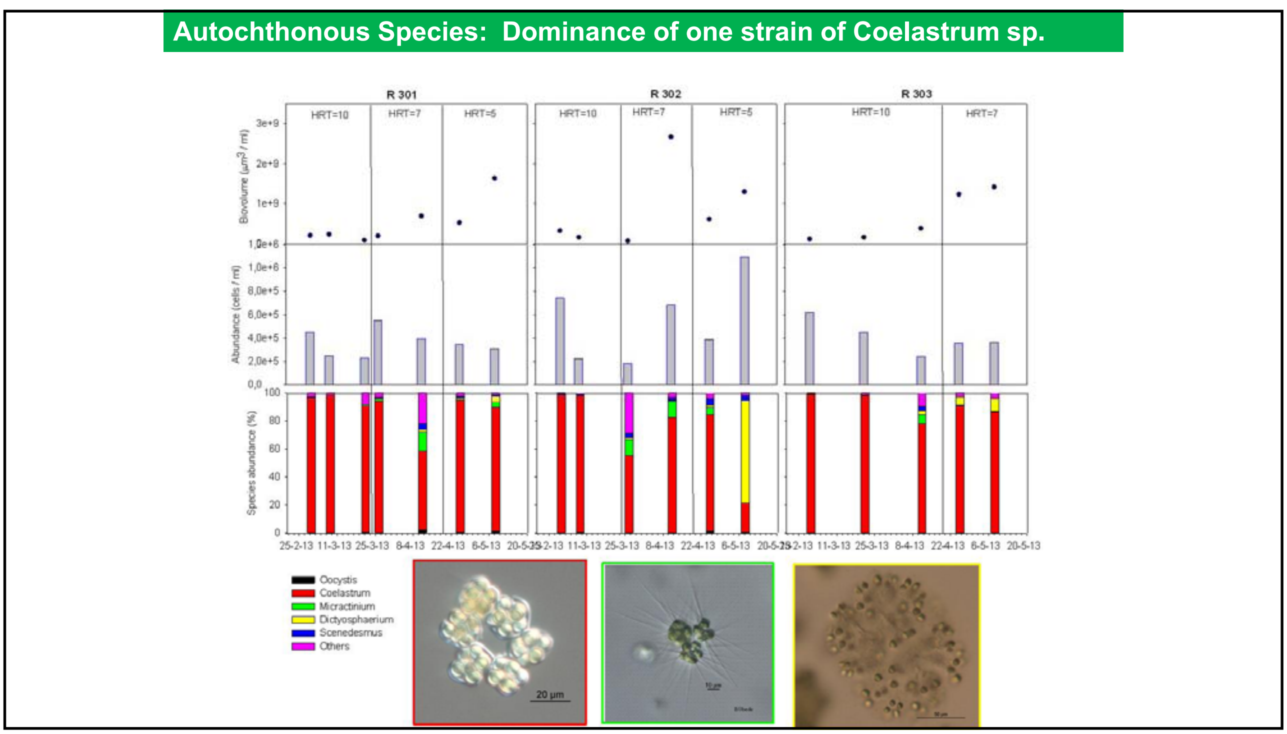
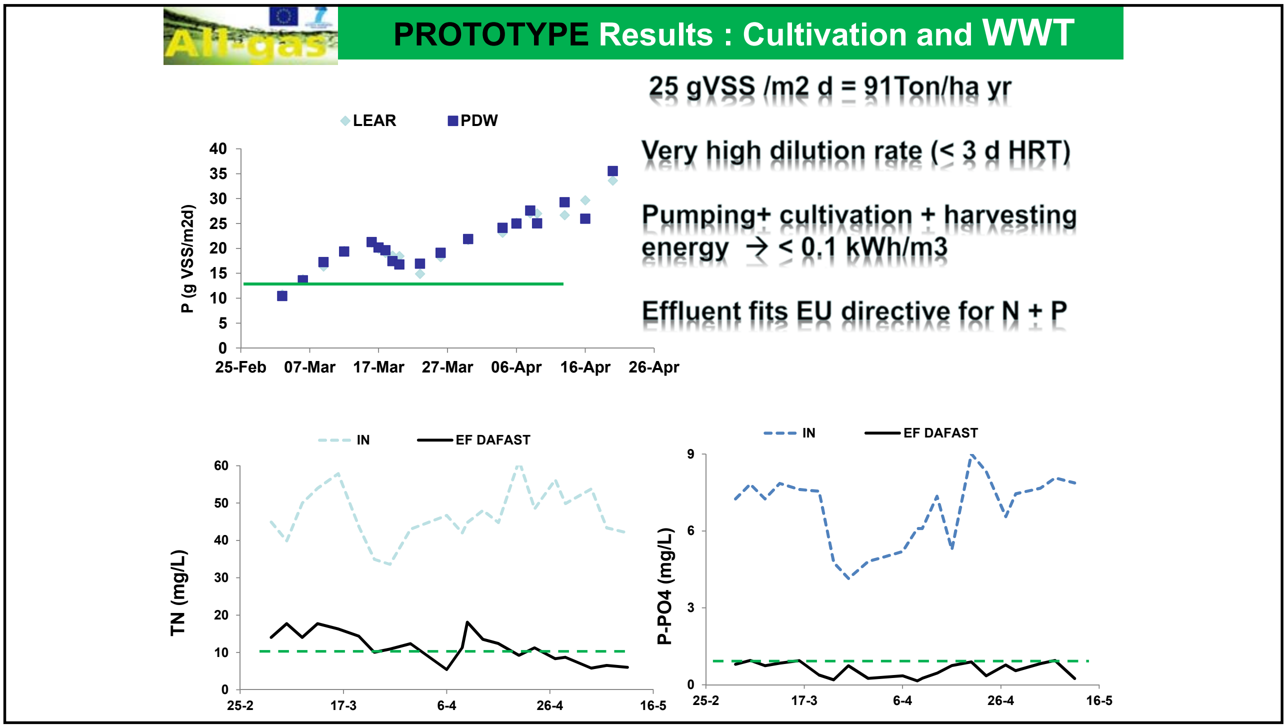
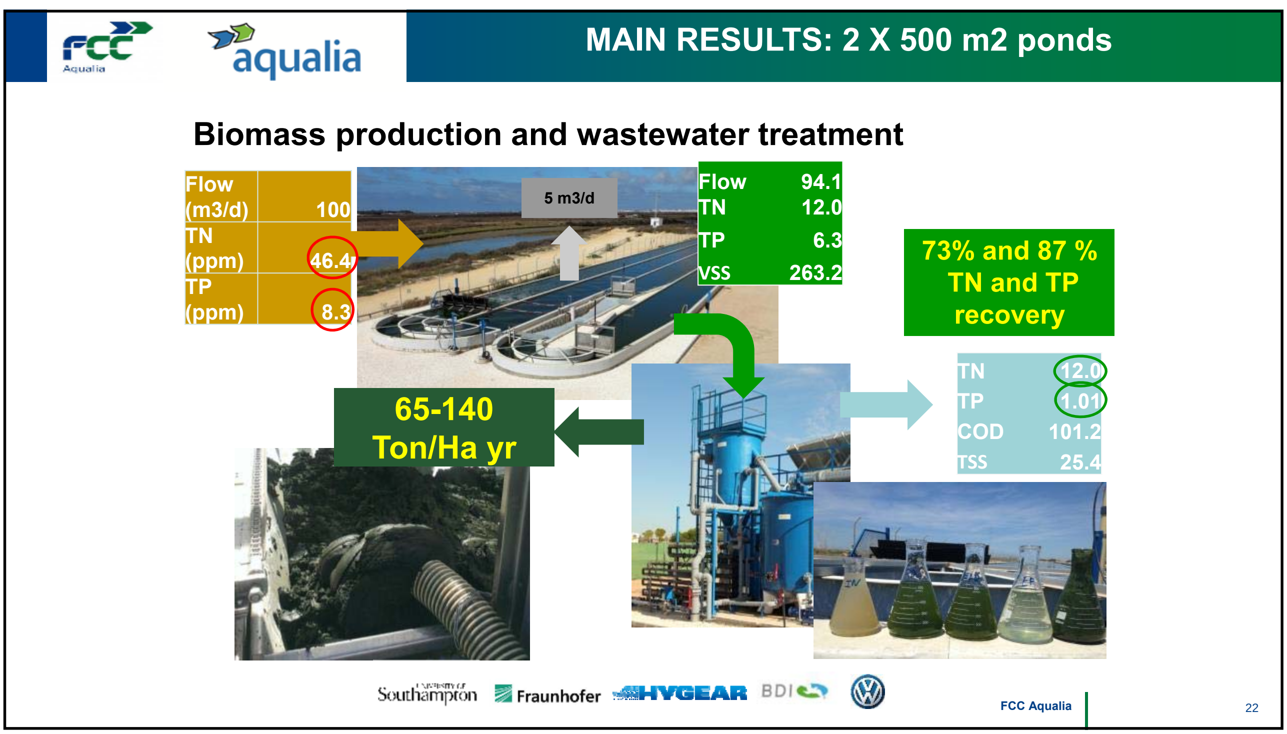

