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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## PANEL 2: Algae for Wastewater: Design, Financing, and Regulations
Moderator Noah Mundt

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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
Activated Sludge Plant

Anaerobic Lagoons

Eutrophic Waterways

Coastal Dead Zones

Municipal Wastewaters

Activated Sludge Plant

Coastal Dead Zones

Nutrients in wastewaters - agricultural, municipal - → algae blooms → eutrophication → dead zones

Wastewater ‘Oxidation Ponds’ - Napa, CA ~100 hectares

UNMIXED PONDS – LOW PRODUCTIVITY
after Oswald and Gootas, 1953, U. Calif. Berkeley

Prof. Oswald

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

Concord, California, ~1960
Facultative Influent Ponds \( \rightarrow \) High Rate Pond \( \leftarrow \) Maturation Ponds \( \leftarrow \) Chlorination

Inflow raw sewage \( \rightarrow \) Influent Ponds \( \rightarrow \) High Rate Pond \( \rightarrow \) Settling Pond

Wastewater Treatment Plant, St. Helena, California, 1965
Design incorporating oxidation ponds with high rate ponds

Plant is still operates!

Chlorination

First TEA for Algae Biofuels Integrated with Wastewater Treatment - Oswald & Golueke, 1960

Prof. Bill Oswald
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 biofuel production (Benemann et al. 1980).

1998: Delhi, California Algae Wastewater Treatment Plant, two 1.4 ha paddle wheel mixed raceway ponds
High Rate Ponds with Paddle Wheels, Hilmar, California

Will we ever invent anything this useful again?
Algae Biotechnology for Wastewater Treatment
Ron Sims, Utah State University

Microalgae-based approaches
Algae-based tertiary wastewater treatment

Suspended

Chlorella
Pediastrum
Scenedesmus
Scenedesmus

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 CO₂
- 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 CO₂ 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
Microalgae Wastewater Processes and Stoichiometry

- Suspended growth - Raceways
- Attached growth – Biofilms
- Stoichiometry:
  - $106 \text{CO}_2 + 16 \text{NO}_3^- + \text{HPO}_4^{2-} + 18\text{H}^+ \rightarrow$
  - $C_{106}H_{263}O_{110}N_{16}P_1 + 138\text{O}_2$
  - (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, CO₂)

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 CO₂)
- 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.

RABR Treatment of Dairy Wastewater (Zak Fica)

- Turbid waste streams
- Seasonal temperature
- Caine Dairy Farm

http://goldenplains.colostate.edu/agri_docs/2011_stock_tank_algae_control.shtml
Cyanobacterial Dominated Biofilm Cultivation in Wastewater derived from Petroleum Refining (Alan Hodges)

- Treatment and methane production

![Graph showing concentration (mg/L)]

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

Anaerobic Digestion of Microalgae Biomass in Upflow Anaerobic Sludge Blanket (UASB) Reactors (Anna Doloman)
Characterization of algalytic bacteria from anaerobic lagoon sediment

![Diagram of UASB reactor and sequence analysis process]

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

10/23/2016
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 and Fermenter Bioplastics Materials
The RNEW® Process: Recycled Water, Fertilizer, and Power from Wastewater

Tryg Lundquist, Ph.D., P.E.¹,², Presenter
R. Spierling¹, L. Parker¹, C. Pittner¹, L. Medina, T. Steffen, J. Alvarez, N. Adler², J. Benemann²

¹California Polytechnic State University
San Luis Obispo, California

²MicroBio 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-owned 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

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

* 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.

![Image](chart.png)

**$1750 per MG O&M**

<table>
<thead>
<tr>
<th>Year</th>
<th>O&amp;M Cost</th>
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<tr>
<td>1998</td>
<td>$985</td>
</tr>
<tr>
<td>2001</td>
<td>$1,129</td>
</tr>
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<td>2004</td>
<td>$1,484</td>
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<td>2007</td>
<td>$1,747</td>
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**TABLE 2 – Operation and maintenance cost category breakdown (2007)**

<table>
<thead>
<tr>
<th>Expenditure</th>
<th>2007</th>
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<tbody>
<tr>
<td>Personnel</td>
<td>45.1%</td>
</tr>
<tr>
<td>Private sector services</td>
<td>16.6%</td>
</tr>
<tr>
<td>Electric power</td>
<td>10.3%</td>
</tr>
<tr>
<td>Service provided by other departments</td>
<td>7.1%</td>
</tr>
<tr>
<td>Supplies and materials</td>
<td>6.4%</td>
</tr>
<tr>
<td>Chemicals</td>
<td>4.7%</td>
</tr>
<tr>
<td>Other utilities</td>
<td>3.9%</td>
</tr>
<tr>
<td>Utility management</td>
<td>1.0%</td>
</tr>
<tr>
<td>Other</td>
<td>4.9%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>

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:

![Image](grade_d.png)

* National Association of Clean Water Agencies, 2011
Green algae typically found in wastewater pond polycultures.

