DOE Bioenergy Technologies Office (BETO)
2023 Project Peer Review

Synergistic Municipal Wastewater Treatment Using a Rotating Algae Biofilm Reactor (RABR)
SWIM Project EE0009271

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Advanced Algal Systems

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Project Overview

BETO DE-FOA-0002203 "FY20 BETO Multi-Topic FOA" Subtopic 2c:SWIM Control No. 2203-1712

Context: Utilize Nation's water reclamation infrastructure to recycle nutrients into biofuels and bioproducts using microalgae

History: USU, CVWRF, and WesTech working together since 2018 on managing **anaerobic digester effluent** with **low volume and high nutrients concentration** with a novel biofilm technology that cultivates and harvests algae biofilm in one process

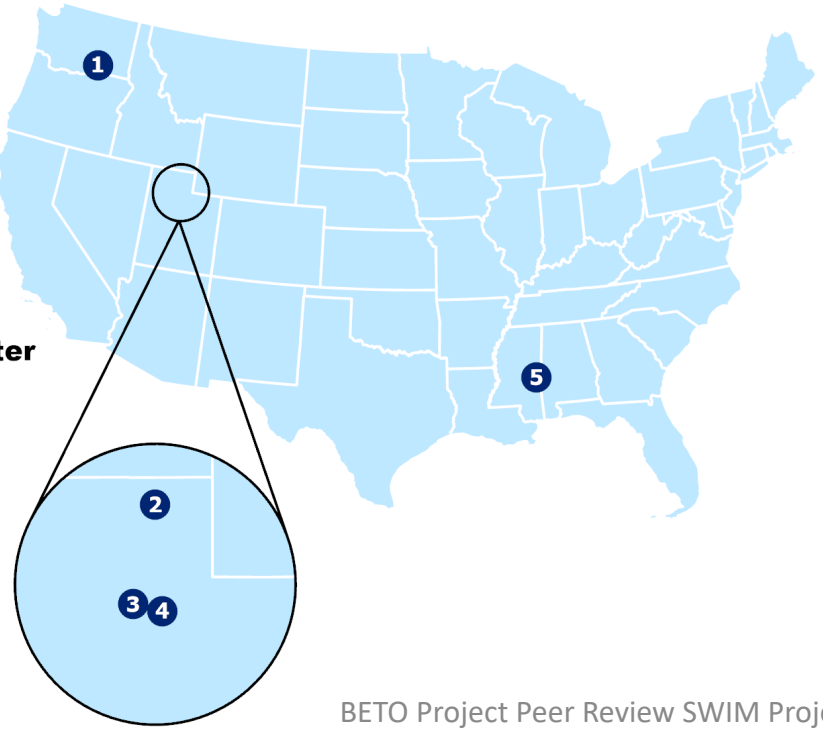
BETO Goals: Lower costs of biofuels; Provide high algae biomass productivity; Reduce cost of nutrient removal and energy

Specific question:

- Can the RABR technology reduce total phosphorus concentration by 70% to obtain biomass yield of 2.4 tons per million gallons treated water while lowering treatment costs and power requirements.

Project Collaborators

1. **Pacific Northwest National Laboratory**
   Richland, Washington
2. **Utah State University**
   Logan, Utah
3. **Central Valley Wastewater Reclamation Facility**
   South Salt Lake, Utah
4. **WesTech Engineering**
   Salt Lake City, Utah
5. **Algix**
   Meridian, Mississippi