aqualia
MAIN RESULTS:
6 X 32 m2 ponds
TN
mg TN /L
50
40
30
20
10
0
IN
PESB
LEAR
DAFAST
IN
Pret.
HRAP
DAF
TP
mg TP/L
12
10
8
6
4
2
0
IN
PESB
LEAR
DAFAST
IN
Pret.
HRAP
DAF
COD
mg O2 /L
500
400
300
200
100
0
IN
Pret.
HRAP
DAF
g VSS/m2 d
50
40
30
20
10
0
HRT 7
HRT 5
HRT 3
HRT 5
02/11/2013
12/12/2013
21/01/2014
02/03/2014
11/04/2014
21/05/2014
30/06/2014
09/08/2014
18/09/2014
28/10/2014
07/12/2014


Autochthonous Species: Dominance of one strain of Coelastrum sp.
R 301
R 302
R 303
HRT=10
HRT=7
HRT=5
Biovolume (µm3 / ml)
Abundance (cells / ml)
Species abundance (%)
Oocystis
Coelastrum
Micractinium
Dictyosphaerium
Scenedesmus
Others
20 µm


PROTOTYPE Results : Cultivation and WWT
25 gVSS /m2 d = 91Ton/ha yr
Very high dilution rate (< 3 d HRT)
Pumping+ cultivation + harvesting energy → < 0.1 kWh/m3
Effluent fits EU directive for N + P
LEAR
PDW
P (g VSS/m2d)
0
5
10
15
20
25
30
35
40
25-Feb
07-Mar
17-Mar
27-Mar
06-Apr
16-Apr
26-Apr
IN
EF DAFAST
TN (mg/L)
0
10
20
30
40
50
60
25-2
17-3
6-4
26-4
16-5
P-PO4 (mg/L)
0
3
6
9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aqualia
MAIN RESULTS: 2 X 500 m2 ponds
Biomass production and wastewater treatment
Flow (m3/d) 100
TN (ppm) 46.4
TP (ppm) 8.3
5 m3/d
Flow 94.1
TN 12.0
TP 6.3
VSS 263.2
73% and 87 % TN and TP recovery
65-140 Ton/Ha yr
TN 12.0
TP 1.01
COD 101.2
TSS 25.4
Southampton
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HYGEAR
BDI
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22

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HARVESTING BY FLOTATION

DAFAST Results – Clarification and Biomass Thickening

Chemicals

Electricity

Coagulation
20 ppm Al_2O_3

+

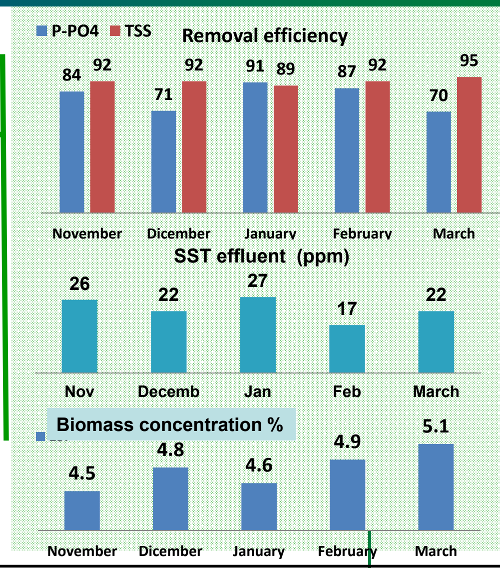
Flocculation
0.5 ppm Poly

+

DAFAST

0.05
kWh/m3

Total cost
0,01 €/m3



aqualia

ALGAE-BACTERIA ANAEROBIC DIGESTION

LAB REACTORS
8X 5 L

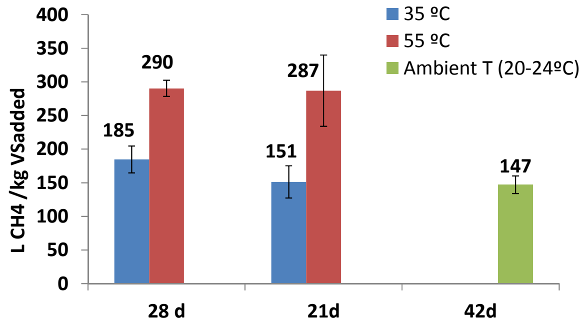
•MESOPHILIC.
•THERMOPHILIC.
•CODIGESTION
•TPAD
•THERMAL HYDROLYSIS

PILOT PLANT
ALGAE DIGESTERS
2 X 600 L, 1 x 1500 L

•MESOPHILIC.
•THERMOPHILIC.
•AMBIENT TEMPERATURE

All-gas Results

Energy production
Anaerobic digestion



Range	L CH_4/kgVSS
Meso 35 C	168
Thermo 55 C	288
Ambient 20 C (2 X HRT)	147

Can we increase the biogas yield

- *Similar to conventional waste activated sludge biogas production*
- *At ambient temperature, similar to mesophilic at twice the HRT*

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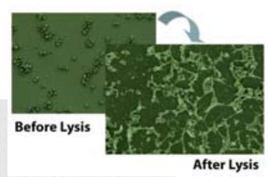
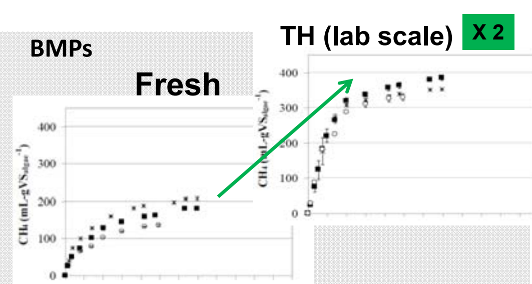
All-gas Results

Energy production
Enhancing the yield



Cell disruption
- Ozonization
- Thermal Hydrolysis (CAMBI)
- Enzymatic pretreatment
- Alcaline (NaOH)



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5

All-gas ENERGY BALANCE

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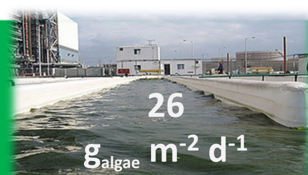
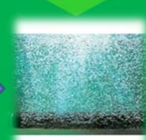
Energy Potential of photosynthetic oxigenation



