U.S. Department of Energy (DOE)
Bioenergy Technologies Office (BETO)
2017 Project Peer Review

Scale-up of Algal Biofuel Production Using Waste Nutrients

MARCH 9, 2017 UPDATE

ADVANCED ALGAL SYSTEMS

TRYG LUNDQUIST, PH.D., P.E.

CIVIL AND ENVIRONMENTAL ENGINEERING DEPARTMENT

CALIFORNIA POLYTECHNIC STATE UNIVERSITY, SAN LUIS OBISPO

MICROBIO ENGINEERING INC.

Goal Statement: Prepare for Scale-Up

- *Prepare for scale-up of 2500 gal/ac-yr of biofuel intermediates (BFI) via hydrothermal liquefaction (HTL) of microalgae grown at 7 acres of existing raceways at a wastewater treatment facility.*
- *Maximize productivity with CO_2 addition and demonstrate bioflocculation/settling harvesting of the algal biomass at pilot scale.*
- *Techno economic analysis (TEA) and lifecycle assessment (LCA).*

Measured Project Outcomes

- ***33 g biomass / m^2-day annual average x 0.35 g HTL oil / g algae***

  → 4,100 gal/ac-yr ignoring losses
- ***$4 - $9 per gal BFI depending on revenue streams & RINs***

Relevance

- *Lower cost by: increasing productivity, using low-cost harvesting, increasing HTL yield/quality, and capturing wastewater revenue and RINs.*
- *Basic algae wastewater treatment is already full-scale and available for demonstration of HTL at pilot scale.*

Quad Chart Overview

Timeline

Project start: September 30, 2013

Project end: June 30, 2016 (extended to June 30, 2017)

Percent complete: 89%

Budget

	Total Costs FY 12 – FY 14	FY 15 Costs	FY 16 Costs	Total Planned Funding (FY 17-Project End Date)
DOE Funded	13,329	361,686	428,873	127,000
Project Cost Share Comp.*	MicroBio 48,583 ______ Cal Poly 0.00	MicroBio 149,664 _______ Cal Poly 11,269	MicroBio 0.00 _______ Cal Poly 115,844	MicroBio 0.00 _______ Cal Poly 93,004

MYPP Barriers: Aft A-D, G, H & J

Mixotrophic data supports projection of 4,100 gal/ac-yr of biofuel intermediate.

Climate-simulation lab reactors developed for autotrophic strain evaluation (LEAPS).

Over a year of pilot cultivation using polycultures, integrated with low-cost, low-input harvesting and thickening.

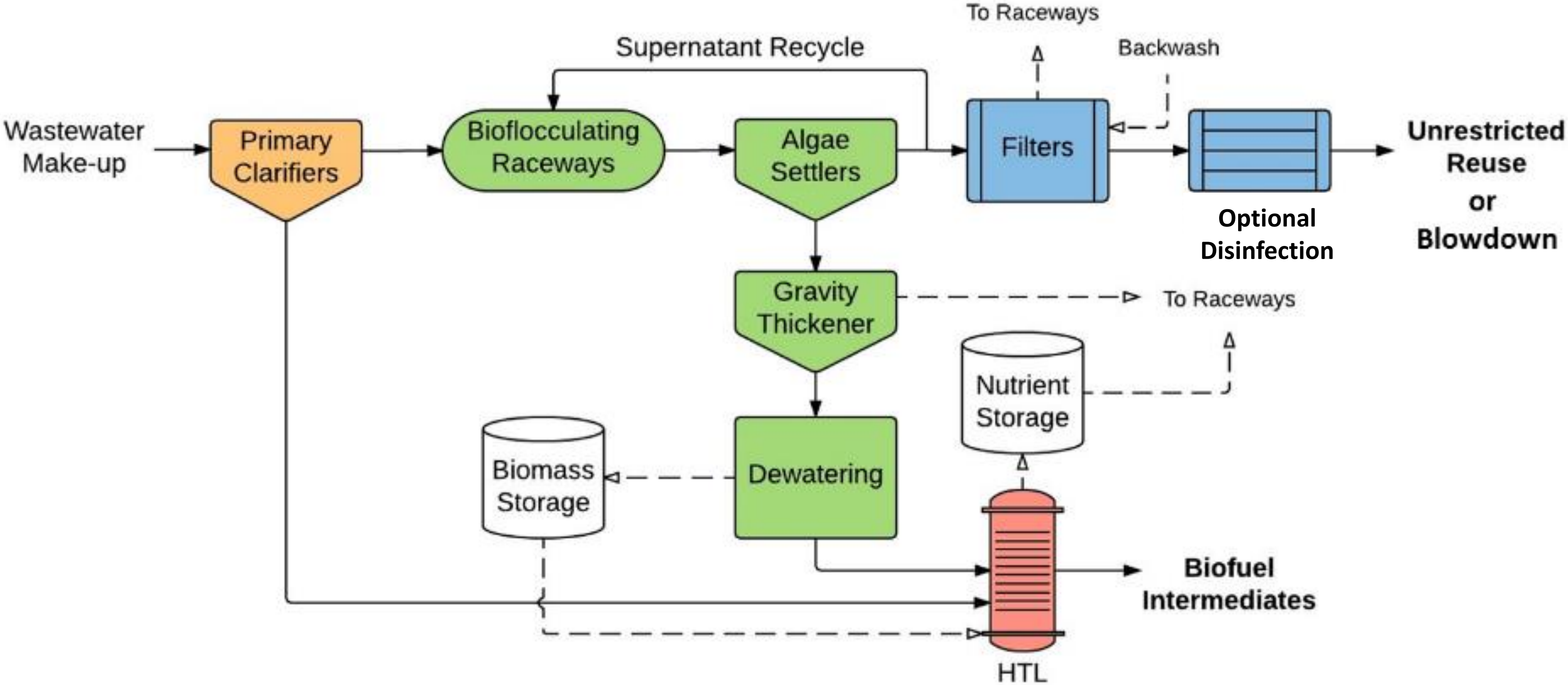
Multiple HTL runs with characterized feedstock and recycling of HTL nutrients.

Partners

- Total project $2,049,157
- SNL (7% of total project incl. cost share all FYs): Look for relationships between dominant organisms and culture performance
- PNNL (27%), hydrothermal liquefaction of algal biomass, modeling strain growth optimization
- MicroBio Engineering Inc. (10% as cost share): LCA/ TEA and engineering services
- Delhi County Water District, support in use of the project site

Scale-up Process Flow (RNEW®):

- Wastewater → algae biocrude + water for reuse
- Reuse can be crop irrigation or further algae production with eventual blowdown.



Pilot systems were operated at a full-scale raceway wastewater treatment plant to learn to maximize productivity for scale-up in Phase-2.

Delhi, California (pop. 11,000, San Joaquin Valley) operates a 0.6 million gallon per day (MGD) wastewater treatment plant that includes two 3.5-acre algal raceways for oxygen production and nutrient removal.

The PI was a design engineer on the original construction in 1998.

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

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

Solar dried algae

Concrete drying pad

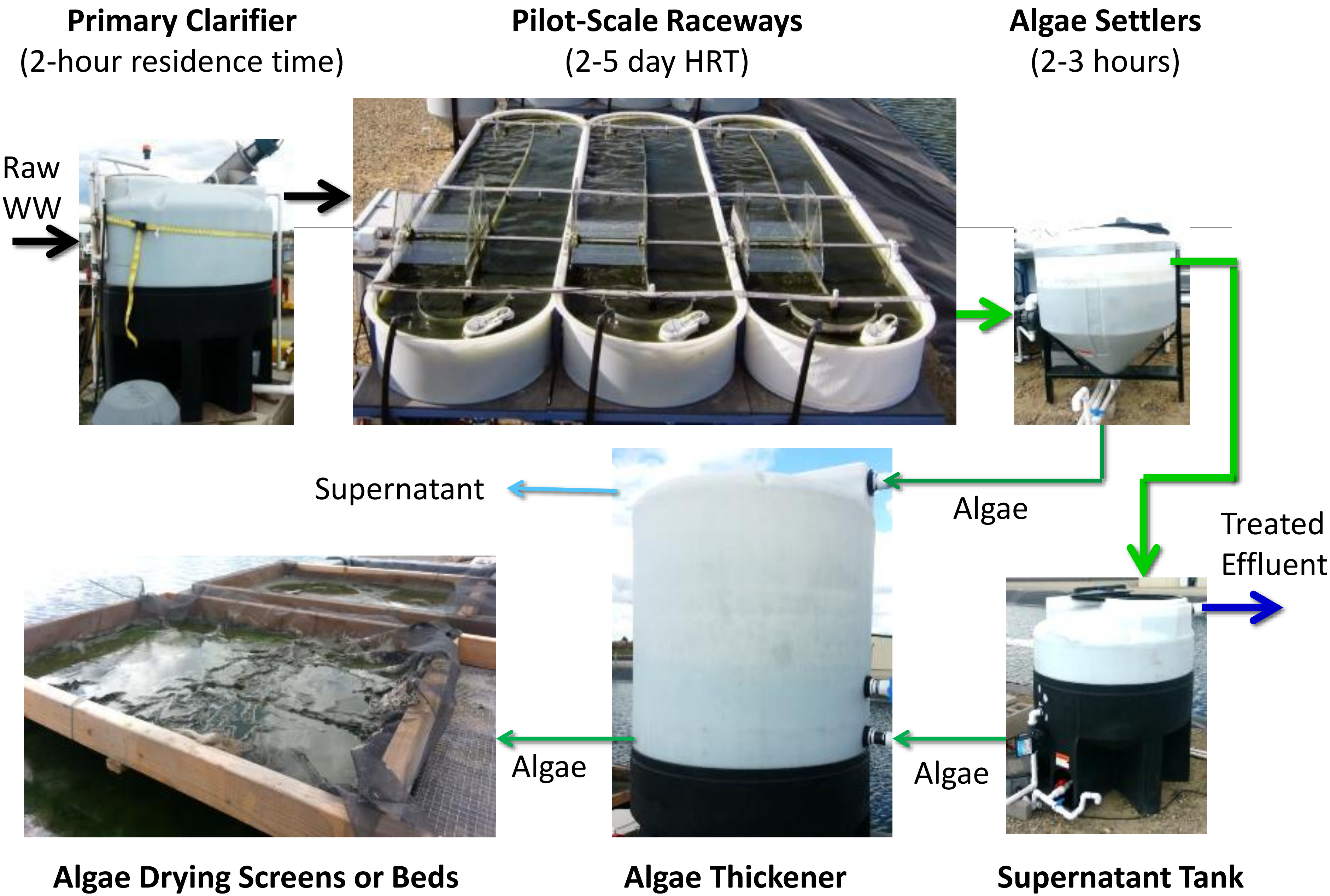
Nine 3.5-m^2 raceways with automated controls, settling units, thickener, and drying beds were installed to study optimization of productivity and harvesting.

<u>Manipulated Variables</u>

Residence time

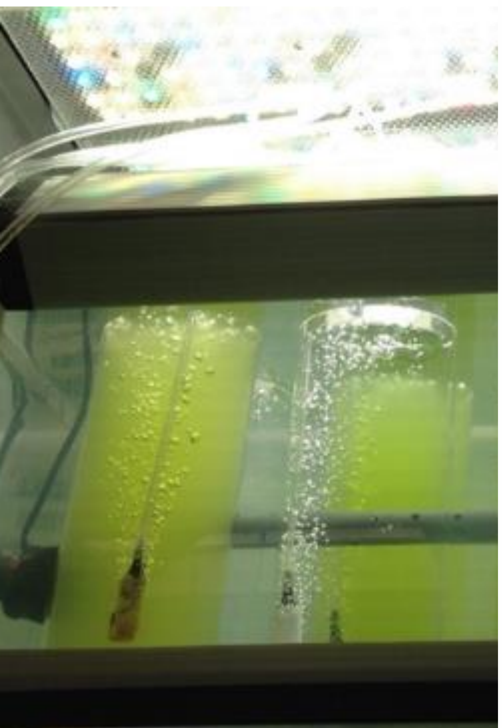
Influent water source

CO_2 addition

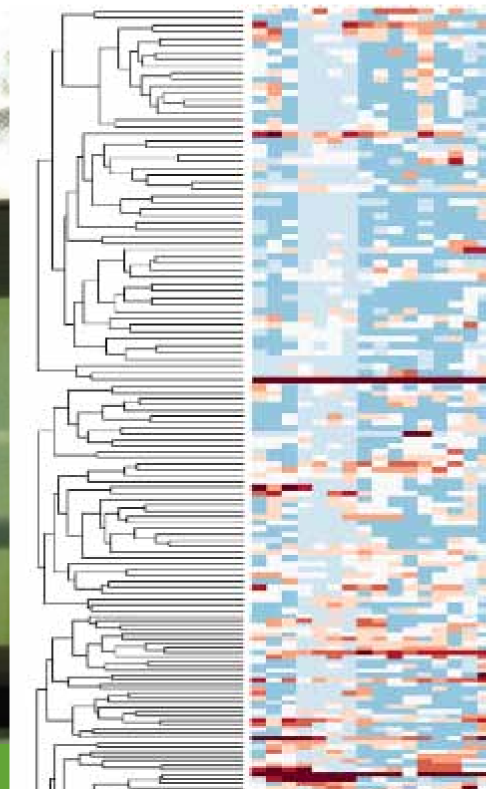

Primary Clarifier
(2-hour residence time)
Pilot-Scale Raceways
(2-5 day HRT)
Algae Settlers
(2-3 hours)
Raw WW
Supernatant
Algae
Treated Effluent
Algae
Algae
Algae Drying Screens or Beds
Algae Thickener
Supernatant Tank

Pacific Northwest & Sandia National Labs supported the pilot with a new PBR, genetic characterization, and conversion to intermediate. Cal Poly closed loop on HTL wastewater. MicroBio provided equipment, hydraulic studies, TEA, LCA, and consulting.