1 - Approach

Technical approach

Functions

PNNL: Biofilm characterization With USU; **TEA/LCA**

USU: Lab, Greenhouse, **Field testing**, cultivation and harvesting

CVWRF: Host site for testing, power supply, biofilm nutrients analyses

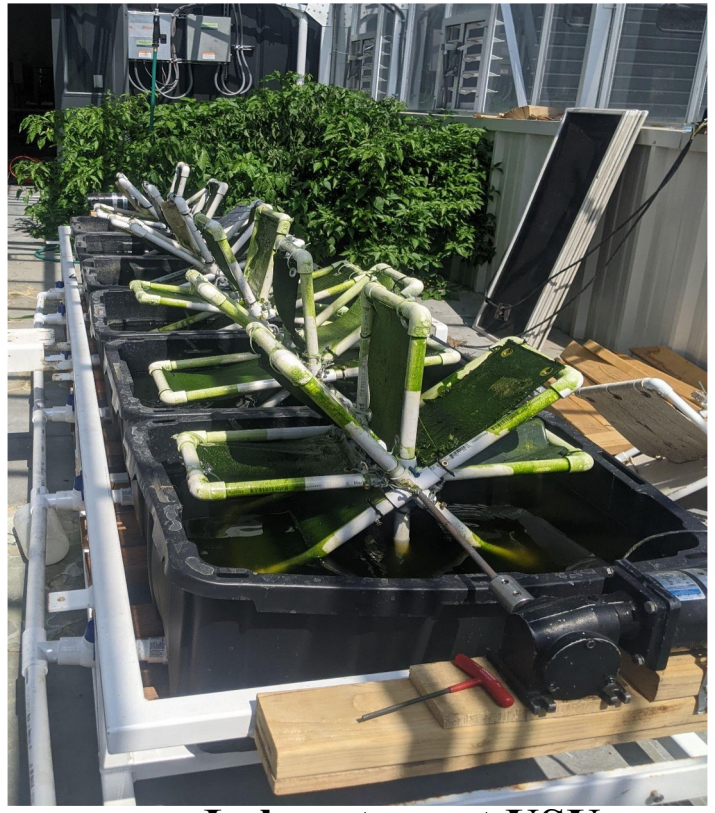
WesTech Environmental: Manufactured RABR frame/scaffolding, RPM control, duty cycle, pH & DO monitoring panel

Algix:Bioplastic from algae-based biofilm

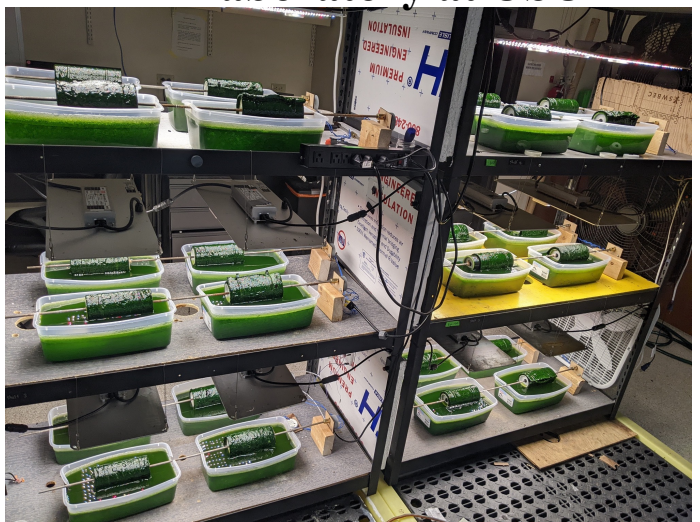
Rotating Algae Biofilm Reactor at CVWRF

- 30 shelves (3 ft by 3 ft) of polyester outdoor recycled plastic
- Variable speed motor
- Duty Cycle control
- 1,200 gallons total with 1,100 gallons water

Greenhouse at USU



Laboratory at USU



1 – Approach with TEA as Driver
M 6.1 TEA for the RABR System Integrated with Wastewater Treatment and Bioproducts

Previous Milestones:

- Capital & Operating Cost
- Algae production rate
- P/N removal efficiency
- Power consumption

Added information:

- Algae feedstock characterization
  - ❖ Seasonal changes
  - ❖ Biochemical parameters
- Evaluation of three pathways
  - ❖ 1. HTL to biocrude
  - ❖ 2. Bioplastics
  - ❖ 3. LEA for biodiesel & bioplastic

1 – Approach with TEA/LCA
M 14.1 Identify TEA Scope/Inputs

Wastewater influent (flow rate, N/P content, etc.)

Testing data

Key factors, data gap

Algae feedstock samples

Algae-growth for WWT system TEA

Algae feedstock data (seasonal flow rates)

Life cycle inventory

Life cycle analysis (optimal final case)

LCA

GHG footprint; Water use; Fossil fuel use

Conversion testing (HTL – USU; Bioplastic – Algix; Lipid extraction - USU)

Testing data

Key factors, data gap

Life cycle inventory

1 - Approach

- **Potential Challenges**
    1. Cold weather operation
    2. Condensation on cover reduces sunlight by 50%
    3. Cotton substratum sustainability due to biological and physical degradation

- **Risk analysis and mitigation strategies**
    1. Cold weather operation – plastic polycarbonate cover for temperature and wind
    2. Condensation on cover – use electric heaters inside cover near roof
    3. Replaced cotton substratum with polyester outdoor carpet made from recycled plastic bottles