1.5 g O_2 /g algae

HRAP ≈ 0.3 m depth

40 g O_2 m^{-2} d^{-1}

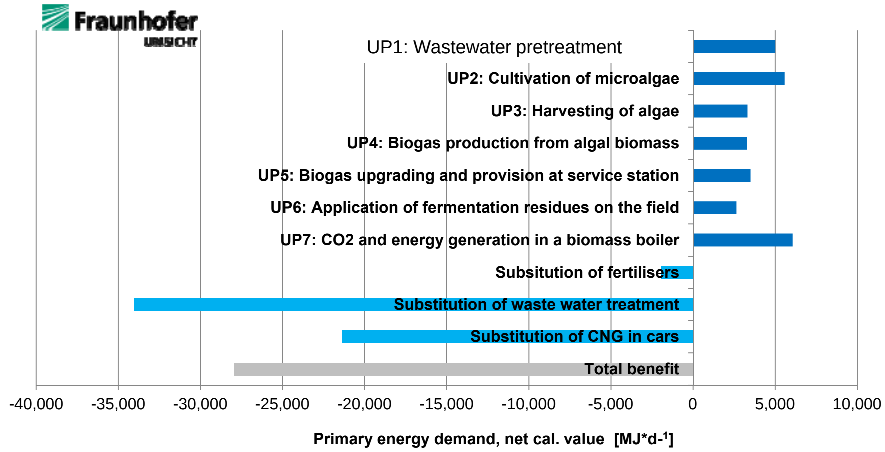


120 g O_2 m^{-3} d^{-1}

On 1000 m2 ponds: 40 kg O2/d
Raw WW with 2 d HRT treats 150 m3/d x 0,25 kg BOD/m3 = 37,5 kg O2/d

Biogas yield 1000 m2 x 0,025 x 0,2 m3/kg x 10 kwh/m3 = 50 kwh/d
Biodiesel (20 % lipid) 25 kg/d x 0,2 x 10 kwh/kg = 50 kwh/d
Biomass energy $E_{biomass}$ ≈ 17,000 MJ ton^{-1} = 5 kwh/ kg = 125 kwh/d

Energy balance of All-Gas (10 ha, 10 000 m^3d^{-1})



- **Credits for WWT, fermentation residues, and CNG in cars allow primary energy savings of ca.**

  25 000 MJ*d^{-1} = 7000 kwh = 0,7 kwh / m3

Does the system provide more usable energy than it consumes? - Energy Return On Investment (EROI)

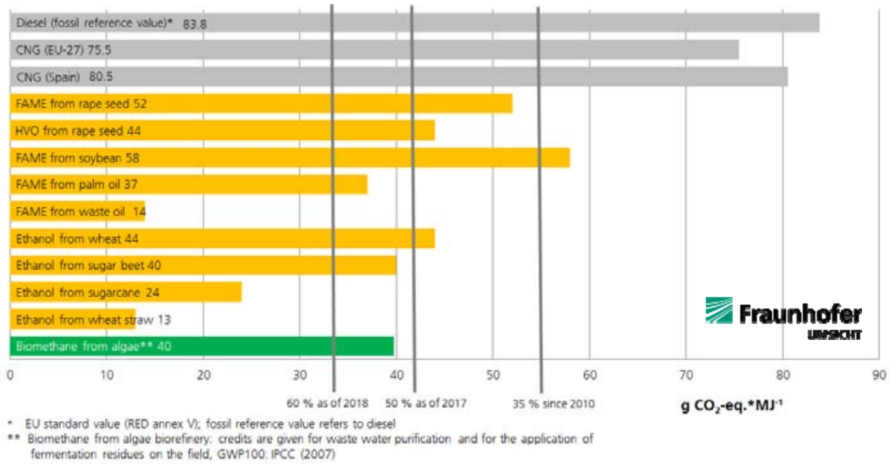
- **EROI: Relation of primary energy supplied to primary energy used in supply process**

$$EROI_{BM} = \frac{EC_{BM} + EC_{CP}}{E_{BM}} = \frac{LHV_{BM} * \rho_{BM} + EC_{CP}}{E_{BM}} = 1.9$$

EC_{BM}: energy content of biomethane
EC_{CP}: primary energy of the co-products fertilizer and water purification
E_{BM}: direct and indirect energy required to produce biomethane

- **Algae WWT produces twice more usable energy than it consumes**
  - **EROI of Corn Ethanol and Biodiesel: 1,3**

Comparison of GHG emissions of biomethane from algae to other fuels



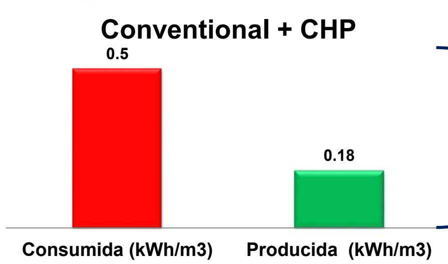
* EU standard value (RED annex V); fossil reference value refers to diesel
** Biomethane from algae biorefinery: credits are given for waste water purification and for the application of fermentation residues on the field, GWP100: IPCC (2007)

- Biomethane from algae allows GHG savings of > than 50 %

All-gas

Comparison: 10,000 m3/d plant = 10 ha surface

Results



0,3 kwh

g. 0,5 kwh

5 kg CH_4/100 km
20,000 km/yr

2375 kg Algae/d
306 kg CH_4/d

> 2.000.000 Km/yr

Consumida (kWh/m3) Producida (kWh/m3)

> 100 cars moved by bio-methane CH4

10 cars / ha

Compare to Bio-ethanol (Sugarcane) or Bio-diesel (Palm Oil):

5 cars / ha

aqualia Southampton Fraunhofer HYGEAR BDI

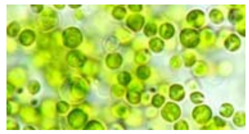
All-gas

Comparing Biofuel Production per hectare

Palm oil diesel

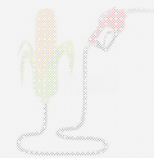
5,000 L/Ha /yr
(5 L/100km)
5 vehicles

µAlgae (BioCH4)



> 10,000 kgCH4/ Ha /yr
(5 kg CH4/100km)
>10 vehicles

Sugar Bioetanol



5,000 L/Ha /yr

Country	Nº pers
Angola	130
UAE	10
España	19
USA	8

Additional benefit in electricity savings
0,5 - 0,2 kWh/m3 → 0,3 kWh/m3 X 1000 m3/d X 365 d =
> 100 000 kWh/año

Species	L oil/ha	Univ. Lab. Reference
Chlorella - 30 % lipids	58,700	Chisti (2007) Biodiesel from microalgae. Biotechnol Adv.
Scenedesmus - 16 % Oil	17,330	*Almeria:* $5g_{lipids}/m^2 \cdot d$, Fernández Sevilla et al., (2008)
Nannochloropsis	23,500	*Firenze*: 2 step process, $9.5\ g_{biomass}/m^2 \cdot d$, Rodolfi et al., (2009)

Thank you for your imagination: Wastewater is Biofuel

ALGAE BIOMASS ORGANIZATION

Water Environment Federation
the water quality people

AZ Water Association
Professionals Dedicated To Arizona's Water

Algae for Wastewater Treatment

Opportunities in Operational Energy Efficiency, Product Recovery and Low Cost Systems