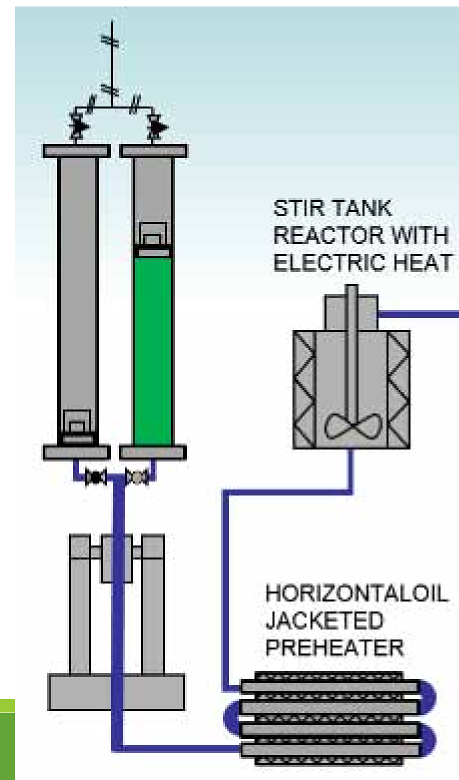
Pond simulators developed & validated (PNNL-Sq)



Community genetics to understand bioflocculation & productivity (SNL)



Wastewater polyculture HTL and hydrotreat (PNNL-R)



HTL aqueous waste recycled for algae growth (Cal Poly)

2 – Approach (Management)

PI Tryg Lundquist and his Cal Poly team carry out algal cultivation studies at Delhi. Dr. Lundquist is responsible for the coordination of all project partners and leading partner meetings.

TASK 1: Develop models to identify high-performance strains and culture methods (Lead: Dr. Michael Huesemann PNNL)

TASK 2: Maximize algal productivity and harvesting efficiency in Delhi pilot ponds (Lead: Cal Poly, Dr. Todd Lane Sandia)

TASK 3: Full-scale raceway hydraulic characterization (Lead: Cal Poly and MicroBio Engineering, Stan Feathers, General Manager, Delhi County Water District)

TASK 4. Biomass processing to biofuel intermediates (Lead: Dr. Dan Anderson PNNL, and Cal Poly)

TASK 5. Scale-up engineering analysis, modeling, and planning (Lead: Dr. John Benemann MicroBio Engineering and Cal Poly)

TASK 6. Stage Gate Review and Preparations (Lead: Cal Poly, with PNNL, SNL, and MicroBio Engineering)

2 – Approach (Technical)

Technical Approach

- Characterize a full-scale algae based wastewater treatment system
  - Productivity
  - Hydraulically
- Use pilot-scale raceway ponds to investigate optimization of biomass production and treatment
- Harvest biomass and convert to biofuel intermediates by hydrothermal liquefaction

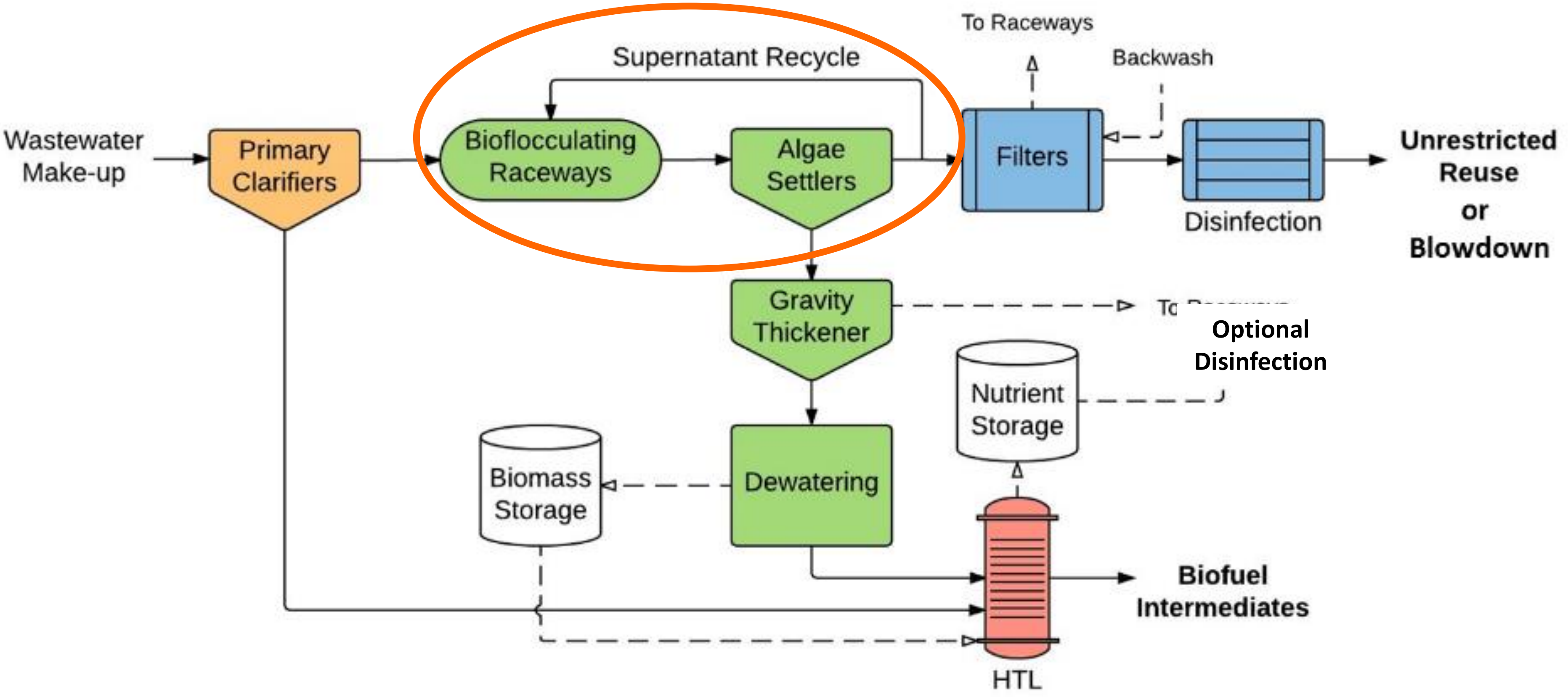
Challenges

- Increasing productivity
- Recycling nutrients from HTL
- Converting algae carbon to fuel

Critical success factors

- **Technical:** Achieving productivity, harvesting efficiency, and conversion to fuel sufficient to produce 2,500 gallons per acre per year.
- **Market & Business:** Achieving at least 25% lower cost than conventional wastewater treatment.

Optimize biomass productivity and settling



Technical progress and Accomplishments

Task 1: Optimize biomass productivity- Complete

Develop laboratory and computer modeling methods capable of rapidly identifying high-productivity strains and optimal culture methods specific to locations.

DOE 1412 growth was optimized in climate simulating photobioreactors in the lab (ML 1.0, 1.1, 1.2, 1.3,1.4) and compared field data (ML 1.5, 1.6).

Rationale:

An accurate species-specific Biomass Assessment Tool (BAT) will accelerate identification of strains best-suited to location and operational parameters in each season. Input to resource analyses, TEA, and LCA.

ML 1.4 Climate-Simulating Photobioreactor Development

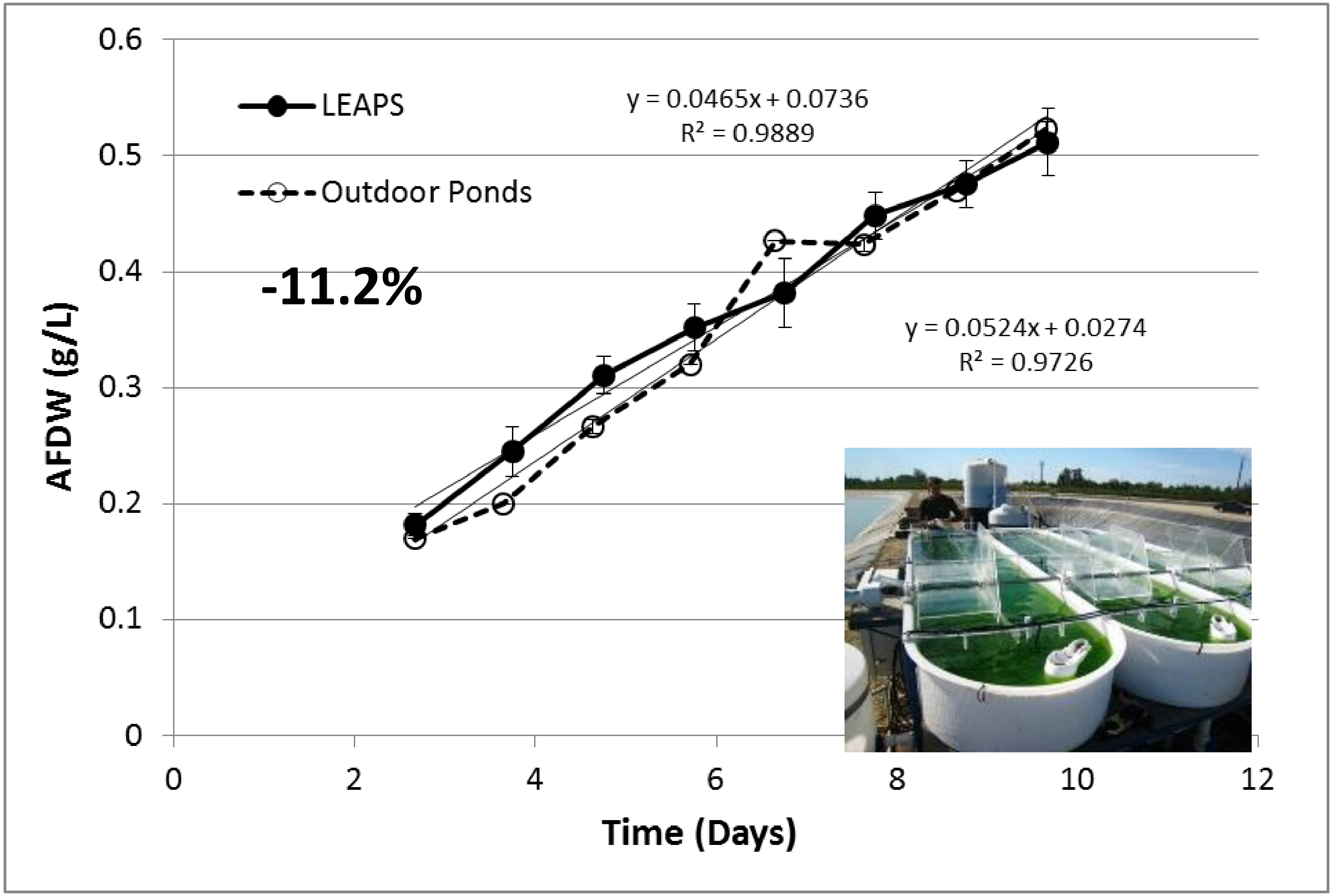
LEAPS pond simulator was developed in this project and has since been used on the following DOE projects:

- RAFT: Tested Scenedesmus, Monoraphidium, and Stichococcus minor.

- Microalgae Analysis AOP project (Mark Wigmosta PI): Evaluated cold strains (e.g., Chlorella antarctica).
- HTL nutrient recycling AOP project: Grew Chlorella sorokiniana with recycled HTL nutrients in the LEAPs, and tested semi-continuous culture conditions.
- DISCOVR consortium project: Will test many strains in climate-simulation of the ASU ATP3 testbed site. Already tested Chlorella sorokiniana 1412, Chlorella sorokiniana UTEX 1228, and a LANL isolate in the LEAPS.
- BETO Incubator project: We will most likely use the LEAPS to conduct a few experiments with carbonic anhydrase addition.

ML 1.5 Initial Validation of csPBRs, and ML 1.6 Validation of Growth Model & csPBRs with the wastewater treatment facility pond data

The LEAPS Successfully Simulates *Chlorella sorokiniana* Outdoor Ponds (Dehli, CA, July). The Biomass growth model over predicts biomass productivity by 23%.



Task 2: Maximize algal productivity and harvesting efficiency in Delhi pilot ponds- 89% Complete

Develop cultivation and harvesting practices to maximize outdoor biomass/biofuel intermediate productivity for polyculture and DOE 1412 (targeting >2,500 gallons/acre-year).

Evaluate current full-scale wastewater treatment plant practices and productivity and settleability. Suggest improvements based on pilot work.