- **Go/No-Go Decision points**
    - At least one season
    - Meet target biomass **yield**: 7.5 gm/m^2/day
    - Meet target reduced **energy** consumption (10%)
    - Achieve RABR TP at < 21 mg/L
    - Achieve calculated TP for CVWRF < 1.0 mg/L if RABR TP at <21 mg/L

    based on CVWRF mass balance calculations based on RABR integration

2 – Progress and Outcomes

- **M 2.5** – Productivity: Avg. 8.1 gm/m^2/day exceeds target of 7.5;
  95% CI: 0.4 mg/m^2/day; Range: 7.7 – 8.5 gm/m^2/day

- **M 3.1** – Energy consumption: from 0.128 kWh to 0.08 kWh = 38% decrease from baseline by decreasing RPM from 1.0 to 0.5

- **M 4.1** - RABR Total Phosphorus at 19 mg/L (Fall + Dec) less than target of 21 mg/L

- **M 4.1 C**alculated TP for CVWRF < 1.0 mg/L if RABR TP at <21 mg/L based on CVWRF mass balance calculations with RABR integration

2 – Progress and Outcomes (TEA)
Major Performance and Cost Results Preliminary

- Performance and cost of single-stage (HRT = 2 days) RABR systems are estimated based on the baseline, intermediate and final design assumptions.

Single-stage RABR	Unit	Baseline	Intermediate	Final
Performance				
P removal	% of influent P	27%	47%	70%
N removal	% of influent N	14%	25%	36%
Power consumption	kWh/kg P removed	152	54	29
Algae production rate	tonne/yr, dry	117	198	292
CO2 offset	tonne/yr	106	180	266
Cost (2020 US$)				
Capital cost	MM$	9.05	9.50	9.51
Operating cost (cloth use and power)	1000$/year	1427	65	53
P removal cost (aggregated)	$/kg P removed	238	30.3	19.7

Note: The aggregated cost for P removal is estimated based on a plant life assumption of 30 years.

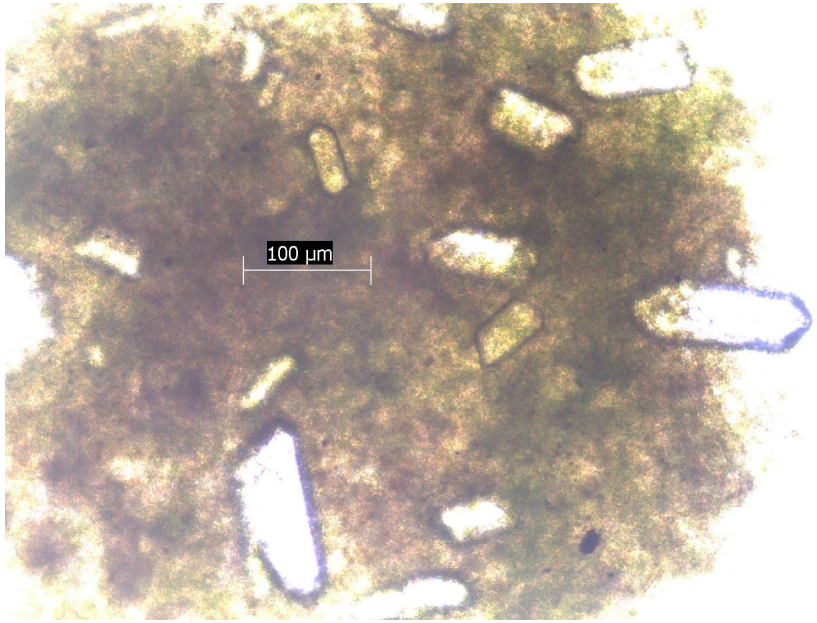
2 – Progress and Outcomes
M 3.1 - Results/Progress: Meet Target Reduced Energy/Power Consumption by ≥ 10%

Reductions in power requirements as kWh were 38% and 50% as speed (RPM) decreased from 1.0 to 0.5 to 0.25.