Renaissance Glendale Hotel & Spa, AZ, October 23, 2016 12:30-4:00pm

PANEL 2 – Algae for Wastewater : Design, Financing, and Regulations

Moderator: Noah Mundt, P.E., Siemens

Daniel B. Higgins, P.E, GE Power & Water

Kuldip Kumar, Ph.D., MWRD Chicago

Bob Bastian, P.E., US EPA

GE Power & Water
Water & Process Technologies

GE Perspective

Algae for Wastewater Treatment Forum

Daniel B. Higgins, P.E. – Director Central US
October 23, 2016

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Today's agenda

- Global Water Challenges
- About Our Business
- What Captured our Attention
- The Beginnings of our Algae Education
- Our Primary Need as a Business
- Obstacles/Challenges


Global water challenges
Availability
• Growing population and industrial use
• Climate change and drought
Quality
• Increased industrial pollution
• Deteriorating water quality
Productivity
• Pressure to improve operational efficiency
• Managing downtime and aging assets
Policy
• Stricter regulation on discharge/withdrawal
• Water reuse incentives and policy mandates
3
Water & Process Technologies
© 2012 General Electric Company


Our Business:
Water & Process
Technologies

Water & Process Technologies

Quick Facts

- Headquartered in Trevose, PA, USA
- 8,000 employees globally
- 50,000 customers in 130 countries
- 50 global manufacturing sites

Expertise and innovation

Acquisition

- **1999:** Glegg Water Conditioning
- **2002:** BetzDearborn
- **2003:** Osmonics, Inc.
- **2005:** Ionics
- **2006:** ZENON Environmental
- **2014**: Monsal

Innovation

- **2007:** GE launches TrueSense
- **2008:** GE launches GenGard
- **2009:** GE launches the Muni.Z depth filter using Z.Plex technology, PROPAK system, and ZeeWeed 1500
- **2010:** GE launches Mobile Evaporator, Mobile M-PAK, HERO and ZCore
- **2011:** GE launches LEAPmbr and SeaPAK

Expansion

- **2009:** The GE/NUS Singapore Technology Center opens
- **2009:** GE opens Water & Process Technology Center in Saudi Arabia
- **2011:** Wuxi plant expansion doubles capacity of water technology manufacturing in China
- **2011-12:** Tripled capacity at Oroszlány, Hungary production site
- **2012:** Opening of new laboratory in Cotia, Brazil

Built on more than 90 years of domain expertise and innovation

Global presence and reach

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Global leadership position

Our leadership in equipment solutions:

- Advanced ultrafiltration, membrane bioreactor, reverse osmosis membranes and membrane chemistries
- Mobile fleet and water outsourcing capabilities
- Tough-to-treat applications, such as unconventional fuels and mining
- Packaged water treatment equipment
- Analytical instruments for measuring water quality

Our leadership in chemical and knowledge management solutions:

- Cooling and boiler water technologies that enable customers to protect their assets
- Chemical treatment for ethylene, styrene and elastomer production facilities
- Refinery treatment solutions focused on tough-to-treat crudes
- Remote monitoring and diagnostic solutions

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Broad product and solutions portfolio

Chemical & Monitoring Solutions

- Cooling Chemistries
- Boiler Chemistries
- Wastewater Chemistries
- Fuel Oil Treatment
- Hydrocarbon Process Chemistries
- Industrial Process Chemistries
- Knowledge Management & Monitoring Solutions

Engineered Systems

- Ultrafiltration/Membrane Bioreactor
- Mobile Water Solutions
- Water Outsourcing
- Thermal/Zero Liquid Discharge
- Reverse Osmosis/Electrolytic Systems
- Filters & Membranes
- Advanced Biological Metals Removal (ABMet)
- Analytical Instruments

Comprehensive solutions

Desalination Technologies | Municipal Solutions | Utility Solutions | Industrial Wastewater

Process Chemicals and Separations | Ingredient Water | Measurement Solutions

ecomagination
a GE commitment

Algae Captured our Attention

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A Better Pathway to Nutrient Removal

- Wastewater is a Resource
- Innovation and Energy Savings
- Low TN and Low TP
- Nutrient Recovery and Protein for Fish

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What to do with all the Biomass

- Farm & Harvest – GE Liquid/Solid Separation
- Process & Package – GE Industrial
- Market & Sell – GE Digital

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Water & Process Technologies

GE's Algae Education

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Recipe to Grow Algae

WaterSolution

Sunlight

Carbon

Nutrients ←

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Water & Process Technologies

Sources of the Growth Necessities

- **Wastewater and Nutrients**
- **Artificial Light?**
- **Carbon- Power Plants - Industry**

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Water & Process Technologies

What to do with all the Algae

- Farm & Harvest – GE Liquid/Solid Separation
- Process & Package – GE Industrial
- Market & Sell – GE Digital

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The GE Business Need

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Collaborators

Integrity

Business Plan - Vision

Self Sustaining

Professional

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Obstacles/Challenges

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Impediments

- **Market Acceptance – Engineers & Owners**
- **Regulatory Environment – Federal and State**
- **Footprint**
- **Cost**
- **Who Owns and Operates –PPP?**
- **Like Solar, Biomass and Wind, to what extent is Government encouragement and support necessary**

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Utilizing Algae Based Technologies for Nutrient Removal & Recovery: Opportunities & Challenges of Phycoremediation

Kuldip Kumar, Ph.D
Monitoring & Research Department
MWRD Chicago
Phone: 708.588.3579
Email: Kuldip.Kumar@mwrd.org

MWRD Chicago
Tom Kunetz
Iowa State University Collaborators
Dr. Zhiyou Wen
Dr. Martin Gross

Phycoremediation Challenge: Overview

- Phycoremediation: the cultivation and harvesting of algae for the purposes of removing nutrients (phosphorus and nitrogen) from wastewater
- Algae is a feedstock for products such as:

Bioplastics	Food additives
Biofuels	Co-composting
Pharmaceuticals	(Fertilizer)
Biomass (biogas)	Aquaculture feed

Sustainable

Phycoremediation Challenge: Drivers

Phosphorus:

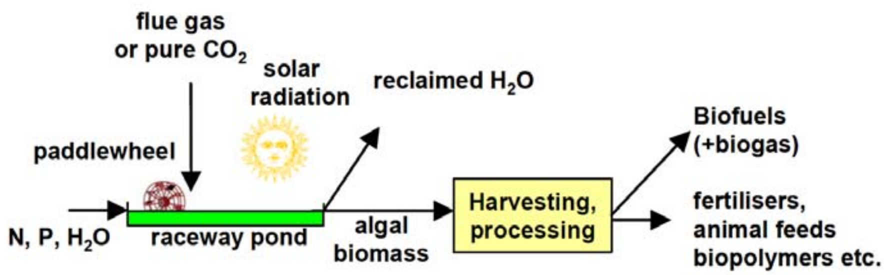
- Enters our WRPs in the raw wastewater
- Is a non-renewable, dwindling resource necessary for life
- Also a pollutant of concern with EPA and will soon be regulated in NPDES permit
- Traditional treatment methods involve chemical addition, precipitation, filtration, and disposal
- "Recovery and reuse" of is preferable to "removal and disposal"

Phycoremediation Challenge:

Algae cultivation requires:

- Water 
- Nutrients 
- Sunlight 
- Moderate water temperatures 
- Large land areas 

Go Back Three Years – How Difficult it Could Be? Schematic of Algae Phycoremediation Process



Challenges of Traditional Algal Culture Systems

- Long HRT & low cell productivity
- Large footprint & land intensive
- Low light use efficiency