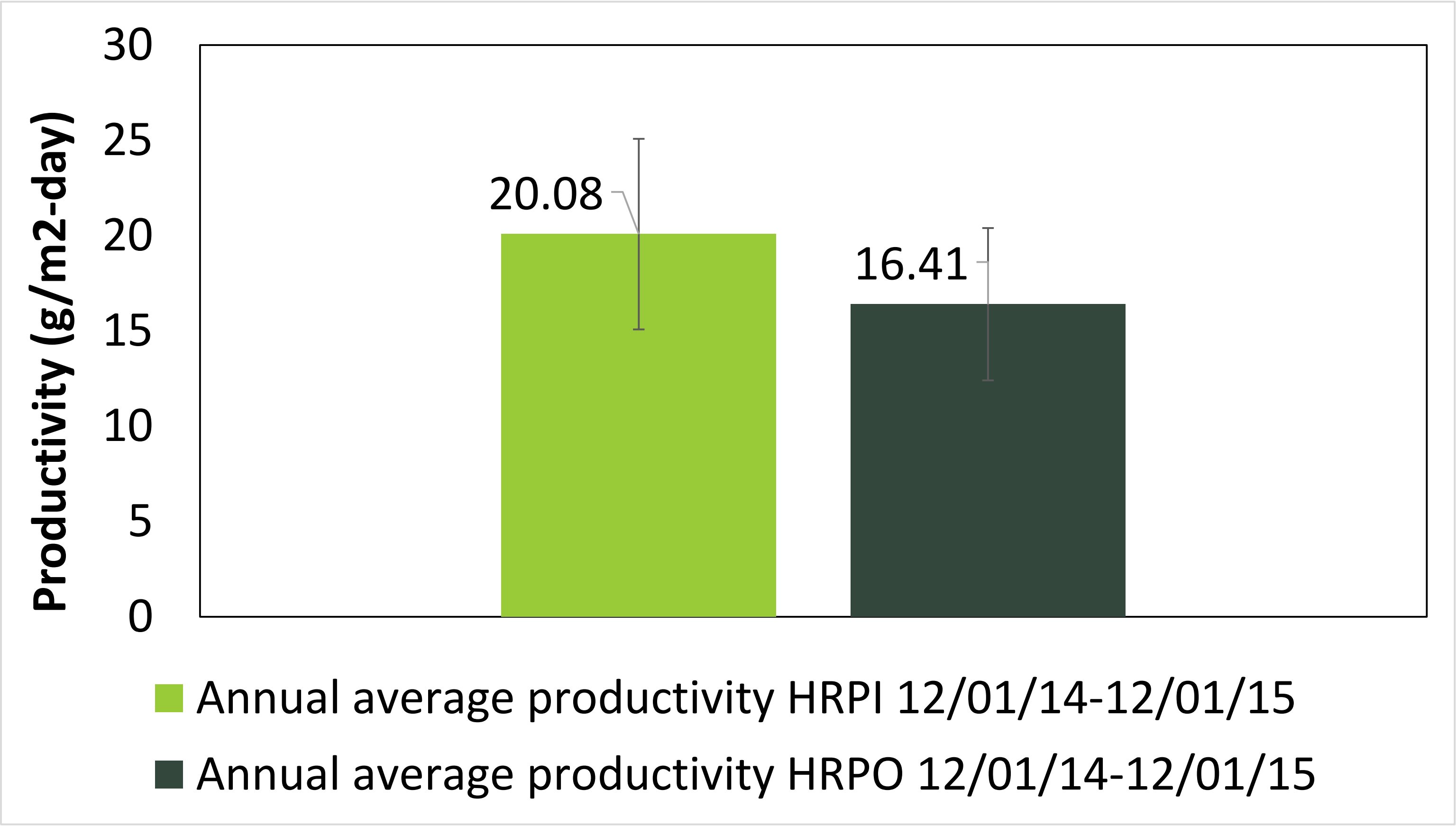
Generate pilot plant performance data to evaluate the Biomass Growth Model and the climate simulating photobioreactors of Task 1.

Rationale:

Delhi full-scale raceways are not optimized for productivity or settling. Operational and hydraulic modifications need to be evaluated for scale-up.   Biomass Growth Model and LEAPS need outdoor pilot validation.

ML 2.0 Annual average productivity - 20 g/m^2-day needed for 2500 gal/ac/yr.

Gross productivity shown. Respiration etc. losses occurred from the full-scale inner to the outer raceways (high rate ponds, HRPI and HRPO) in series. Harvesting suggested for between ponds and shorter residence time.



ML 2.1 Design and install pilot plant.
ML 2.2 Shakedown pilot: Feed rates, CO_2 dosing, paddle speeds, etc. can be changed on timer basis or remotely.

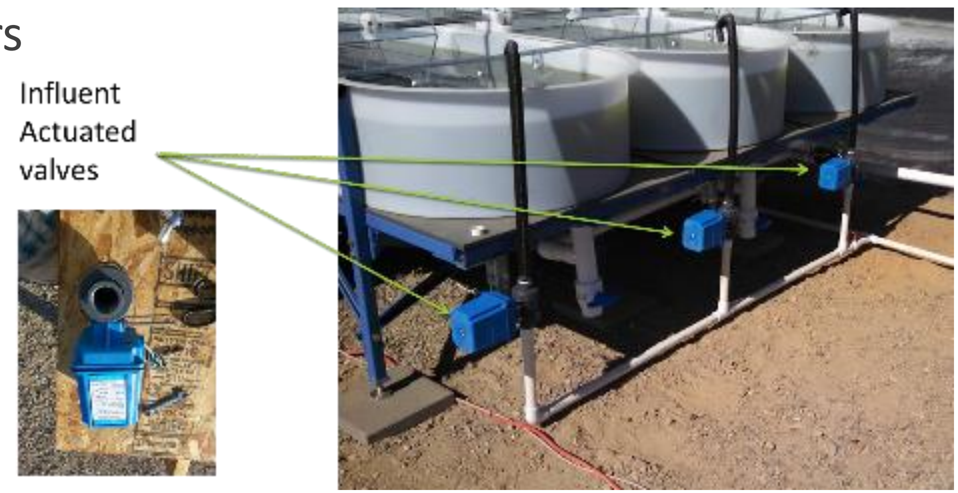
Install influent flow rate controllers

Settling Tanks

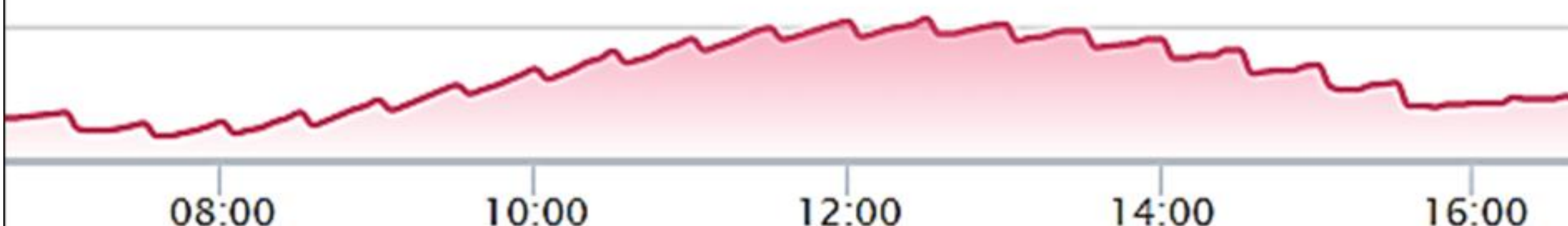
Pond temperature monitors

pH controllers

Dissolved oxygen probes



Dissolved oxygen conc. indicating influent pulses.



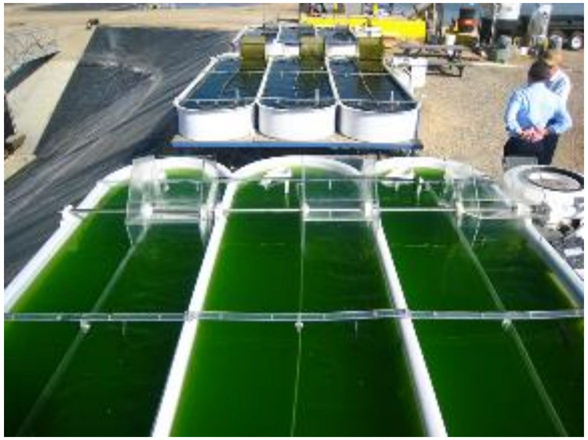
ML 2.3 Strain comparison

Compare the productivity of a wastewater polyculture to DOE 1412 (*Chlorella sorokiniana*) grown on defined media

Use the DOE 1412 data for ML 1.6 model and csPBR validation

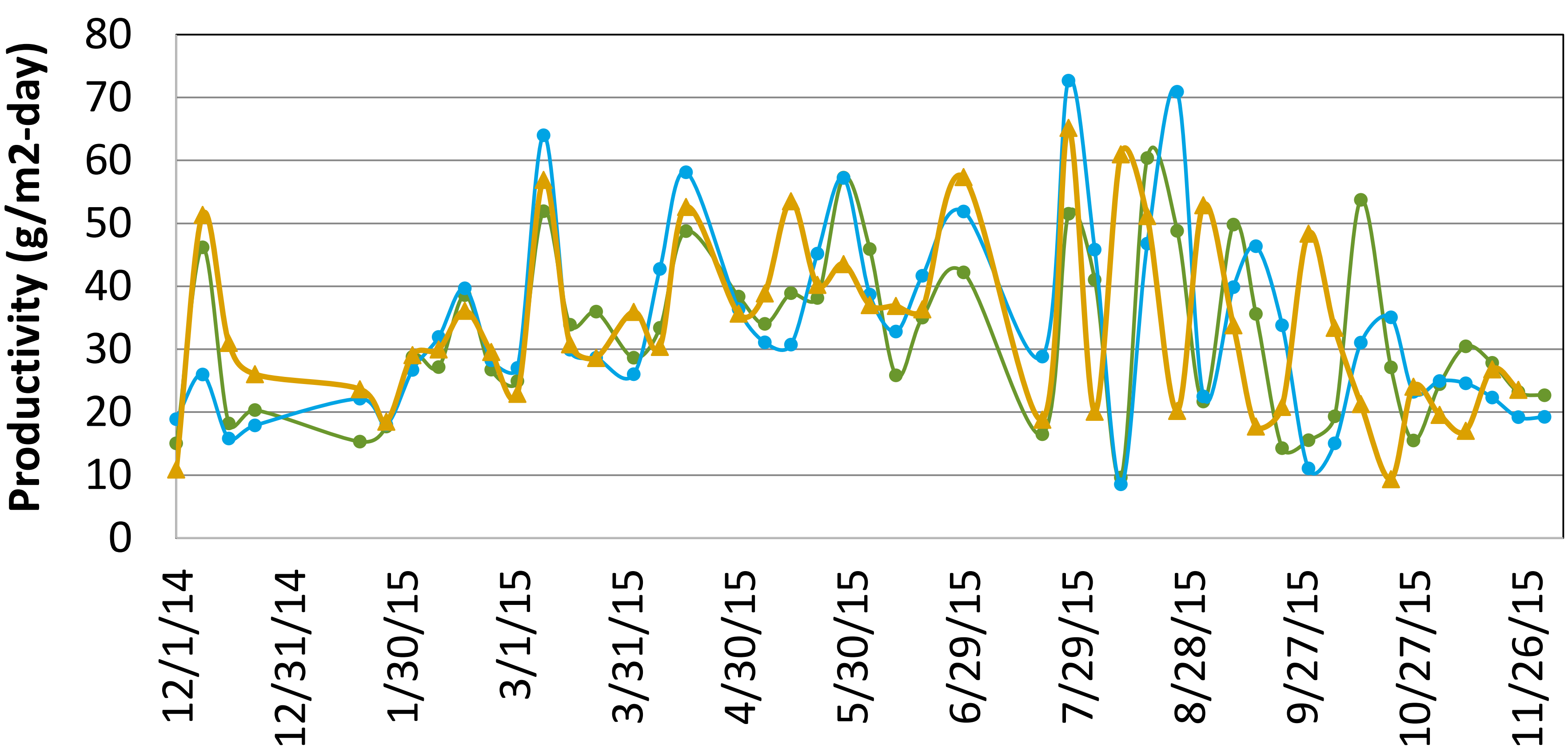
DOE 1412 remained the dominant strain through 10 days of batch cultivation.

- DOE 1412 Biomass productivity : 15 g/m^2-day During the same period
- Polyculture biomass productivity: 41 g/m^2-day (primary-fed, 2 day)
- Polyculture biomass productivity: 20 g/m^2-day (facultative pond-fed, 3.7 day)



The experimental data set, including light intensity and pond water temperatures, were sent to PNNL for csPBR validation (ML 1.6).

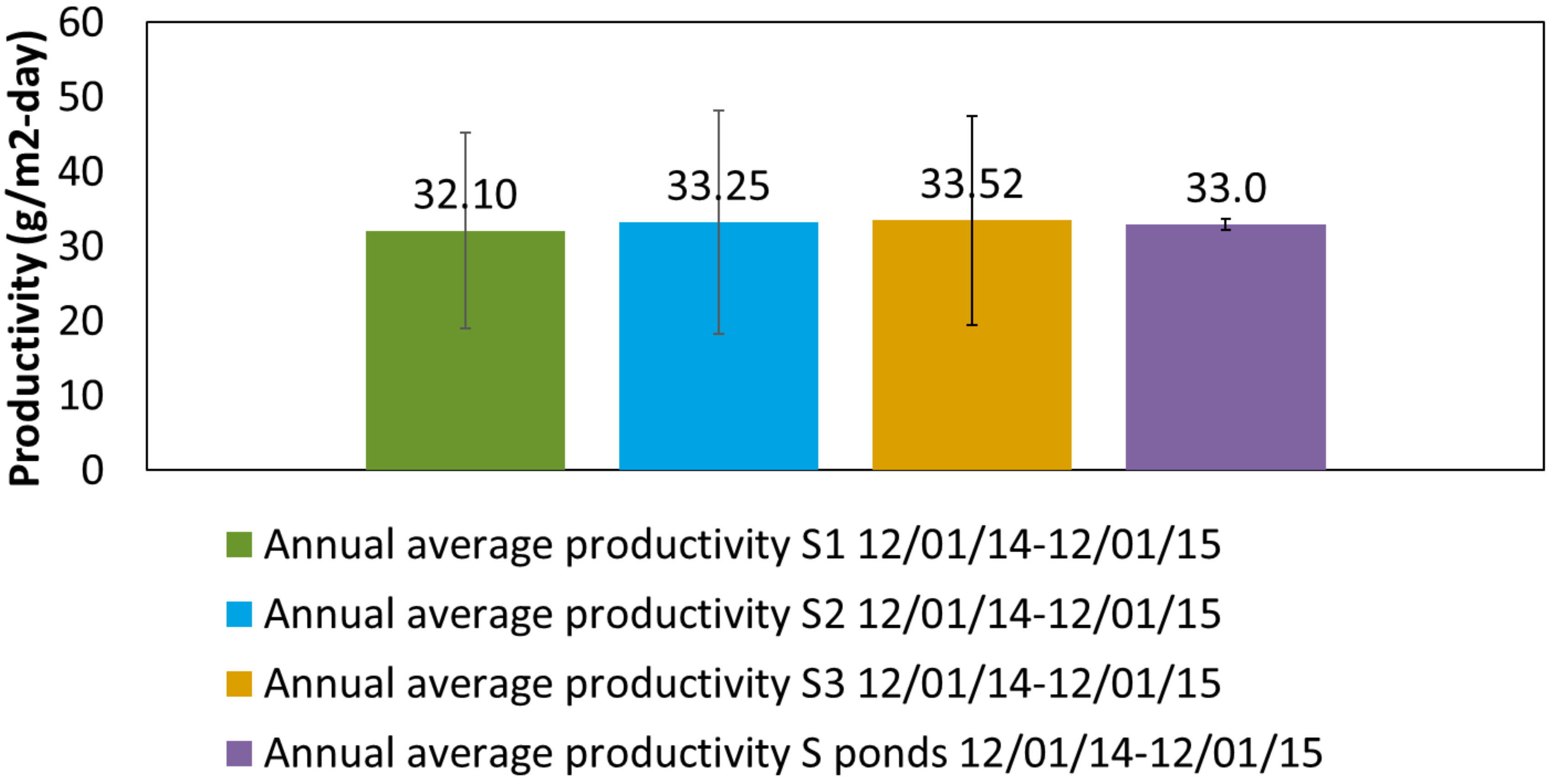
Pilot Productivity: One set of triplicate raceways was operated with primary effluent at a 2-day residence time all year.