RPM/ft s^{-1} peripheral velocity	1.0/0.38	0.5/0.2	0.25/0.1
Power (kWh)		0.08	0.064
Decrease in power consumption (%) Duty Cycle 1.0			

2 – Progress and Outcomes
M4.1- Results/Progress
Demonstrate Struvite Formation in Biofilm

1. NH_4:Mg:PO_4·$6H_2O$ = 5.7% N; 10% Mg; 12.6% P
2. Pilot RABR Biofilm and Trickling Filter Analyses
   - RABR Biofilm 11% TP ± 1.2% (95% C.I.)
   - Trickling Filter 1.5 % TP (Control)
3. Struvite present in RABR biofilm removes P and N
4. Bioprecipitation influenced by:
   - pH (algae increases pH of water due to CO_2 sequestration)
   - biomass serves as nucleation sites for precipitation
   - high concentrations of NH_4^+, PO_4, and Mg in digestate



Struvite Crystals in RABR Biofilm

2 – Progress and Outcomes
M4.2- Results/Progress
Show Cost Decrease of ≥ 10% Below Baseline

Reductions in cost as $/hr were 39% and 50% as speed (RPM) decreased from 1.0 to 0.5 to 0.25, corresponding to peripheral velocities of 0.38, 0.2, and 0.1 ft/sec

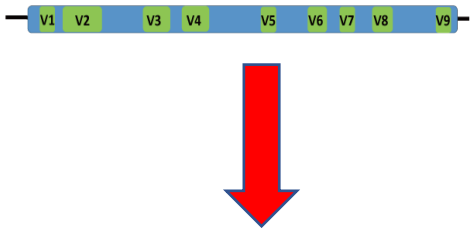
RPM/ft s^{-1} peripheral velocity	1.0/0.38	0.5/0.2	0.25/0.1
Cost for RABR Power ($0.09/kWh) as $/hr	0.012	0.007	0.006
Decrease in cost of power consumption (%) Duty Cycle 1.0	N/A	39	50

2 – Progress and Outcomes
M 2.2, 2.4, 2.6, and 2.7 - Results/Progress
Visual and Genetic Characterization of RABR Biofilm

Microscopy

Genomic DNA extraction

PCR



Sequencing

16S rDNA: prokaryotes
18S rDNA: eukaryotes
23S rDNA: phototrophs
ITS rDNA: fungi

Taxonomic analysis

2 – Progress and Outcomes
M 2.2 - Biofilm Characterization

Milestone	Milestone Description	Summary of Results and Ongoing Efforts
M2.2	Determine the population composition and structure of the established active algae-bacteria biofilm	**TF dominant microalgae**: *Pleurocapsa, Tychonema,* Nostocales, unclassified Cyanobacteria, *Stigeoclonium, Oedogonium,* and *Chlorella.* **Lab-scale dominant microalgae**: *Pleurocapsa, Tychonema,* Phormidiaceae, Nostocales, unclassified Chlorophyta, *Micractinium,* and *Chlorella.* **Bench-scale RABR dominant microalgae**: *Pleurocapsa, Dictyosphaerium,* Unclassified Chlorophyta, and *Chlorella.* **Pilot-Scale RABR dominant microalgae**: *Tychonema, Pleurocapsa,* unclassified Cyanobacteria, *Stigeoclonium,* and *Chlorella.*