Algae harvesting is costly and energy intensive

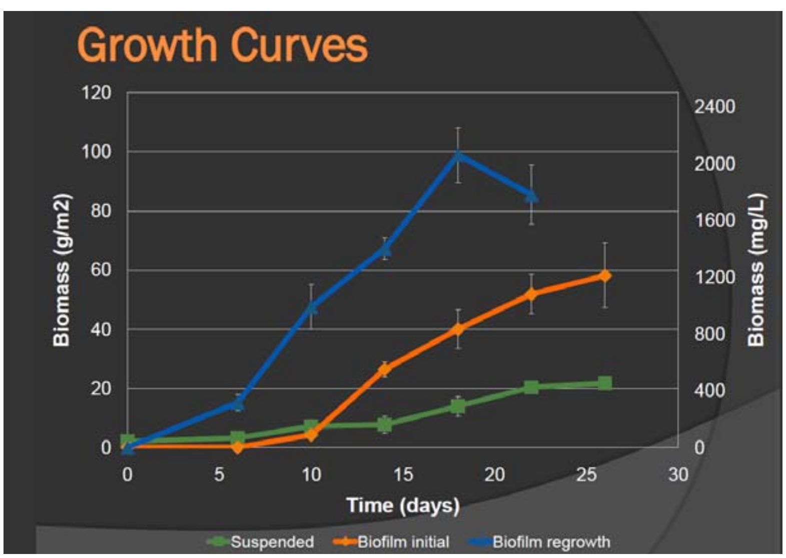
- Low algal cell densities (99.9-99.95 % water)
- Separating microscopic cells from water requires specialized technologies which increase cost

Earthrise Nutritionals LLC, California

Pilot Plant Goals

- Seek an approach that breaks the ***"footprint barrier"*** to make phycoremediation a practical technology, through evaluation of bioreactor configurations, operational strategies, and process enhancements.
- Determine the effect of seasonal conditions on the efficiency of the processes.
- Develop a working knowledge of the ***mechanics of algae harvesting and drying***, for further beneficial use of the algae as a feedstock.
- Support research both in-house and in the industry.

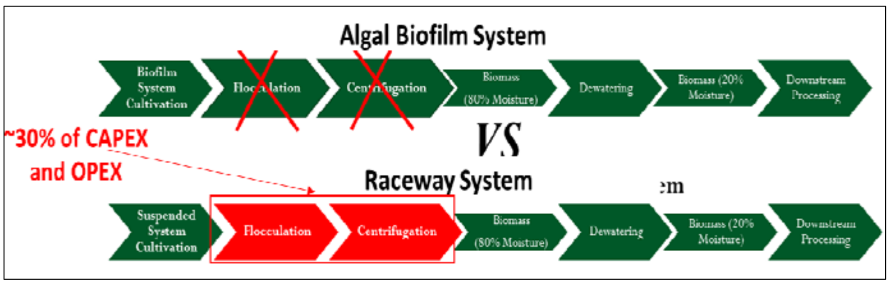
Early Lessons



Biofilm-based Algae Systems - Concept

- Algal cells are allowed to grow on a surface of a material to form a biofilm
- Harvesting can be done simply by scraping algae off attached surface
- Harvested algae has similar water content as algae post centrifugation

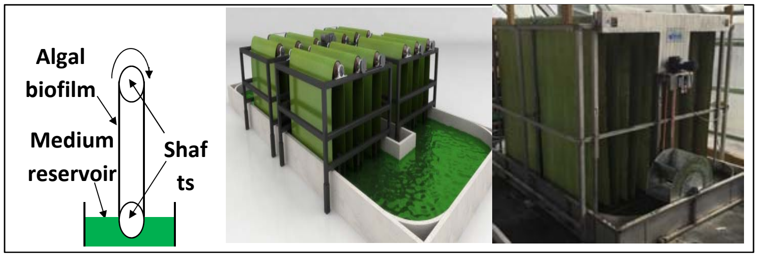
Johnson and Wen (2010)



Technologies Evaluated

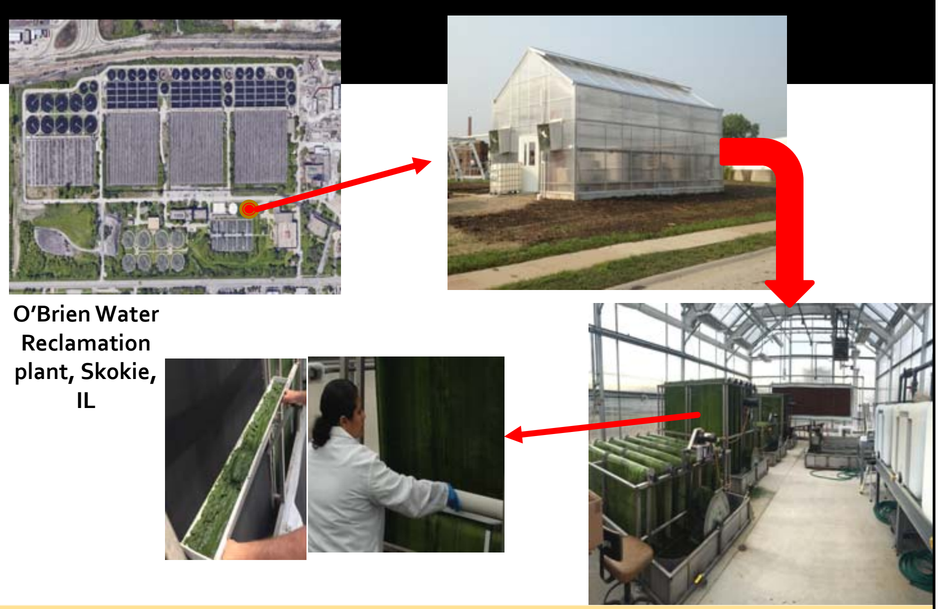
- Raceway Ponds
- Photo-bioreactors
- Revolving Algal Biofilm (RAB)

Revolving Algal Biofilm (RAB) Treatment System



Features/Advantages

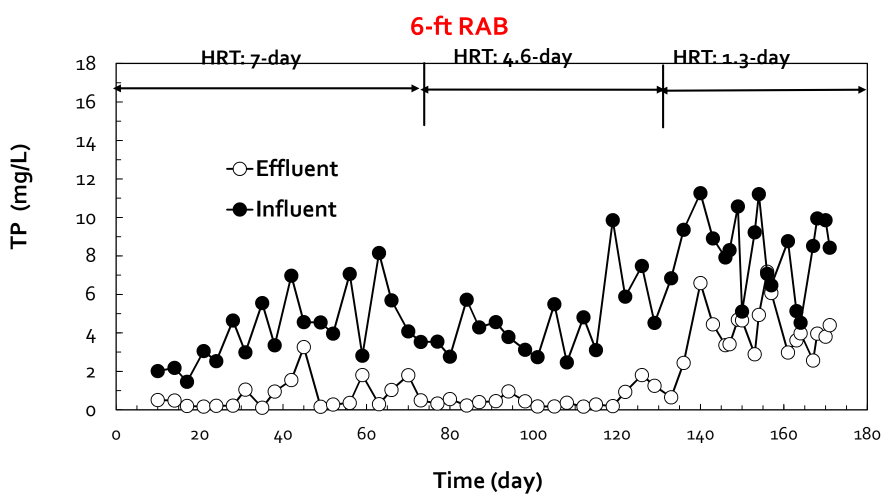
1. Inexpensive harvest
2. Efficient space utilization
3. Reduced light limitation
4. Enhanced CO_2 mass transfer
5. Enhance algal productivity
6. Adsorption of N,P, & metals