ML 2.4 Dilution study

•*Productivity: 33 g biomass / m^2-day annual average. This exceeds the goal of 20 g/m^2-day and 2500 gal/ac-yr of biofuel intermediates*

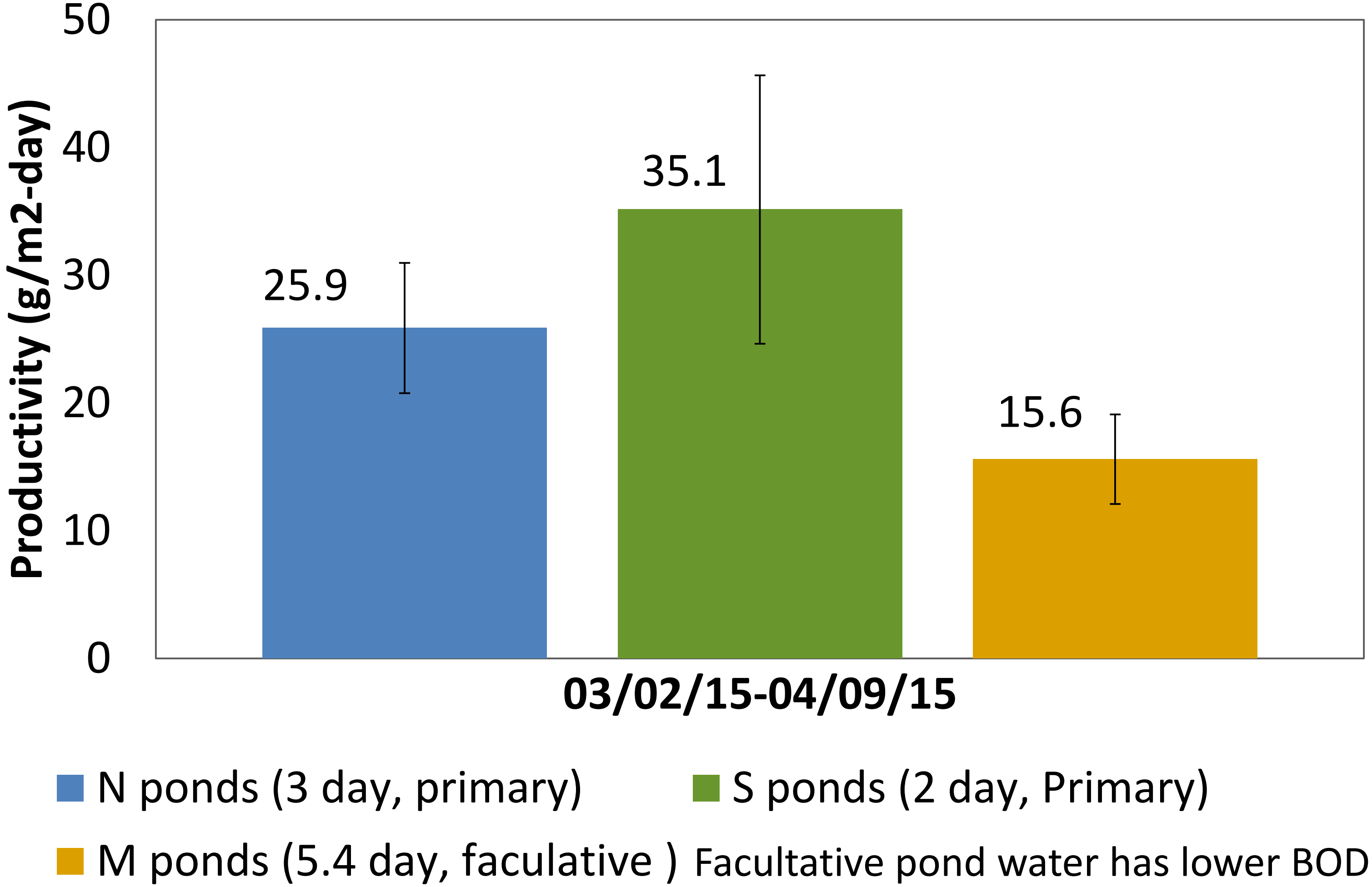
- *HTL conversion: 0.35 g oil/ g algae*
- ***4,100 gal/ac-yr** excluding any harvest losses*



About 50% of the productivity was autotrophic, based on mixo/heterotrophic yields.

ML 2.4 Dilution and productivity

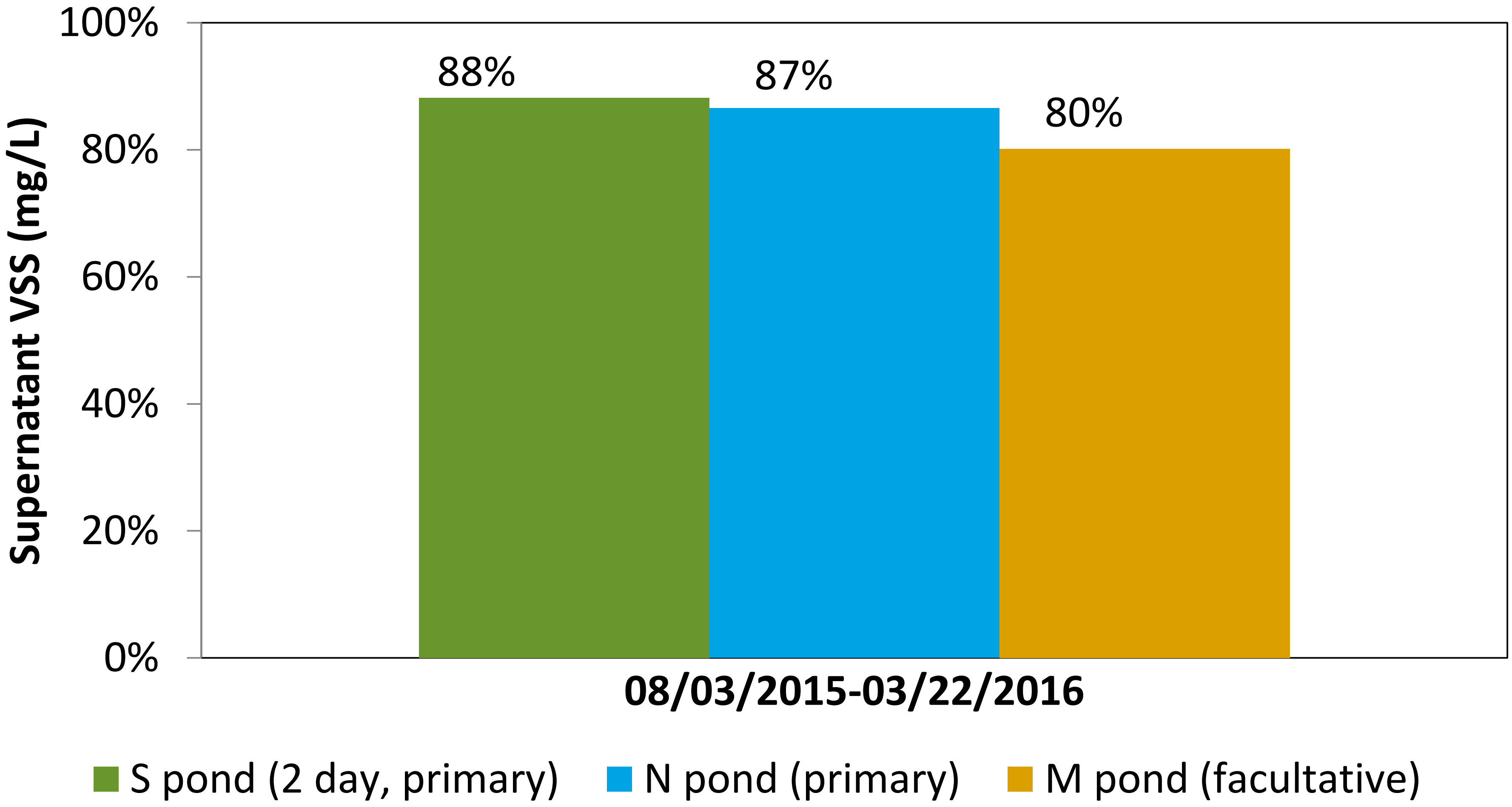
Conclusions: Shorter residence times and higher BOD (organic matter) loads are generally more productive



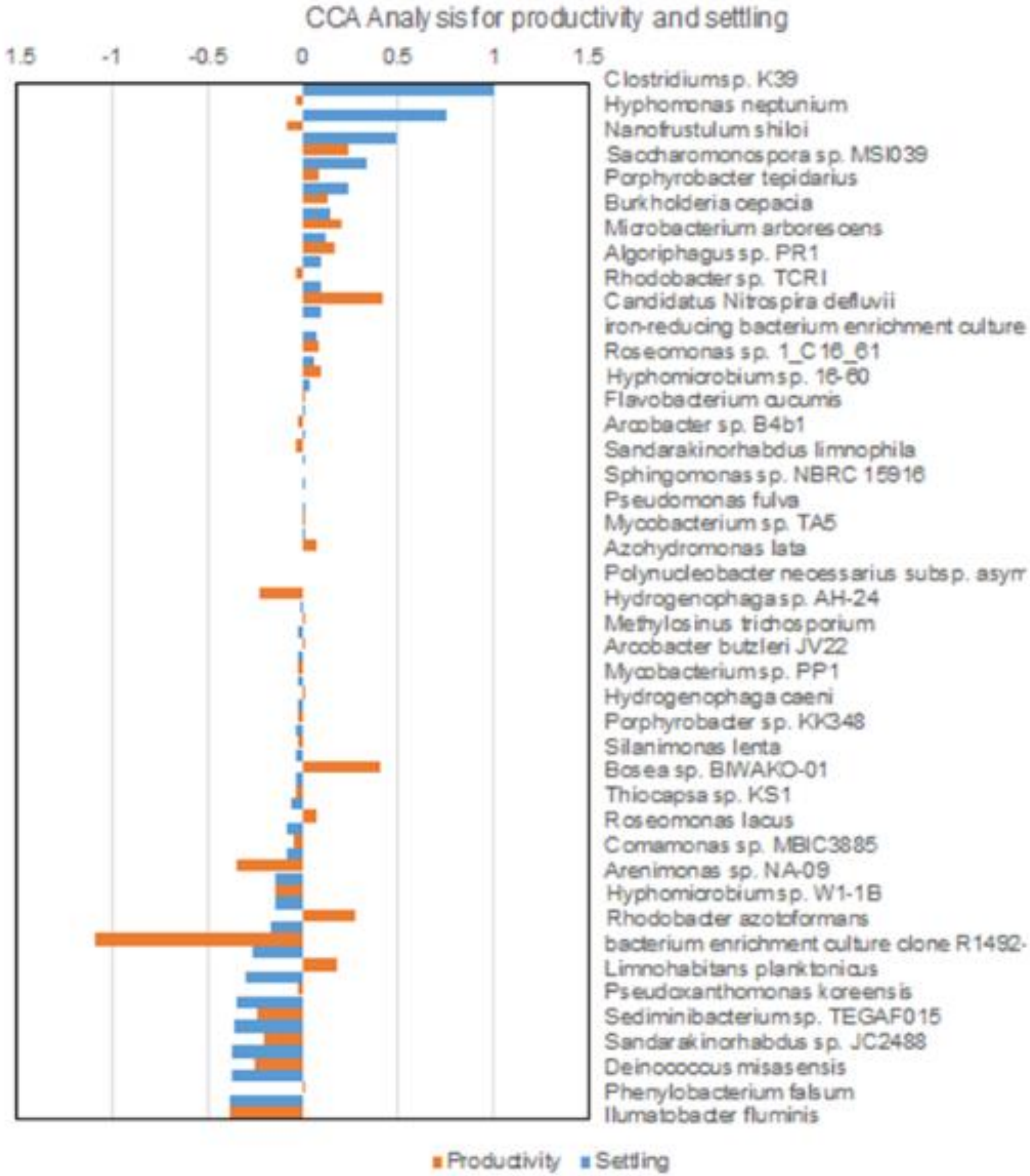
Facultative pond water has lower BOD.