Add CO₂ to balance C:N:P ratio and achieve completed nutrient assimilation.

<table>
<thead>
<tr>
<th>Control</th>
<th>CO₂ Enhanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>600 mg/L Algae</td>
<td>130 mg/L Algae</td>
</tr>
<tr>
<td>&lt;1 mg/L NH₄⁺-N</td>
<td>25 mg/L NH₄⁺-N</td>
</tr>
<tr>
<td>&lt;0.3 mg/L PO₄³⁻-P</td>
<td>3 mg/L PO₄³⁻-P</td>
</tr>
</tbody>
</table>

CO₂ Enhanced

Air Sparged
RNEW® Technology

Recycle
Nutrients
Energy
Water

- Nutrient removal with CO₂ 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.

CO₂
Make-up Water & Nutrients
Primary Sludge
Algae Raceways
Clarifiers
Thickeners
Dewatering
Conversion to Biofuel Intermediate
Reclaimed Water Option
Blowdown Option
Transportation Fuel
Fertilizer
Reclaimed Water Option
Primary Sludge
Media Recycle
C,N,P Recycle
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

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, CO₂ 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

- 2015 -2017 Algae Culture Air CO₂ (w. PNNL & Cal Poly)
- 2013 -2016 Water & Nutrient Recycling (w. Cal Poly)
- 2015 - 2017 Microalgae CO₂ 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 CO₂ for nutrient removal & biofuels.
Delhi, Calif. plant designed for secondary treatment, but now total nitrogen removal will be required.

- 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 CO₂ to balance C:N:P ratio and achieve completed nutrient assimilation.

**CO₂ Enhanced**
- 600 mg/L Algae
- <1 mg/L NH₄⁺-N
- <0.3 mg/L PO₄³⁻-P

**Air Sparged**
- 130 mg/L Algae
- 25 mg/L NH₄⁺-N
- 3 mg/L PO₄³⁻-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 \text{BOD}_{\text{consumed}})

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

Y_{obs} = observed heterotrophic yield (g VSS/g scBOD₅)
Y = theoretical biomass yield (g VSS/g scBOD₅)
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.

![Graph showing productivity over different rounds and days](image-url)
CO₂ addition to integrate wastewater treatment & biofuels at San Luis Obispo, Calif.

Pilot Plant Process Diagram

Grow 2-6 days

To crops

Supernatant

1-4% VS Algae

Digest 40 days

Thicken 12-24 hours

Supernatant

Algae Water

Tube Settler Supernatant Effluent

Algae Slurry
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

Concrete drying pad
“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.

DOE-NETL Algae → biogas for power generation

Orlando Utilities Commission Stanton Energy Center (OUC-SEC) ~900 MW Coal-fired PP

Landfill Gas → Flue Gas CO₂ & Electricity → Biogas → wastewater / Nutrients & water
Conclusion on algae wastewater treatment

Cost

<table>
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<tr>
<th>$/yr-MGD treated</th>
<th>$1,000,000</th>
<th>$900,000</th>
<th>$800,000</th>
<th>$700,000</th>
<th>$600,000</th>
<th>$500,000</th>
<th>$400,000</th>
<th>$300,000</th>
<th>$200,000</th>
<th>$100,000</th>
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<tr>
<td>Activated Sludge Secondary</td>
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<tr>
<td>Algae Seasonal N Removal</td>
<td>$100,000</td>
<td>$200,000</td>
<td>$300,000</td>
<td>$400,000</td>
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<td>$700,000</td>
<td>$800,000</td>
<td>$900,000</td>
<td>$1,000,000</td>
<td>$0</td>
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GHG