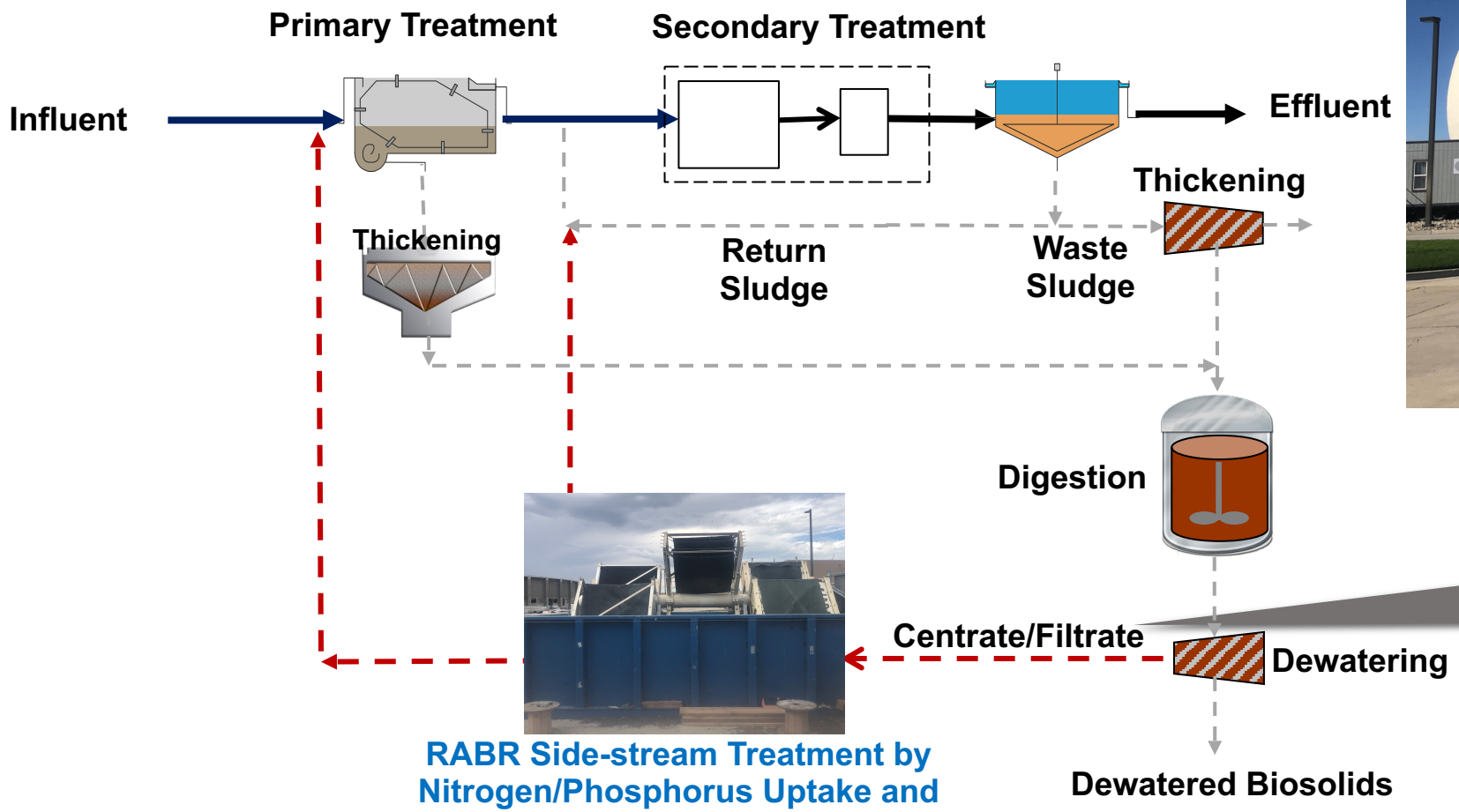
3 – Impact on Water Reclamation Facilities

CVWRF – Largest Municipal Wastewater Plant in Utah

Host Site for Testing the RABR Technology

- Population Served: 615,000
- Rated Flow Capacity: 75 MGD
- TP 2025: 1 mg/L
- NH_3 Limit: 3.6 mg/L

3 - Impact: RABR Reclamation of Anaerobic Digester Effluent Nationwide

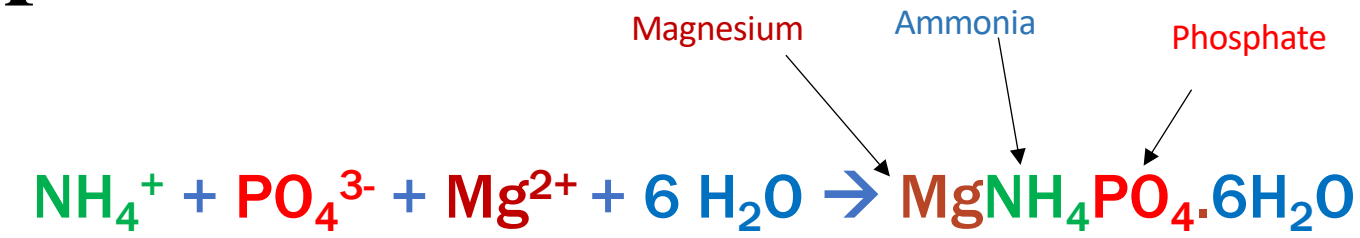


RABR Side-stream Treatment by Nitrogen/Phosphorus Uptake and CO_2 Sequestration by Algae

- 1% Plant Influent Flow (0.6 MGD)
- 15 to 30% Plant Influent TN and TP load
- Ammonia Conc. 500 mg-N/L
- TP Conc. = 50 mg/L

3 – Impact

Additional Nutrients Removal by Biological Precipitation of Struvite Fertilizer (Industry)



- Magnesium-Ammonia-Phosphate precipitate (MAP)
- Scaling of pipes, pumps, mixers, dewatering equipment
- Accumulation in digesters
- Is a major maintenance issue at reclamation facilities with anaerobic digesters

Summary

- **Specific question:** Can the RABR technology reduce total phosphorus concentration by 70% to obtain biomass yield of 2.4 tons per million gallons treated water while lowering treatment costs and power requirements.