ML 2.4 Dilution and settleability

Up to 88% of the algae biomass is recovered on average through low-cost, low-input gravity settling. Data are from lab batch settling.



ML 2.7 Organism ID: Identify genetically strains or consortia.



Look for relationships between dominant organisms and culture performance. *Clostridium, Hyphomonas* and *Saccharamonas* are correlated to high settling efficiency

TASK 3: Full-scale Raceway Hydraulic Characterization. 90% Complete

Characterize hydraulics of full-scale raceways at Delhi, including

- Paddle wheel energy consumption
- Mixing characteristics
- Create input parameters for CFD modeling by Sandia National Laboratories for modeling larger raceways (ATP^3) –ongoing

Parameters observed:

- Channel velocity
- Hydraulic head (lift) from paddle wheels
- Channel cross section profile (depth, width, etc.)
- Electrical Paddle Wheel Power Input

Rationale:

Evaluation of energy inputs to a full-scale system are needed to perform accurate lifecycle and techno-economic analyses

(ML3.3) Energy consumption and dispersion observed in two 1.4-ha raceways at 60-cm and 90-cm depths

- Area-normalized power consumption was 0.8-1.2 kW/ha at ~12 cm/s, which is sufficient for full scale algae wastewater treatment.
- Raceway mixing energy does not significantly impact algal biofuel cost if power consumption is < 2.0 kW/ha which is achieved by maintaining velocity at < 30 cm/s and properly sizing motors

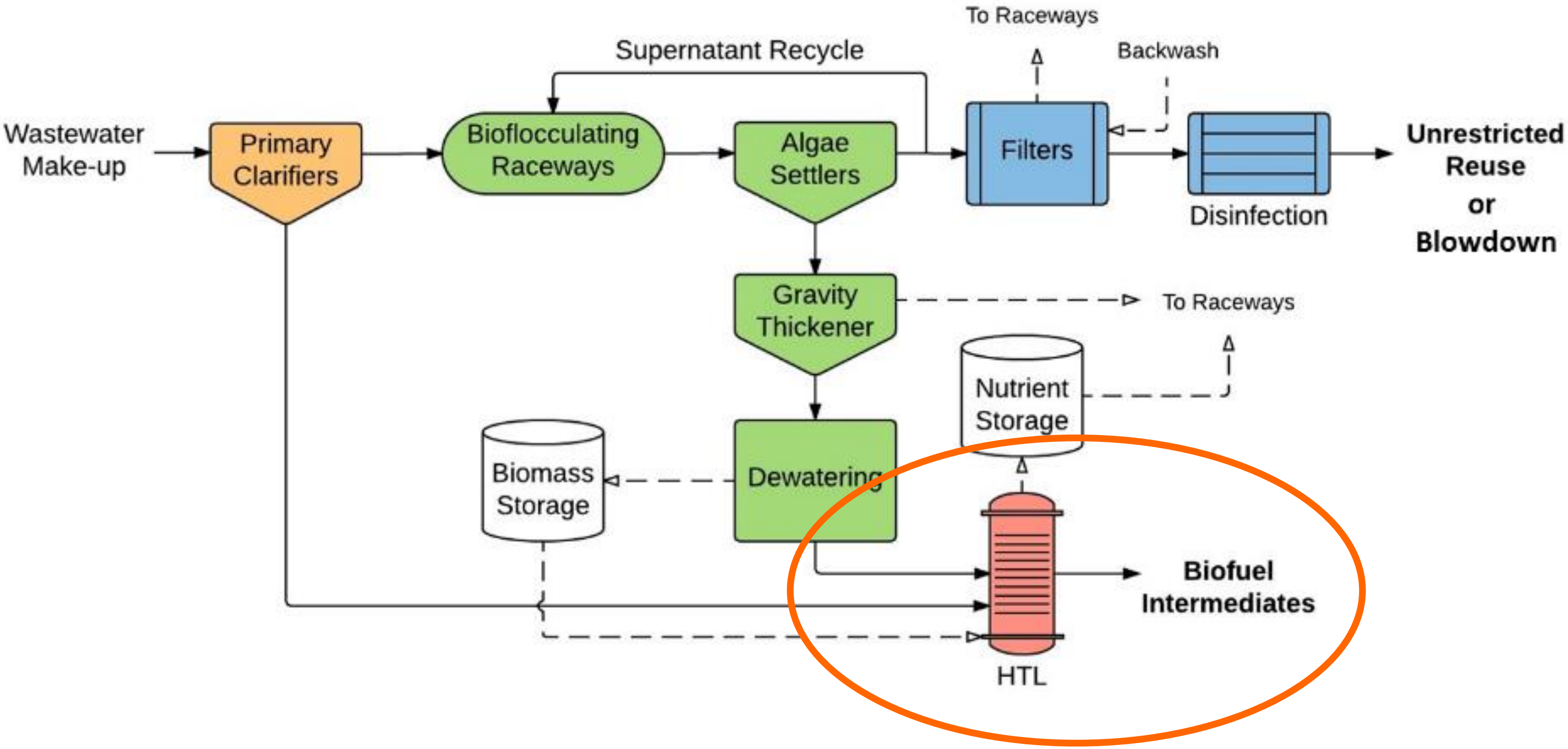
Velocity (m/s)	2-ft depth	3-ft depth
Inner HRP	0.13	0.12
Outer HRP	0.14	0.12

Normalized Motor Power (kW/ha)	2-ft depth	3-ft depth
Inner HRP	1.19	0.93
Outer HRP	1.07	0.80

Lift (inches)	2-ft depth	3-ft depth
Inner HRP	0.53	0.84
Outer HRP	0.64	0.84

MicroBio Engineering

Biomass processing to biofuel intermediates



TASK 4: Biomass processing to biofuel intermediates

Demonstrate and optimize the conversion of wastewater grown microalgal feedstock into a biofuel intermediate suitable for further upgrading.

Characterize air emissions to allow refinement of capital and operating cost estimates.

For all samples, process performance will be characterized by mass (C, N, P, S, H, and O).

Both Delhi and San Luis Obispo algae tested.

Rationale:

Evaluate the conversion of wet algal biomass to fuel intermediates.

ML4.1: HTL run 1: Biomass processing to biofuel intermediates

Mass Yields (Dry, Ash Free, Normalized):

Parameter	Unit	Run 1	Run 2a	Run 2b
Mass Balance	%	98%	99%	100%
Oil Yield, Mass (N)	g_{oil}/g_{fd}	15%	35%	36%
Solid Yield, Mass (N)	g_{solid}/g_{fd}	5%	3%	4%
Gas Yield, Mass (N)	g_{gas}/g_{fd}	2%	6%	5%
Aq. Yield, Mass (N)	g_{aq}/g_{fd}	78%	56%	55%

ML4.2 Hydrotreating

Conduct hydrotreating and distillation tests

Characterize the biofuel intermediate for downstream upgrading requirements

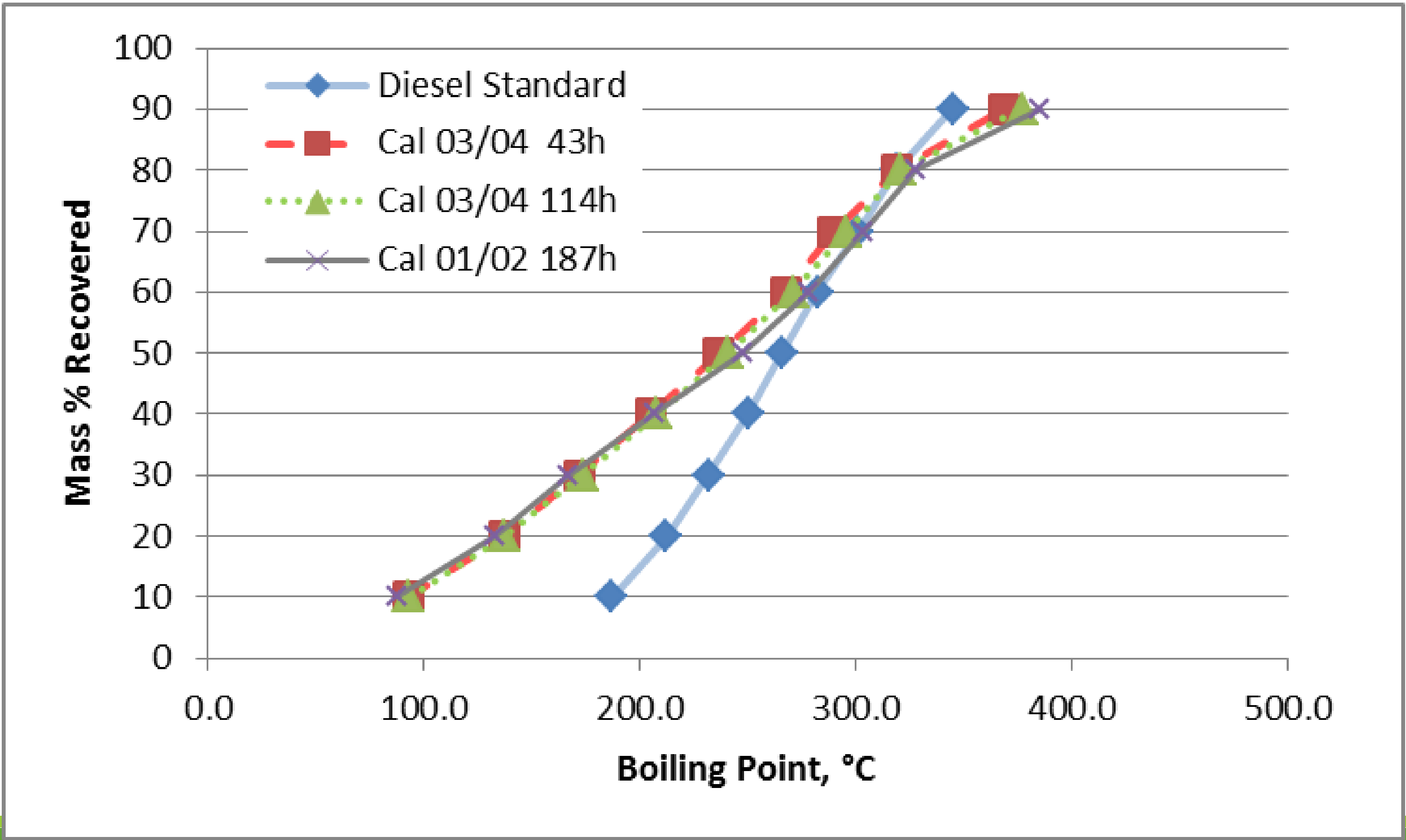
Report mass balances and fuel yield

Results:

- HTL oil from several previous Cal Poly runs were used in series to reach 202 hours of HT operation.
- All available biocrude was consumed
- **Average yield (g dry/ g dry feed) for the entire hydroteating run was 0.84 with an average H_2 consumption of 0.046 g/ g of dry feed**
- Product density was steady although Cal 01 and Cal 02 biocrude samples consumed less hydrogen and resulted in a higher aqueous product yield than Cal 03 and 04

Simulated distillation to determine quality of the hydrotreated product

The produced oil was within 50% of the boiling point range of diesel, 30% that of gasoline. The mass fraction of diesel in the simulated distillation was ~52%.



ML4.3 HTL Runs 2-5

Conduct at least four HTL runs on wastewater-derived biomass

Characterize air emissions on at least one run

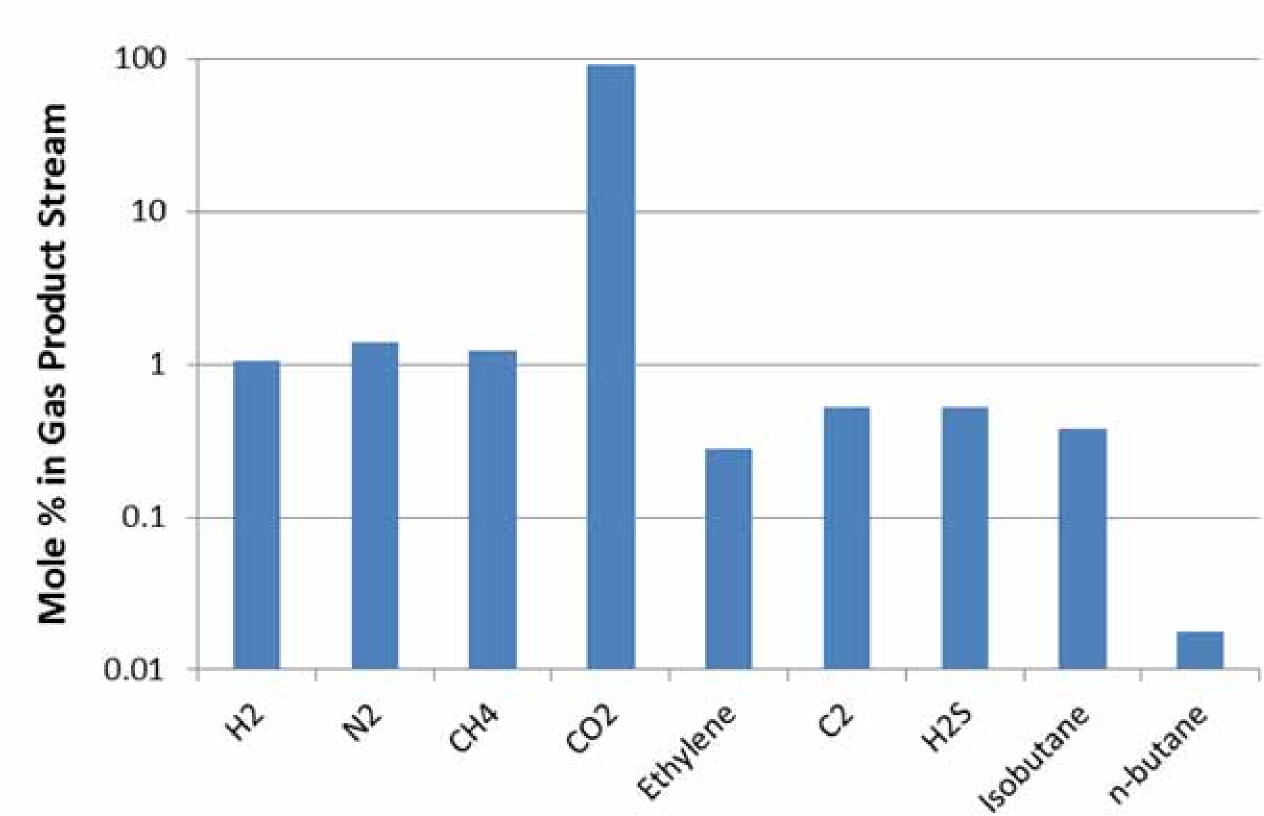
Four algae biomass samples were converted to biocrude

These samples came from various sources including the Cal Poly pilot plant, Delhi full-scale wastewater treatment plant and Delhi pilot pant

Samples were homogenized in a high shear mixer, diluted to approximately 20% solids, and characterized to determine HTL feed composition

Task 4.3: Biomass processing to biofuel intermediates

Gaseous emissions characterized for air permitting



Gas is predominantly CO_2

Unlikely to trigger air-pollution controls at pilot scale.