<table>
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<th>kgCO2/ML treated</th>
<th>250</th>
<th>150</th>
<th>50</th>
<th>-50</th>
<th>-150</th>
<th>-200</th>
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</table>

- Sludge
- Electrical cost
- Maintenance
- Labor
- Capital Charge
- Electricity produced
- Sludge hauling
- Electricity consumption
- Electricity production
- Net Emissions

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

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
www.All-gas.eu:
Partners and main objectives

All-gas project: From Wastewater to Bio-energy

Partners

Coordinator
Cultivation, Harvesting, Anaerobic Digestion
DEMO design

Lab scale Anaerobic Digestion

Biogas Fleet vehicles

Fraunhofer

Life Cycle Assessment

BDI

Lipid Extraction and Biodiesel

HYGEAR

Biogas upgrading

FCC Aqualia
All-gas project: From Wastewater to Bio-energy

All-gas concept: Symbiosis

Raw screened WW rich in C, N and P

Microalgae

N, P, C

O2

CO2

Bacteria

COD

Biofuels

Reusable WW

Bio-fertilizers

All-gas project: From Wastewater to Bio-energy

SCREENING 1mm

LEAR

Low energy algae reactor

Water Reuse

DAFAST

Algae harvesting

Algae Biomass

Biofertilizers

ANAEROBIC DIGESTION

Biogas

Biogas upgrading

Biomethane

Fleet Demo
Installations:
From pilot plant to demo scale

FROM WASTEWATER TO BIOENERGY

Light & Temperature
Water
Space

No arable Land: unused salt ponds

No Freshwater

El Torno WWTP
10 000 m3/d
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

FROM WASTEWATER TO BIOENERGY
All-gas project: From Wastewater to Bio-energy

DEMO plant: Start construction March 2016

- 4 raceways of 5205 m²
- 2 X 110 m³/h DAF
- 1 X 2700 m³ Anaerobic Digestor

Innovative design
INNOVATIVE LOW ENERGY ALGAE REACTOR: LEAR

PADDLE WHEEL
Total energy efficiency:
~5% U. Florence
<17% Borowitzia
~30% Weissmann

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)

INNOVATIVE ALGAL POND: LEAR

HRAP Longitudinal section
and two main cross sections
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

Prototype: 1000 m² cultivation surface

Conventional

LEAR®

Paddlewheel
0.5 W/m²
0.12 kW/m³ WW

80% Energy savings

Propeller
0.1 W/m²
0.02 kW/m³ WW
LAB TESTS:
• COAG/FLOC
• FLOTATEST

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

PROTOTYPE
DAFAST
15 m³/h
**MAIN RESULTS:**

6 X 32 m² ponds

**Autochthonous Species:** Dominance of one strain of Coelastrum sp.
**PROTOTYPE Results: Cultivation and WWT**

- **25 gVSS/m²d = 91 Ton/ha yr**
- **Very high dilution rate (<3 d HRT)**
- **Pumping + cultivation + harvesting energy < 0.1 kWh/m³**
- **Effluent fits EU directive for N + P**

**Flow** 94.1 m³/d  
**TN** 12.0 ppm  
**TP** 6.3 ppm  
**VSS** 263.2 g/m²

**MAIN RESULTS: 2 X 500 m² ponds**

**Biomass production and wastewater treatment**

**Flow** 100 m³/d  
**TN** 46.4 ppm  
**TP** 8.3 ppm

**65-140 Ton/Ha yr**

**73% and 87 % TN and TP recovery**

**TN** 12.0 ppm  
**TP** 6.3 ppm  
**COD** 101.2 ppm  
**TSS** 25.4 ppm
**DAFAST Results – Clarification and Biomass Thickening**

### Chemicals
- Coagulation: 20 ppm Al2O3
- Flocculation: 0.5 ppm Poly
- DAFAST

### Electricity
- 0.05 kWh/m³

### Removal efficiency

<table>
<thead>
<tr>
<th>P-PO4</th>
<th>TSS</th>
<th>Biomass concentration %</th>
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<tr>
<td>84</td>
<td>92</td>
<td>4.5</td>
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<tr>
<td>92</td>
<td>71</td>
<td>4.8</td>
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<tr>
<td>92</td>
<td>82</td>
<td>4.6</td>
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<tr>
<td>91</td>
<td>89</td>
<td>4.9</td>
</tr>
<tr>
<td>87</td>
<td>92</td>
<td>5.1</td>
</tr>
<tr>
<td>92</td>
<td>95</td>
<td>5.1</td>
</tr>
</tbody>
</table>