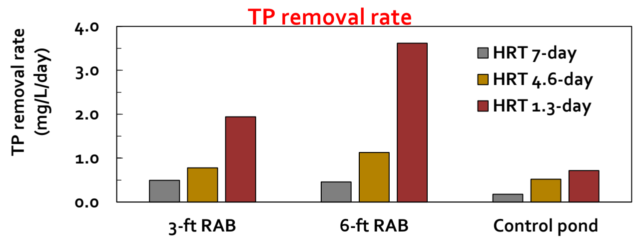
Goal: Determine if RAB system is a viable nutrient recovery method

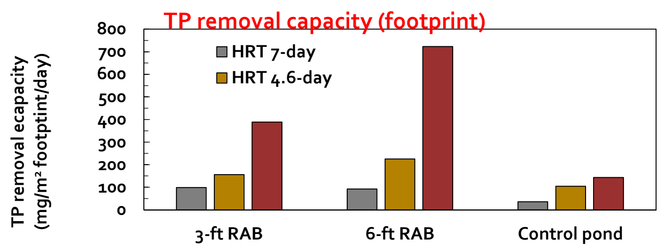
Revolving Algal Biofilm Harvesting System

Total Phosphorus (TP) Concentration in Influent and Effluent



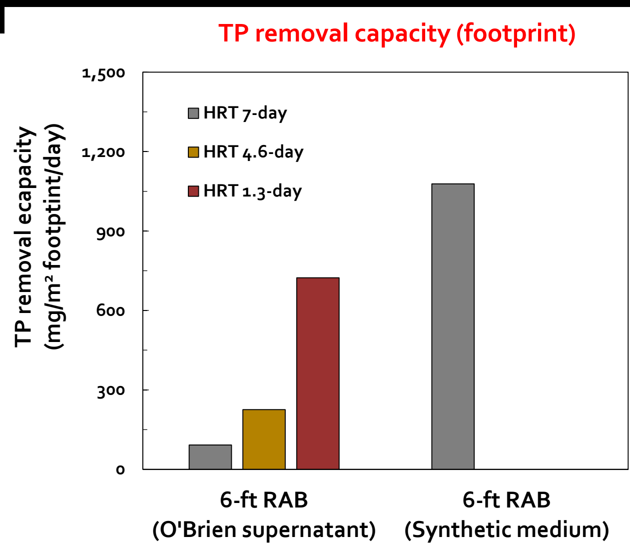
Total Phosphorus (TP) Removal Performance



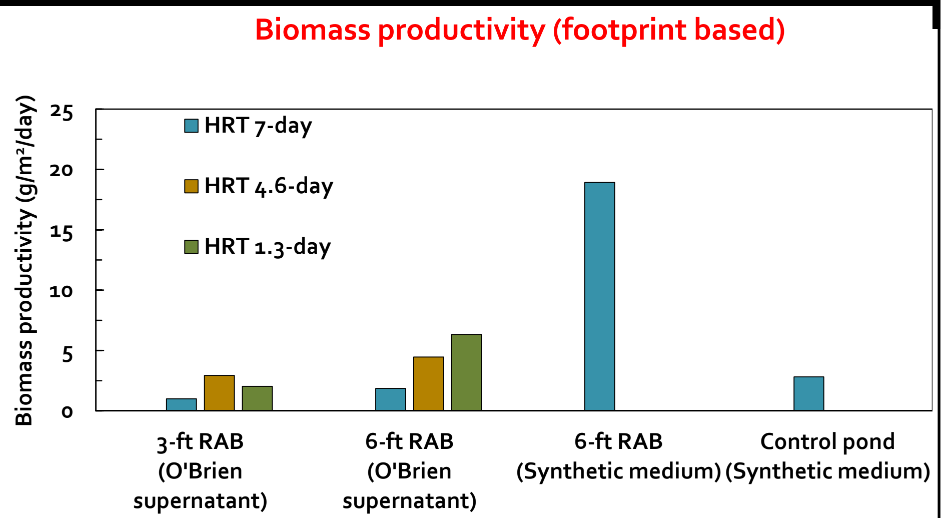


TP removal performances of the RAB systems were much higher

Comparison of Total Phosphorus (TP) Removal Capacity (footprint based)

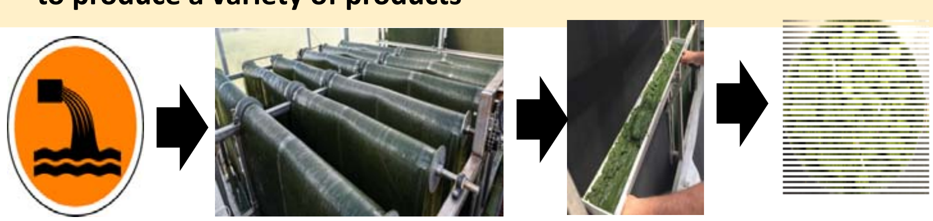


Comparison of Biomass Productivity (footprint-based)



Conclusions

1. RAB system has the potential for recovering nutrients from wastewater
2. RAB system is capable of producing concentrated algae biomass (10-25% solids)
3. The algae biomass from the RAB system has value and can be used to produce a variety of products



Future Work

1. **Running the RAB systems in series in a continuous flow operation**
2. **Running the RAB system at much lower HRT levels (ranging from 1-24 hr)**
3. **Increasing the height of RAB to 9 ft & 12ft**
4. **Improving performance by LED lights**
5. **Testing plant effluent for tertiary treatment**
6. **Evaluating biomass for commodity products**

Acknowledgements

MWRD Monitoring & Research Staff: Ms. Tiffany Tate; Mr. Jeffrey Simpson; Ms. Mina Patel
O'Brien WRP Managers: Mr. Sanjay Patel; Mr. Aruch Poonsapaya; Mr. Pinakin Desai
O'Brien WRP Maintenance & Operations Staff: Ms. Matual; Mr. Stubing; Mr. McNamara

Show-Ling Lee (Iowa State University)

Daren Jarboe (Iowa State University)

Funding support:

Metropolitan Water Reclamation District of Greater Chicago

Iowa Regent Innovation Fund

USDA SBIR

Questions?

Algae for Wastewater Treatment?

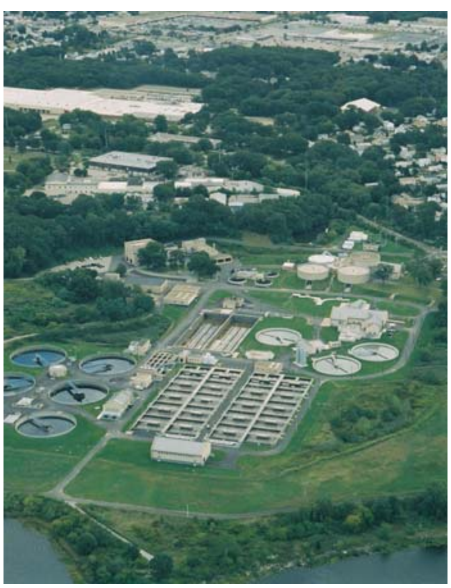
Robert Bastian
U.S. Environmental Protection Agency
Office of Wastewater Management
Washington, D.C. 20460

Isn’t the production of excess algae in receiving waters one of the things we are trying to control when we design wastewater treatment plants to reduce nutrient levels in the treated effluent?

Most of our existing laws and regulations that deal with wastewater treatment plants were designed with conventional treatment systems in mind.






Ponds/lagoons are one of the most commonly used forms of wastewater treatment technology, especially by smaller treatment plants.