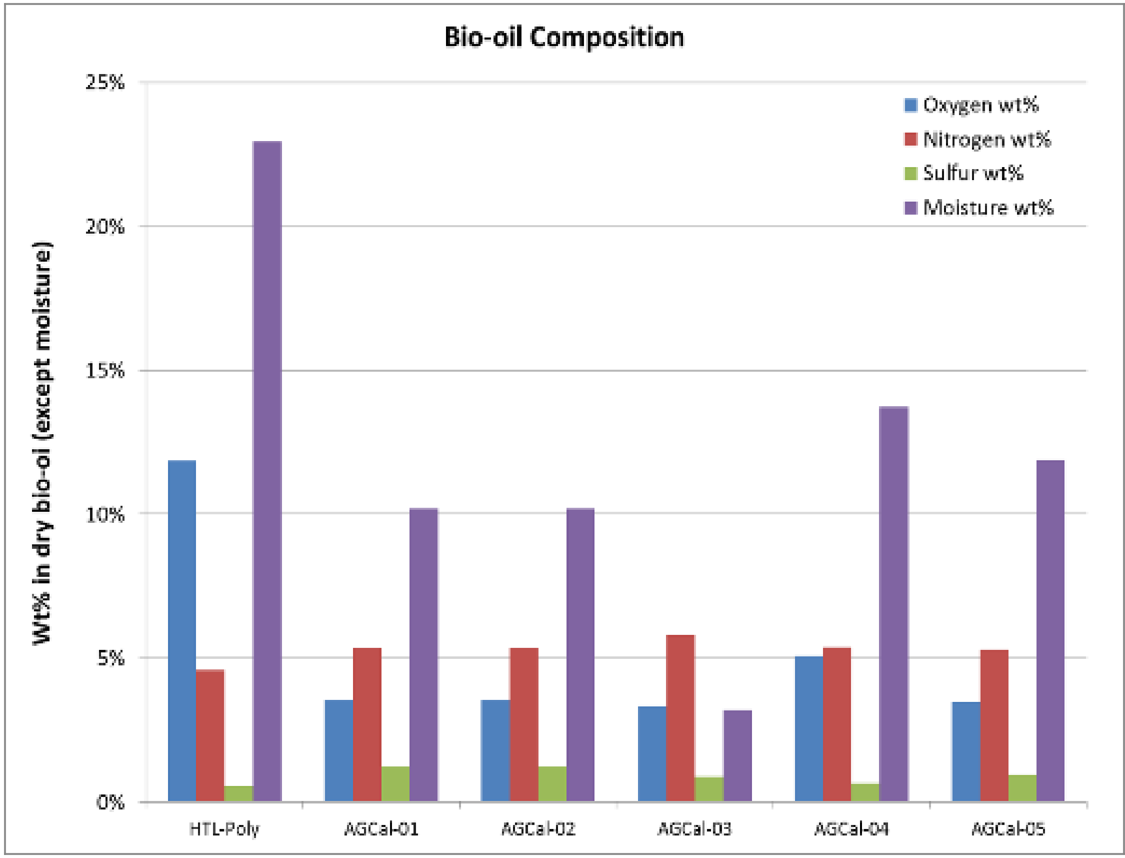
Normalized mass yield of oil

Normalized mass yield of oil ranged from 17-36% over five HTL runs.

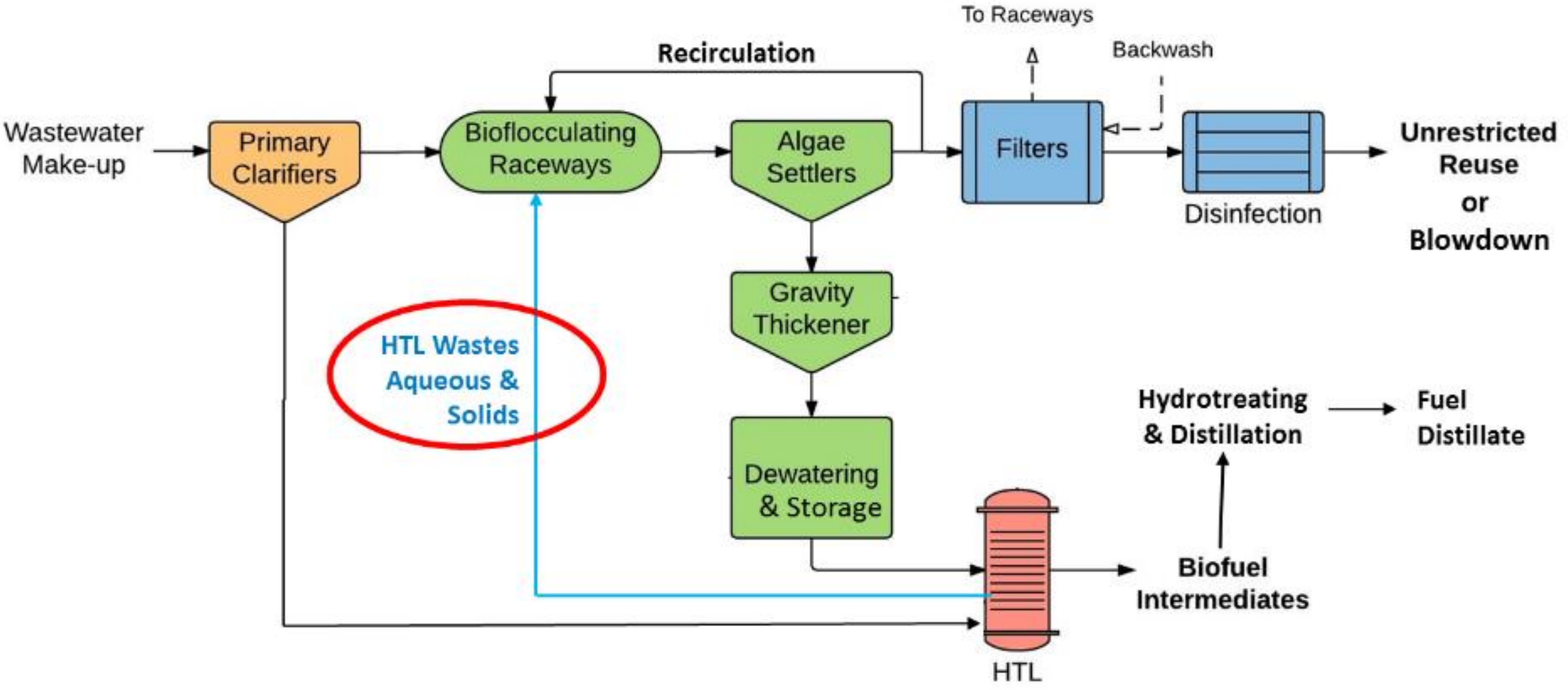
Normalized mass yield of carbon ranged from 33-55%.

Highest yield was algae harvested by bioflocculation from the San Luis Obispo pilot plant

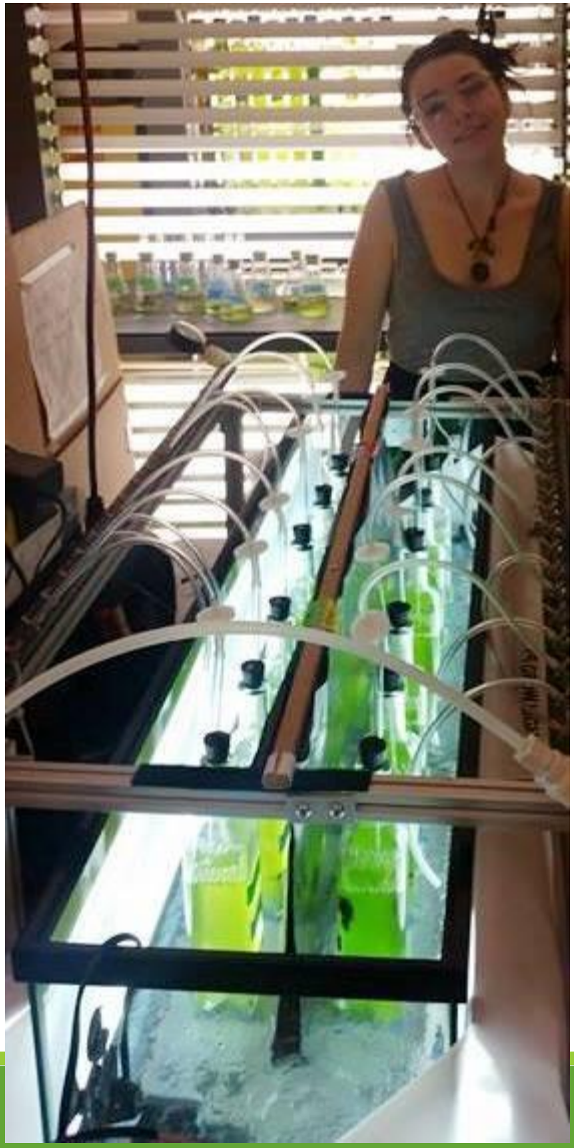
This sample also had the highest normalized carbon yield in the oil of 55%, and lower oxygen, moisture and nitrogen in the bio-oil

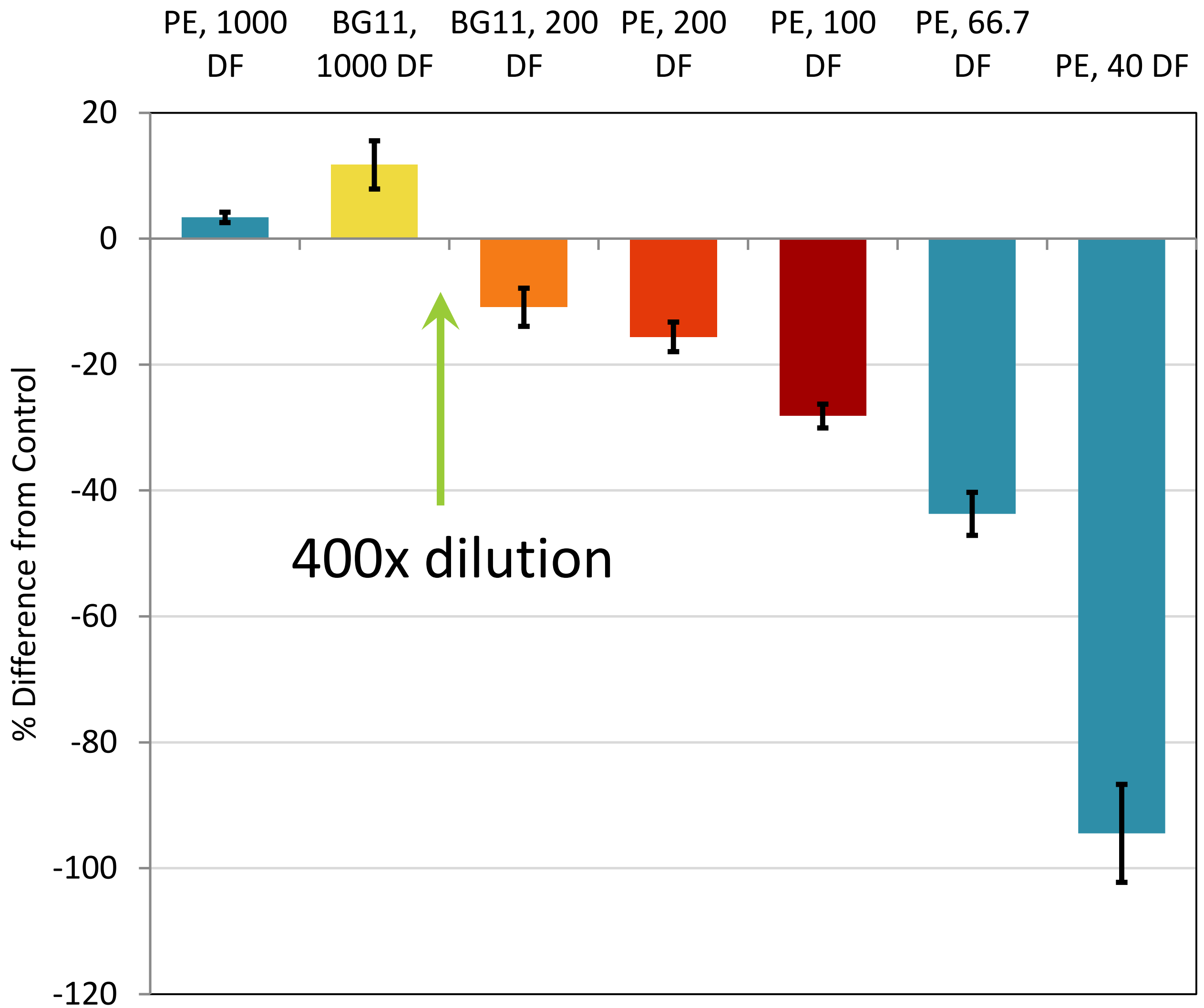


Recycle of HTL process water and solids is required to reuse nutrients



Re-growth of algae on the HTL wastewater is likely minimally inhibitory compared to the control (BG-11) at concentrations needed to satisfy algae nitrogen requirements at full-scale (400x).