- **Results for Fall/Winter operations**:
  - Phosphorus removal at 47%
  - Productivity at 1 ton/MG
  - Power/energy consumption reduced by 52% (kWh/kg P removed) from baseline by controlling rotation rate of RABR

- **Impact**
  - Central Valley Water Reclamation Facility – Users of the technology
  - WesTech Environmental – Manufacturer of the technology
  - Other water reclamation facilities
  - Bioplastics industries

- **Budget Period 3:** through May 2024 to test technology robustness over four seasons

Quad Chart Overview

Timeline

- *Project start date: 05/01/2021*
- *Project end date: 05/31/2024*

	FY22 Costed	Total Award
DOE Funding	*(10/01/2021 – 9/30/2022)* *$529,303*	*(negotiated total federal share)* *$1,837,735*
Project Cost Share *	$150,552	$469,440

TRL at Project Start: 6

TRL at Project End: 7

*Only fill out if applicable.

Project Goal

The goal of this project is to test a field-scale outdoor pilot rotating algae biofilm reactor (RABR) to remove nutrients including total phosphorus total nitrogen from anaerobic digester effluent treating municipal wastewater and to produce biofilm biomass to produce biofuel and bioplastic

End of Project Milestone

Reduce total phosphorus concentration in anaerobic digester effluent by 70% and obtain a biofilm biomass yield of 2.4 tons per million gallons of anaerobic digester treated water using the Rotating Algae Biofilm Reactor (RABR) technology.

Funding Mechanism

BETO DE-FOA-0002203 "FY20 BETO Multi-Topic FOA" Subtopic 2c:SWIM Control No. 2203-1712

Project Partners*

- PNNL
- Central Valley Water Reclamation Facility
- WesTech-Inc.
- Algix, Inc.

Publications, Patents, Presentation, Awards, and Commercialization

- Presentations at professional meetings
  - Microalgae biofilm characterization for a rotating algae biofilm reactor (RABR) treating anaerobic digester effluent. Moravek, Amanda; Miller, Charles; and Bohutskyi, Pavlo. Institute of Biological Engineering Annual Conference, Athens, GA. 2022. Poster.
  - Struvite formation associated with microalgae biofilm treating anaerobic digester effluent. Goldsberry, Parker; Sims, Ronald. Institute of Biological Engineering Annual Conference, Athens, GA. 2022. Poster.

Responses to Previous Reviewers' Comments

A DOE Intermediate Verification meeting took place at the host site (Central Valley Water Reclamation Facility) January 26, 2023. Reviewers comments and project team responses for three significant questions are shown below:

1. **Comment**. The verification team recommends investigating duty cycle effects in BP3 for potential further energy savings. Within this work, reduced rpm at certain times of the day could be investigated as well as the conditions of on vs. off.

Response: A Programmable Logic Control (PLC) panel for control of duty cycle will be installed by WesTech-Inc. by April 1, 2023. The PLC panel will allow for reduction in rpm during the night when sunlight energy is not available.

2. **Comment.** Since temperature has a big effect, the verification team recommends investigating if there are opportunities to recycle waste heat from other parts of the plant to maintain temperature in an economical manner.

Response: Influent pressate in the equalization basin will be heated using a propane tank during the winter and when pressate temperature falls below 25^{o}C. At full scale implementation, digester effluent will be heated within the CVWRF to a minimum 25^{o}C.

3. **Comment**. The verification team recommends changing the goal language for phosphorus removal to account for influent concentration variability. A relative removal rate seems more applicable.

Response: The goal language for phosphorus removal will be $\geq$70% total phosphorus removal through the RABR system, which will account for influent concentration variability. The use of % reduction for the goal language is preferred by the Central Valley Water Reclamation Facility and as used in the TEA/LCA.

Go/No-Go Review: was conducted at the Intermediate Verification meeting that took place on January 26, 2023. The project met the criteria for the Go/No-Go Review and the project team is waiting on approval for Budget Period 3.