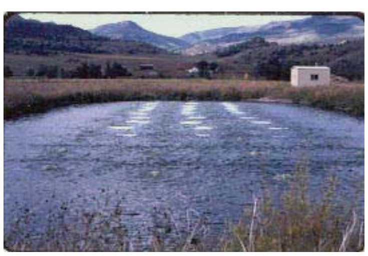
Number of Operational Treatment Facilities in 2000

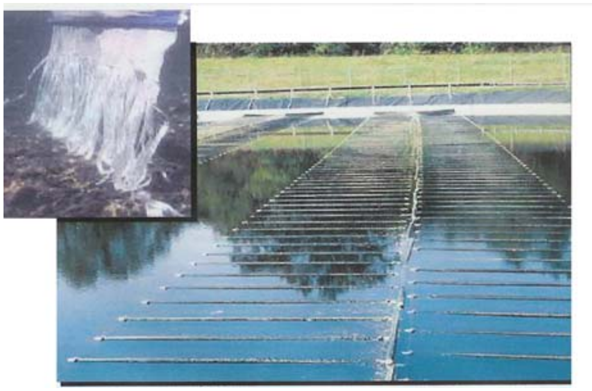
Total POTWs = 16,255

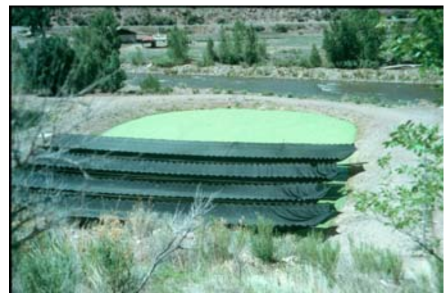
Systems with ponds/lagoons = 8,176

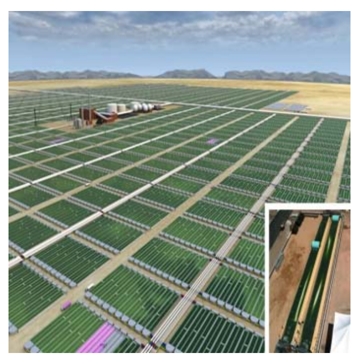
- including stabilization ponds, aerated ponds, anaerobic ponds, and total containment ponds

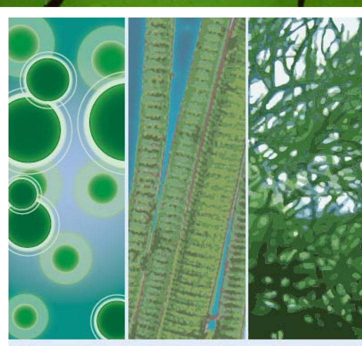


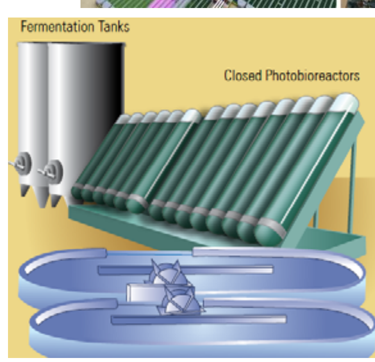


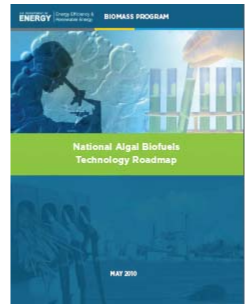


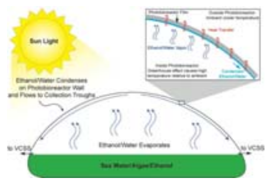


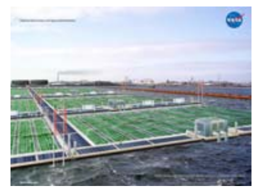



MICROALGAE
CYANOBACTERIA
MACROALGAE


Fermentation Tanks
Closed Photobioreactors







$100,000 WE&RF 2016 Paul L. Busch Award Winner

On Tuesday September 27, 2016, WE&RF awarded Dr. Jeremy S. Guest, Assistant Professor in the Department of Civil & Environmental Engineering, University of Illinois at Urbana-Champaign with the 2016 Paul L. Busch Award …

… working on the use of microalgae for wastewater treatment within conventional treatment plants

tps://www.youtube.com/watch?v=i19qbDf4ogQ

http://www.werf.org/i/Awards/Paul_Busch_Award/a/Awards/PaulLBuschAward/Paul_L_Busch_Award.aspx?hkey=810816a2-97d5-40b0-bdce-c64ef4b57116

So if we go with wastewater treatment with algae, then what can we do with all of the algae ?

Wastewater Nutrient Removal and Reuse with Algae

WEFTEC
October 8, 2013
Chicago, Illinois

Matthew Hutton (Presenter)
MicroBio Engineering, Inc.
San Luis Obispo, CA

Algae solids compare favorably with biosolids

Typical sludge vs algae solids

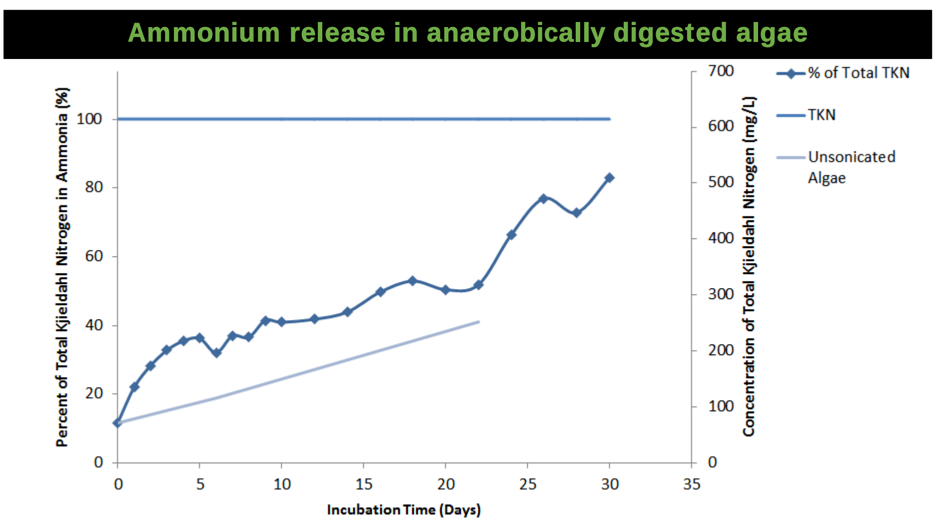
Algae air dried for ~1 yr, 80,000 to 100,000 ppm typical

Concentration (ppm, dry basis)

	Sewage sludge	Algae solids
Nitrogen	30000	7960
Phosphorus	15000	20000
Sulfur	10000	6630
Calcium	40000	8800
Magnesium	4000	1100
Potassium	3000	2460
Iron	17000	1200
Zinc	1200	1500
Copper	750	38
Manganese	250	150
Boron	25	11.6
Molybdenum	10	1.3

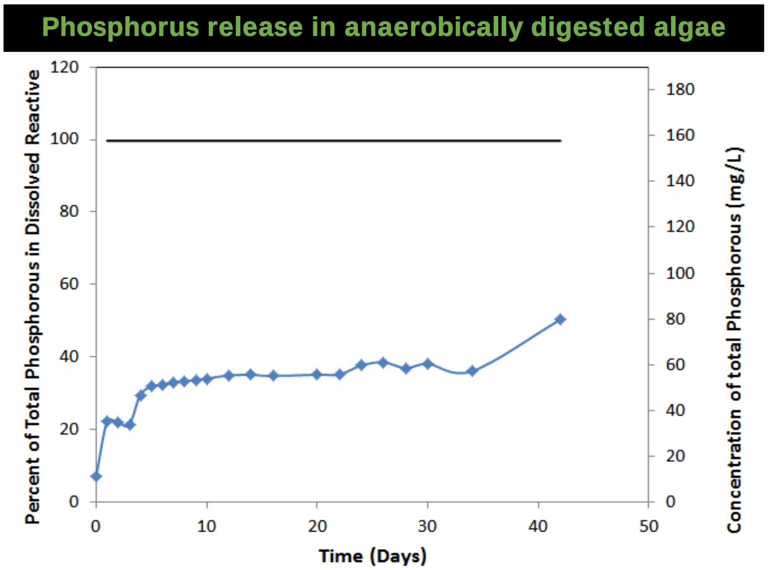
But how can nutrients be *recovered*?