TASK 5: Scale-up engineering analysis, modeling and planning . 80% complete

Develop refined engineering models of the process developed and evaluate its projected costs and net greenhouse gas emissions.

Rationale:

Evaluate sustainability and economics of process scale-up

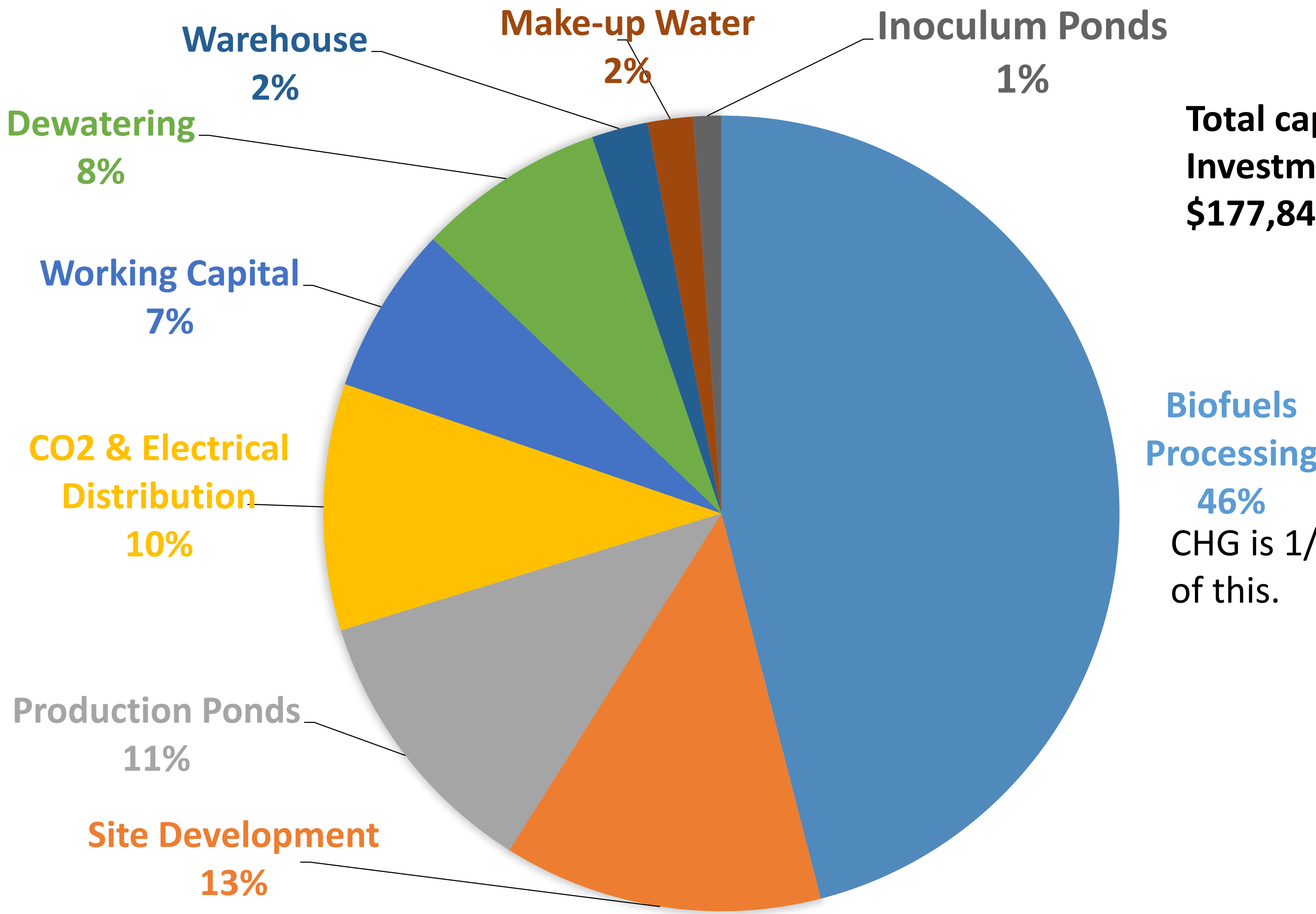
ML 5.6. Economics and Lifecycle Study: Prepare facility economic and LCA analyses for the algae wastewater treatment/biofuels process for conditions in California's Central Valley.

Major Modeling Assumptions

- Facility Size: **400 ha of pond surface area**
- Location: **San Joaquin Valley, CA**
- Annual Average Productivity: **33 g/m^2-d**
- Peak Hourly Productivity: **3 g/m^2-hr**
- Growth Media: **Wastewater**
- Influent Flow: **14 MGD**
- Biofuel Product: **HTL Biocrude**

MicroBio Engineering

Direct Capital Cost Distribution



Total capital Investment $177,845,366

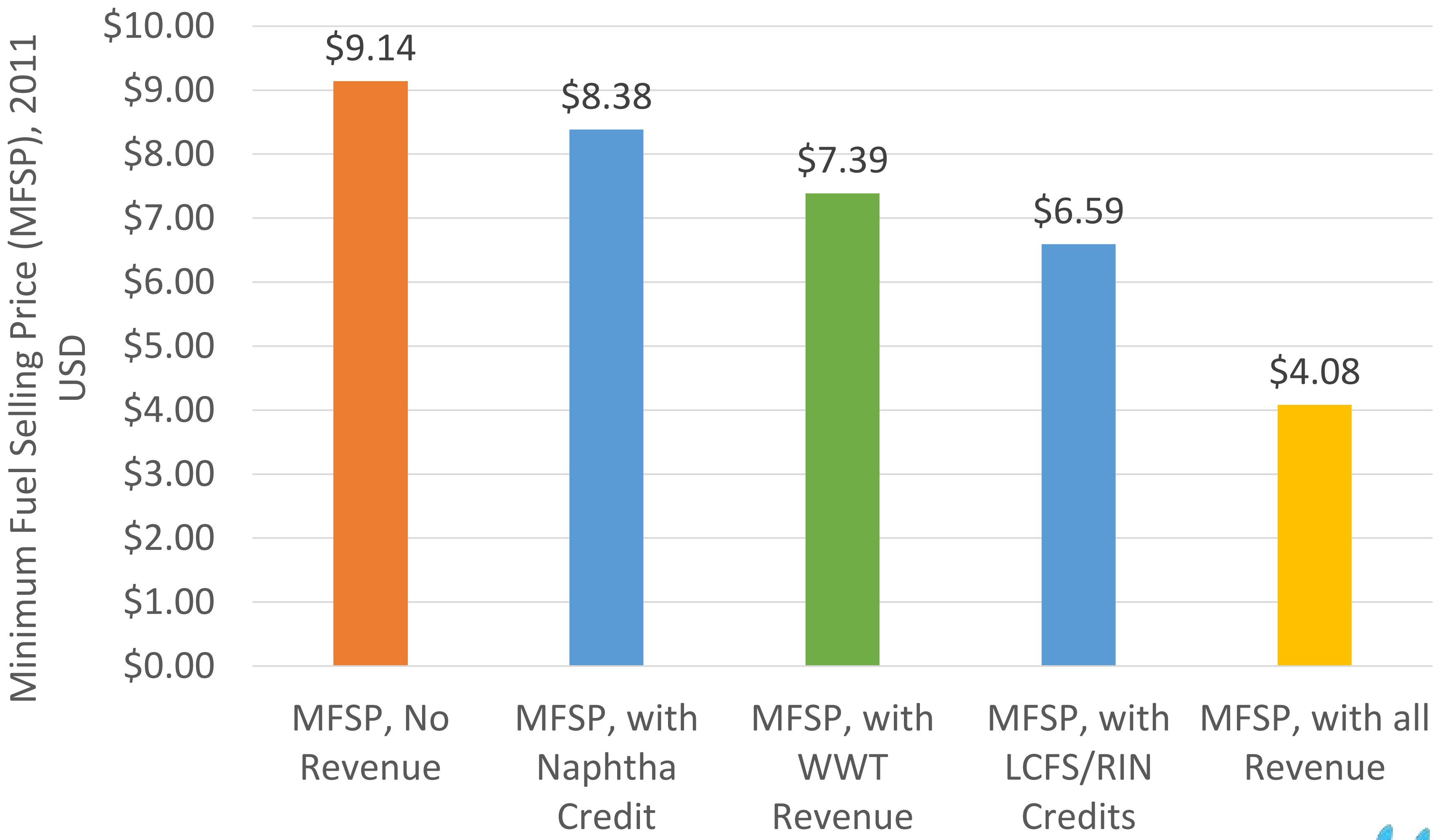
CHG is 1/3rd of this.

Biofuels Processing estimate from Jones et al. 2014

Operations Expenses

Description	Value	Units	Unit Rate	Total Cost
Make-up Water Pumping	6,357,600	kWh	$0.120	$763,548
Primary Clarifier and Pumping	64,382	kWh	$0.120	$7,732
Raceway Mixing	4,636,808	kWh	$0.120	$556,881
Settler Harvesting and Pumping	5,371,758	kWh	$0.120	$645,148
Thickener Harvesting	221,700	kWh	$0.120	$26,626
Biofuel Processing	581,625	kWh	$0.120	$69,853
Natural Gas				$630,919
Catalysts and Chemicals				$812,547
Solids Hauling	9,962	tonne	$30	$298,872
CO2	124,020	mt	$45.00	$5,580,895
			Total Variable OPEX	**$9,393,021**
			Total Fixed OPEX	**$14,587,891**
			Total OPEX	**$23,980,912**

Total Cost Distribution



20% equity, 5% APR, 15% IRR

μBIO MicroBio Engineering

Life Cycle Assessment Summary

Source	Energy Required (J/MJ)	GHG Emissions (gCO2e/MJ)
Biomass Production *(pure CO2 transport)*	65,914	6.9
Biofuel Processing Electricity	2,179	0.23
Biofuel Processing NG	128,598	10.08
Transport and Distribution	4721	0.35
Anthropogenic CO2 Credit	189,124	-71
Wastewater Treatment Credit	-147	-2.85
Avoided Flaring Credit (LCFS pathway)	0	-5.34
Total Well to Tank	**390,389**	**-61.59**
Carbon in Fuel	1,000,000	74.10
Vehicle CH4 and N2O	0.00	0.76
Total Tank to Wheel	**1,000,000**	**74.86**
Total Well to Wheel	**1,390,389**	**13.3**

HTL + CHG + hydrotreating estimates from Jones et al. 2014

TEA/LCA Results Summary

87% reduction in greenhouse gas emissions and approaching $3/ GGE.

• Total Capital Investment:	**$177,800,000**
• MFSP (including all revenue streams):	**$4.08-9.14 /GGE (2011 USD)** **$4.29-9.62 /GGE (2014 USD)**
• Carbon Intensity:	**13.3 g CO_2e/MJ** **(87% reduction from CARBOB)**
• Net Energy Ratio (Consumed/Produced):	**0.39**

4 – Relevance

- Increased biomass yield to 33 g/ m^2-day annual average, exceeding MYPP goals of 2,500 gal/ac-yr by 2018, and 3,700gal/ac-yr by 2020.
- Reduces GHG emissions by 87% over fossil fuels, exceeding MYPP goal of 50% reduction.
- Demonstrated successful recycling of HTL wastewater nutrients without inhibition at dilution factors that meet nitrogen requirements.
- Improvements in lab-scale modeling of outdoor systems and organism identification.
- Values obtained from pilot and full-scale algae raceway facility and incorporated into CA-GREET and the BETO Algae Program harmonized TEA/LCA approaches.
- Reductions in cost through the utilization of wastewater, increases in productivity, and LCFS/RINS, Naptha credits.
- Validation of the process as a low-cost wastewater treatment/biomass production technology that can meet stringent wastewater treatment goals.