- November
- December
- January
- February
- March

### Total cost
0.01 €/m³

**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
Energy production
Anaerobic digestion

![Graph showing energy production](image)

**Range**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Energy Production (L CH4/kgVSS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meso 35°C</td>
<td>168</td>
</tr>
<tr>
<td>Thermo 55°C</td>
<td>288</td>
</tr>
<tr>
<td>Ambient 20°C (2xHRT)</td>
<td>147</td>
</tr>
</tbody>
</table>

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

Energy production
Enhancing the yield

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

**BMPs**

**Fresh**

**CAMBI ®**

Energy production
Enhancing the yield

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

**BMPs**

**Fresh**

**CAMBI ®**

Can we increase the biogas yield

- Similar to conventional waste activated sludge biogas production
- At ambient temperature, similar to mesophilic at twice the HRT
All-gas ENERGY BALANCE

Energy Potential of photosynthetic oxygenation

26 g algae m⁻² d⁻¹

40 g O₂ m⁻² d⁻¹

1.5 g O₂/g algae

HRAP = 0.3 m depth

120 g O₂ 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 m³ d⁻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

\[
\text{EROI}_{BM} = \frac{EC_{BM} + EC_{CP}}{E_{BM}} = \frac{LHV_{BM} \cdot \rho_{BM} + EC_{CP}}{E_{BM}} = 1.9
\]

- 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

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

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

- 58 cars / ha
- Compare to Bio-ethanol (Sugarcane) or Bio-diesel (Palm Oil): 5 cars / ha
Comparing Biofuel Production per hectare

- **μAlgae (BioCH4)**
  - > 10,000 kg CH4/ Ha/yr
  - (5 kg CH4/100km)
  - >10 vehicles

- **Sugar Bioetanol**
  - 5,000 L/Ha/yr
  - (5 L/100km)
  - 5 vehicles

**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

**Country Nº pers**
- Angola 130
- UAE 10
- España 19
- USA 8

**Species** | L oil/ha | Univ. Lab. Reference
--- | --- | ---
Scenedesmus - 16 % Oil | 17,330 | Almeria: 5g lipid/m²-d, Fernández Sevilla et al., (2008)
Nannochloropsis | 23,500 | Firenze: 2 step process, 9.5 g biomass/m²-d, Rodolfi et al., (2009)

Thank you for your imagination: Wastewater is Biofuel
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 Perspective
Algae for Wastewater Treatment Forum
Daniel B. Higgins, P.E. – Director Central US
October 23, 2016

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

---

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

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

Key
- CMS Manufacturing Sites
- ES Manufacturing Sites
- Technology Sites
- GE Global Research Centers
- Locations with 75+ Employees

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
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
Algae Captured our Attention

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
What to do with all the Biomass

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

GE’s Algae Education
Recipe to Grow Algae

WaterSolution
Sunlight
Carbon
Nutrients

Sources of the Growth Necessities

• Wastewater and Nutrients
• Artificial Light?
• Carbon - Power Plants - Industry
What to do with all the Algae

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

The GE Business Need
Collaborators

Integrity
Business Plan - Vision
Self Sustaining
Professional

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

Kuldip Kumar, Ph.D
Monitoring & Research Department
MWRD Chicago
Phone: 708.568.3579
Email: Kuldip.Kumar@mwr.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
  - Biofuels
  - Pharmaceuticals
  - Biomass (biogas)
  - Food additives
  - Co-composting (Fertilizer)
  - 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 🙄
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

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

![Growth Curves](image)
**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

---

**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 CO₂ mass transfer
5. Enhance algal productivity
6. Adsorption of N,P, & metals

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

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

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O’Brien WRP Maintenance & Operations Staff: Ms. Matual; Mr. Stubing; Mr. McNamara

Show-Ling Lee (Iowa State University)
Daren Jarboe (Iowa State University)

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Iowa Regent Innovation Fund
USDA SBIR
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
$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