Anaerobic digestion



But how can nutrients be *recovered*?

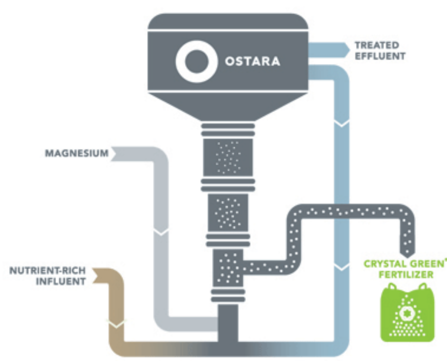
Anaerobic digestion



But how can nutrients be *recovered*?

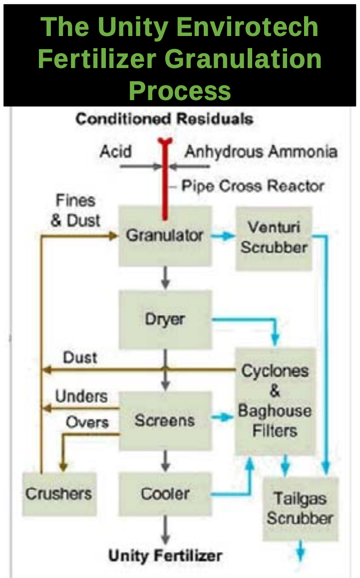
Struvite precipitation

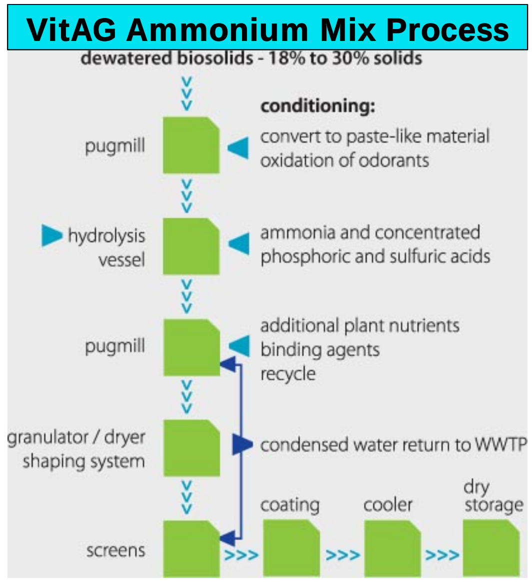
- The Pearl® process
- Chemical precipitation of struvite crystals in fluidized bed
- $NH_4MgPO_4{\cdot}6H_2O$
- Valuable product
- ~85% of soluble P
- 5-15% total N



But how can nutrients be *recovered*?

Other proprietary processes





But how can nutrients be *recovered*?

Settling, drying, land application

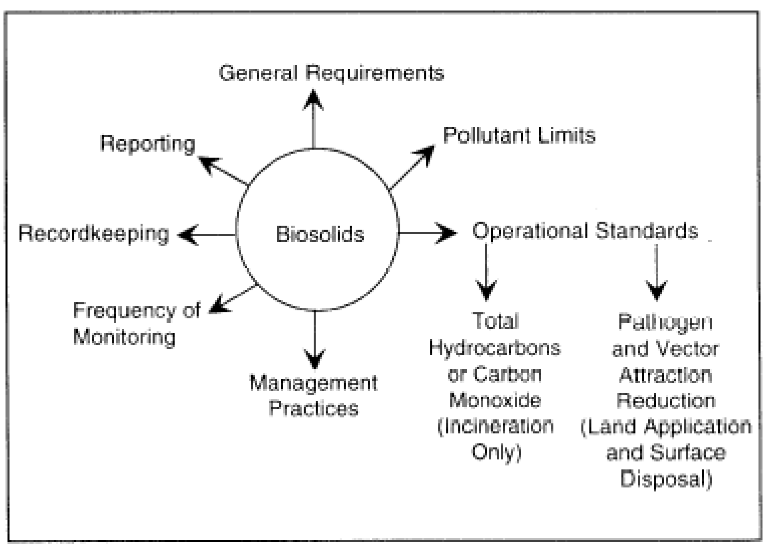
~100,000 gallons 3% solids algae in decanted settling basin

Solar dried algae

40 CFR Part 503 for biosolids … also applicable to algae solids from wastewater treatment

- Minimum national requirements applicable to the use/disposal of sewage sludge
- Part 503 includes, for Class A and Class B
  - Sewage Sludge quality limits
  - Management practice requirements
  - Monitoring/Recordkeeping/Reporting requirements
  - Additional state, local requirements
- Applicable to algae solids from wastewater

Regulatory map of Part 503



40 CFR Part 503
Key land application requirements

- Heavy metal limits
  - Maximum concentration limits
  - High quality concentration limits
  - Cumulative loading limits
- Pathogen reduction
  - Class A (below detectable levels)
  - Class B (significant reduction treatment req's.)
    - w/harvesting and site restrictions
- Vector attraction reduction requirements

Fertilizer properties of algae solids

- 8-10% N
- 1-2% P
- EPS for improved soil structure
- Slow release of biomass
  - Digestion solubilizes particulate nutrients
  - Lysed, digested algae release nutrients more quickly
  - Biogas co-product

Metals removal in high rate ponds

(March 28 to April 13, 1994, Northern CA)

Heavy Metals Removal in Raceway Ponds

	Mean Influent (ug/l)	Mean Effluent (ug/l)	Percent Removal
Zinc	141	20.6	85
Copper	47.3	9.51	80
Mercury	0.96	0.33	66
Lead	2.61	1.00	62
Chromium	3.37	2.43	28
Arsenic	2.07	2.00	3
Silver	4.13	4.00	3
Selemium	2	2	0
Cadmium	2	2	0
Nickel	13.4	13.6	-1

Algae solids metal and 503 limits

(Central California municipal pond, 2008)

	Algae solids metals		503 requirements			
	HRP	ASP	Ceiling	Cum. load	High Qual.	Annual load
	ppm unless indicated		(ppm)	(kg/ha)	(ppm)	(kg/ha-yr)
Arsenic	2.2	4.4	75	41	41	2
Cadmium	0.45	0.87	85	39	39	1.9
Chromium	5.1	10	-	-	-	-
Cobalt	<0.5	1.1	-	-	-	-
Copper	69	140	4300	1500	1500	75
Lead	1.9	5	840	300	300	15
Mercury	270 (ppb)	610 (ppb)	57	17	17	0.85
Molybdenum	1	5	75	-	-	-
Nickel	2.8	7.3	420	420	420	21
Selenium	0.9	2.3	100	100		5
Zinc	140	280	7500	2800	2800	140
Fecal coliform	<2/g	<2/g	2M MPN/g		1000 MPN/g	
Salmonella					3 MPN/4 g	

Review

- Algae from municipal wastewater (as part of the treatment system) *are* subject to Part 503
- Algae solids from municipal treatment could meet class A or Class A/EQ in a number of ways
- Metals unlikely problematic
- Consistent low metals and pathogens may provide basis for reduced monitoring

- Alternatively, grow algae on treated disinfected water