5 – Future Work

Complete project (June 2017), data analysis, and final report

Publications

Next presentation:

Build on results with ABY2 by:

- *Autotrophic yield increases*
- *Better understanding of mixotrophy*
- *Increasing conversion of biomass carbon to fuel intermediates*

Summary

1. Overview-Optimize productivity in out-door wastewater treatment algae raceways
2. Approach
   - Characterize the full-scale system
   - Optimize the pilot scale system
3. Technical Accomplishments/Progress/Results
   - 33 g/m^{2}day
   - 0.35 g oil/ g algae
   - 55% of carbon contained in fuel
   - 4,100 gal/ac-yr
   - $4.08/gge and an 87% reduction on GHG
4. Relevance
   - Increased biomass yield to 33 g/ m^2-day annual average, exceeding MYPP goals of 2,500 gal/ac-yr by 2018, and 3,700gal/ac-yr by 2020.
5. Future work

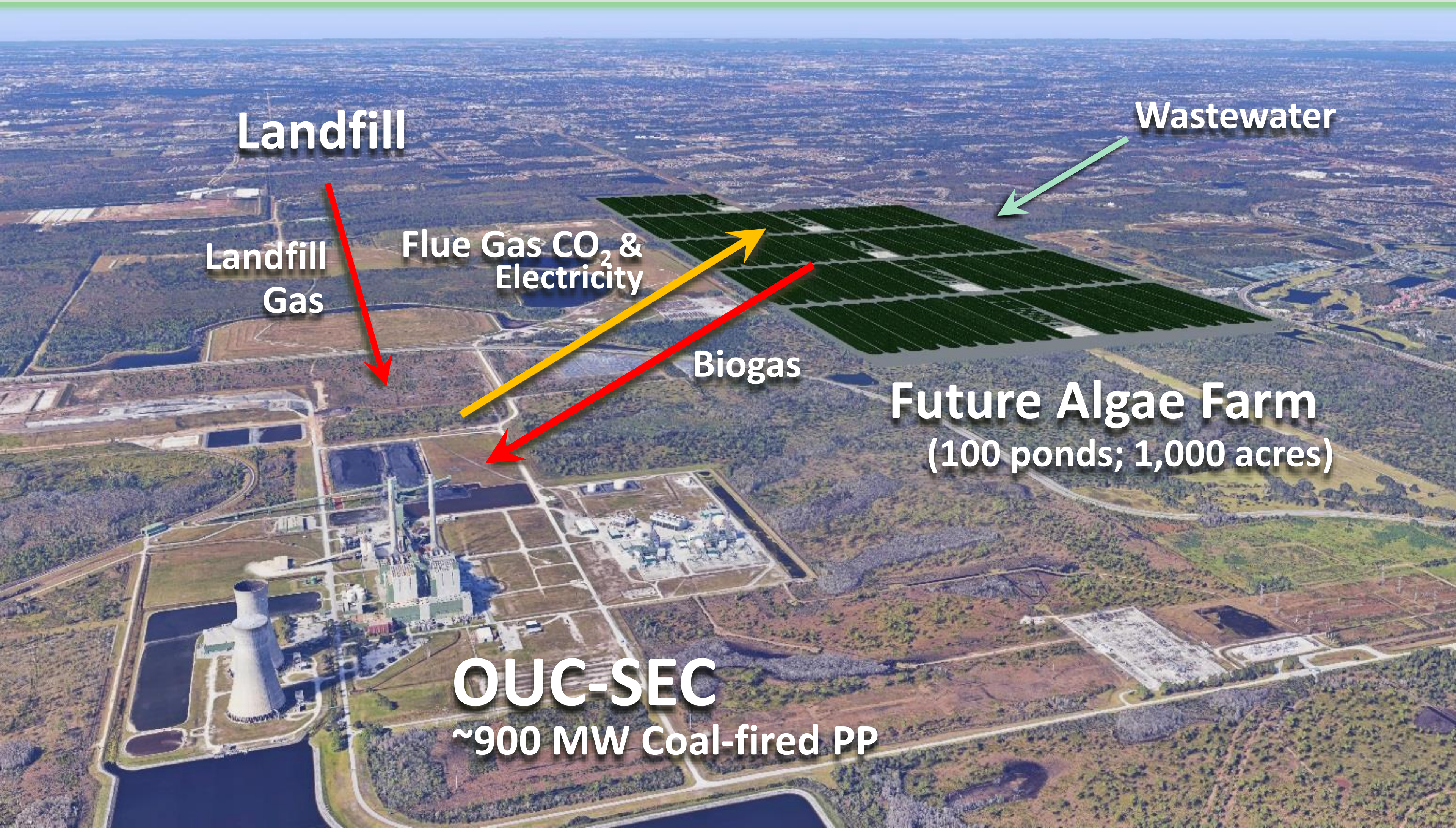
Thank you for your attention

Acknowledgments

PNNL, Sequim: Michael Huesemann, Scott Edmundson
PNNL, Richland: Dan Anderson, Doug Elliott, Andy Schmidt
SNL, Livermore: Todd Lane, Kunal Poorey
MicroBio Engineering Inc.: John Benemann, Kyle Poole,
Neal Adler
Delhi County Water District: Stan Feathers, Doug Paulson

Additional Slides

Algae → biogas @ Orlando Utilities Commission



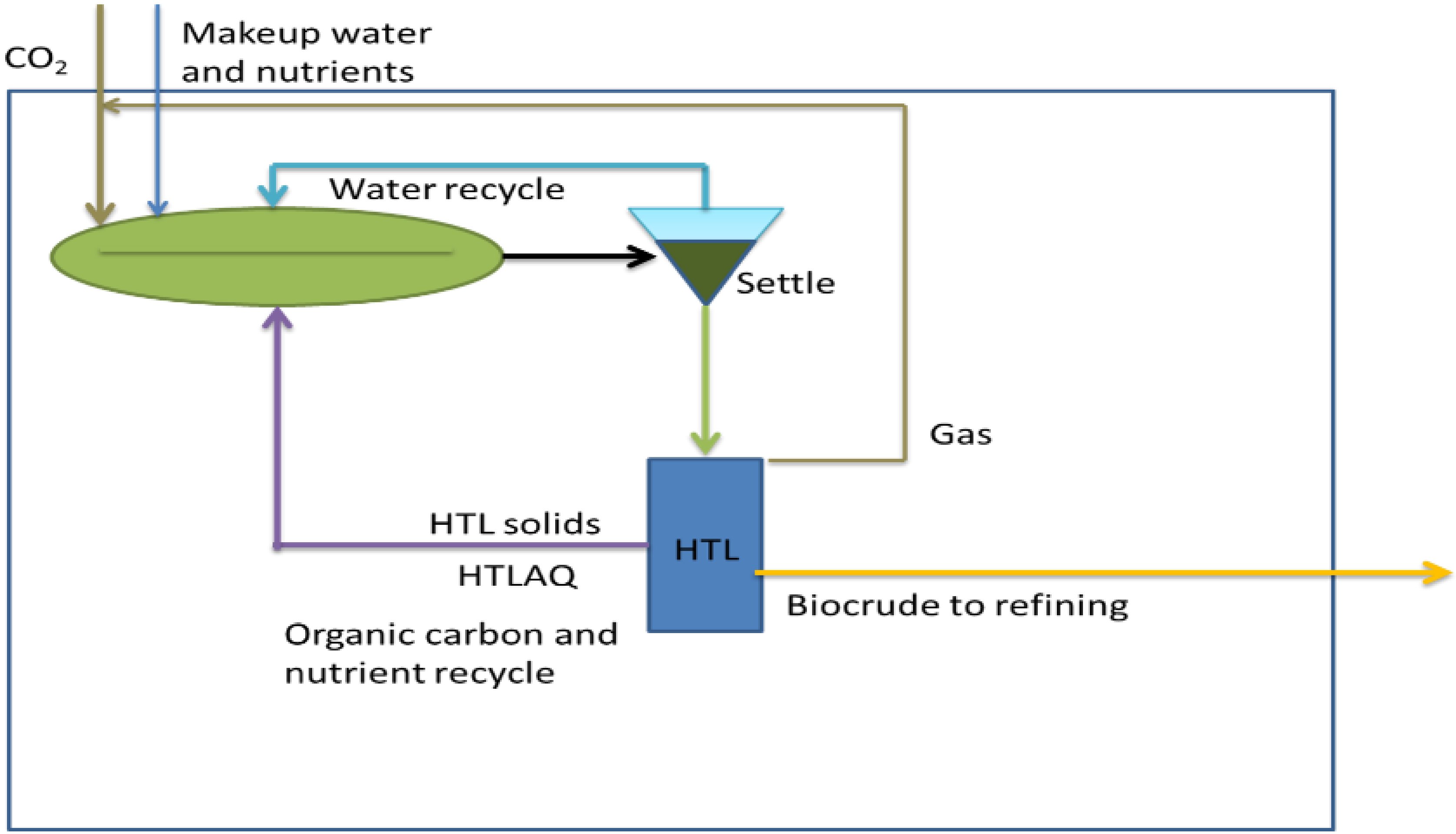
Responses to Previous Reviewers' Comments

TEA and LCA not contextualized: MicroBio Engineering Inc., used the CA-GREET and the BETO Algae Program harmonized TEA/LCA approaches allowing integration of these project results directly into the BETO evaluation process.

Wastewater will be a small portion of algae biofuel feedstocks and carbon mass balance must be closed: Recycling nutrients is critical to the future sustainability of algae biofuels. No fuel process or combination of fuel processes to date are able to recover 100% of the carbon into fuel; therefore, carbon recycling may be part of nutrient recycle. With wastewater we have identified mixo- and heterotrophic growth (both algal and bacterial) as approximately 33% of the total biomass (see Cal Poly ASAP project). Even discounting this mass results in a yield of 3,400 gal/acre-yr, but with carbon and nutrient recycling some of this heterotrophic growth is likely even if municipal wastewater is not used and is instead replaced with HTL wastewater. Our research has demonstrated that at normal nitrogen loading rates the aqueous phase of HTL can be recycled successfully.

Responses to Previous Reviewers' Comments

Process wastewater recycle will likely contain residual carbon making heterotrophic growth likely even in systems without municipal wastewater carbon.



Presentations

S. Blackwell, R. Spierling, M. Hutton, T. Lundquist, K. Poorey, and T. Lane. (2016). Dynamics in Algal Productivity and Bioflocculation in Wastewater fed Raceway Ponds. Presentation. Algae Biomass Summit, October 26, 2016, Phoenix, AZ. Conference Presentation.

R. Spierling, L. Parker, C. Pittner, C. Quigley, J. Haserot, N. Hess, B. Crowe, N. Adler, and T. Lundquist. (2016). Enhanced nitrogen conversion and removal in algae-based wastewater treatment systems. Algae Biomass Summit, October 26, 2016, Phoenix, AZ. Conference Presentation.

M. Hutton, S. Blackwell, E. Zardouzian, R.Spierling, T. Lundquist. (2016). Long term study of low cost harvesting by bioflocculation. Algae Biomass Summit, October 26, 2016, Phoenix, AZ. Conference Presentation.

T. Lundquist, B. Crowe, L. Gevorkian, R. Spierling, C. Pittner, L. Parker, N. Adler, M. Hutton, J. Benemann, A, Schmidt, D. Elliot. (2016). From wastewater to fuel distillates: cultivation and processing of microalgae grown during sewage treatment. Algae Biomass Summit, October 26, 2016, Phoenix, AZ. Conference Presentation.

Presentations

T. Lundquist, R. Spierling, N. Adler, B. Crowe, M. Hutton, A. Schmidt, D. Elliot. (2016). Integrated algae cultivation- hydrothermal liquefaction pilot studies using wastewater media. Presentation. Algae Biomass, Biofuels and Bioproducts Conference June 18-21 San Diego CA.

J. Benemann, T. Lundquist. (2016). Multi-trophic algal municipal wastewater treatment. Presentation. Algae Biomass, Biofuels and Bioproducts Conference June 18-21 San Diego CA.

R. Spierling, T. Lundquist, B. Crowe, L. Gevorkian. (2016). Water, nutrient and carbon recycling in the biorefinery system. Presentation. Algae Biomass, Biofuels and Bioproducts Conference June 18-21 San Diego CA.

T. Lundquist, C. Pittner, Y. Suvorov, T. Chene, L. Medina, T. Steffen, B. Crowe, N. Adler, R.Spierling. (2015). Towards scale-up of biofuel production and wastewater treatment using microalgae. Presentation. Algae Biomass Summit. October 1 Washington DC.

Posters

L. Parker, Y. Survov, C. Pittner, S. Blackwell, N. Adler, R. Spierling, T. Lundquist. (2016). Effect of Sampling Frequency on Microalgae Productivity Estimates. Algae Biomass Summit, October 26, 2016, Phoenix, AZ. Poster Presentation.

L. Gevorkian, R. Spierling, and T. Lundquist. (2015). Anaerobic co-digestion of hydrothermal liquefaction process water with wastewater solids. 9th Annual Algae Biomass Summit; September 29th – October 2nd; Washington, D.C. Poster Presentation.

Y. Suvorov, C. Pittner, N. Adler, R. Spierling, T. Lundquist. (2015). Optimization of Algae Biomass Productivity and Harvesting at Existing High-Rate Pond Municipal Wastewater Treatment Plant. Algae Biomass, Biofuels and Bioproducts Conference Jun 7-10, San Diego CA. Poster presentation.

Papers

Huesemann, M., A. Chavis, S. Edmundson, D. Rye and M. Wigmosta, "Climate-Simulated Pond Culturing of *Chlorella sorokiniana* DOE 1412: Quantifying the Maximum Achievable Annual Biomass Productivity in the United States", *Journal of Applied Phycology*, to be submitted.

A. Solimento, L. Parker, T. Lundquist, J. Garcia, Integral microalgae-bacteria model (BIO-ALGAE): application to wastewater high rate algal ponds, Bioresour. Technol. (2017).

Michael Huesemann, Patrick Williams, Scott Edmundson, Peter Chen, Robert Kruk, Valerie Cullinan, Braden Crowe, Tryg Lundquist. The Laboratory Environmental Algae Pond Simulator (LEAPS) Photobioreactor: Validation Using Outdoor Pond Cultures of *Chlorella sorokiniana and Nannochloropsis salina*, *Algal Research*, submitted.

Gevorkian et al. "Recycling carbon and nutrients in am algae biocrude production system using hydrothermal liquefaction," in preparation

K. Poorey, T. Lane. Relating community genomics to productivity and harvesting of algal-bacterial biomass for biofuel production. In preparation.

L. Parker, R. Spierling. Effect of Sampling Frequency on Microalgae Productivity Estimates. In preparation