<table>
<thead>
<tr>
<th></th>
<th>Sewage sludge</th>
<th>Algae solids</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>30000 ppm</td>
<td>7960 ppm</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>15000 ppm</td>
<td>20000 ppm</td>
</tr>
<tr>
<td>Sulfur</td>
<td>10000 ppm</td>
<td>6630 ppm</td>
</tr>
<tr>
<td>Calcium</td>
<td>40000 ppm</td>
<td>8800 ppm</td>
</tr>
<tr>
<td>Magnesium</td>
<td>4000 ppm</td>
<td>1100 ppm</td>
</tr>
<tr>
<td>Potassium</td>
<td>3000 ppm</td>
<td>2460 ppm</td>
</tr>
<tr>
<td>Iron</td>
<td>17000 ppm</td>
<td>1200 ppm</td>
</tr>
<tr>
<td>Zinc</td>
<td>1200 ppm</td>
<td>1500 ppm</td>
</tr>
<tr>
<td>Copper</td>
<td>750 ppm</td>
<td>38 ppm</td>
</tr>
<tr>
<td>Manganese</td>
<td>250 ppm</td>
<td>150 ppm</td>
</tr>
<tr>
<td>Boron</td>
<td>25 ppm</td>
<td>11.6 ppm</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>10 ppm</td>
<td>1.3 ppm</td>
</tr>
</tbody>
</table>

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

But how can nutrients be recovered?

Anaerobic digestion

![Ammonium release in anaerobically digested algae](image)
But how can nutrients be recovered?
Anaerobic digestion

**Phosphorus release in anaerobically digested algae**

- The Pearl® process
- Chemical precipitation of struvite crystals in fluidized bed
- $\text{NH}_4\text{MgPO}_4\cdot6\text{H}_2\text{O}$
- Valuable product
- ~85% of soluble P
- 5-15% total N
But how can nutrients be recovered?

Other proprietary processes

- The Unity Envirotech Fertilizer Granulation Process
- VitAG Ammonium Mix Process

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

<table>
<thead>
<tr>
<th></th>
<th>Mean Influent (ug/l)</th>
<th>Mean Effluent (ug/l)</th>
<th>Percent Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc</td>
<td>141</td>
<td>20.6</td>
<td>85</td>
</tr>
<tr>
<td>Copper</td>
<td>47.3</td>
<td>9.51</td>
<td>80</td>
</tr>
<tr>
<td>Mercury</td>
<td>0.96</td>
<td>0.33</td>
<td>66</td>
</tr>
<tr>
<td>Lead</td>
<td>2.61</td>
<td>1.00</td>
<td>62</td>
</tr>
<tr>
<td>Chromium</td>
<td>3.37</td>
<td>2.43</td>
<td>28</td>
</tr>
<tr>
<td>Arsenic</td>
<td>2.07</td>
<td>2.00</td>
<td>3</td>
</tr>
<tr>
<td>Silver</td>
<td>4.13</td>
<td>4.00</td>
<td>3</td>
</tr>
<tr>
<td>Selenium</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Cadmium</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Nickel</td>
<td>13.4</td>
<td>13.6</td>
<td>-1</td>
</tr>
</tbody>
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### Algae solids metal and 503 limits

(Central California municipal pond, 2008)

#### Algae solids metals

<table>
<thead>
<tr>
<th></th>
<th>503 requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic</td>
<td>ppm unless indicated</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.45 0.87 85 39 39 1.9</td>
</tr>
<tr>
<td>Chromium</td>
<td>5.1 10 - - -</td>
</tr>
<tr>
<td>Cobalt</td>
<td>&lt;0.5 1.1 - - -</td>
</tr>
<tr>
<td>Copper</td>
<td>69 140 4300 1500 1500 75</td>
</tr>
<tr>
<td>Lead</td>
<td>1.9 5 840 300 300 15</td>
</tr>
<tr>
<td>Mercury</td>
<td>270 (ppb) 610 (ppb) 57 17 17 0.85</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>1 5 75 - - -</td>
</tr>
<tr>
<td>Nickel</td>
<td>2.8 7.3 420 420 420 21</td>
</tr>
<tr>
<td>Selenium</td>
<td>0.9 2.3 100 100 5</td>
</tr>
<tr>
<td>Zinc</td>
<td>140 280 7500 2800 2800 140</td>
</tr>
<tr>
<td>Fecal coliform</td>
<td>&lt;2/g &lt;2/g 2M MPN/g 1000 MPN/g</td>
</tr>
<tr>
<td>Salmonella</td>
<td>3 MPN/4 g</td>
</tr>
</tbody>
</table>
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