DOE Bioenergy Technologies Office (BETO)
2023 Project Peer Review

Process Optimization and Real-Time Control for Synergistic Microalgae Cultivation and Wastewater Treatment

DE-EE0009270

April 3, 2023
Advanced Algal Systems Technology

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Pronouns: he, him, his
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ILLINOIS

Process characterization, process modeling

Prof. Jeremy Guest

Dr. Hannah Molitor

Dr. Ga-Yeong Kim

Nick Avila

Georgia Institute of Technology

Real-time community structure monitoring

Prof. Ameet Pinto

Ben Gincley

Farhan Khan

University at Buffalo

'Omics

Prof. Ian Bradley

Mahbub Alam

Mahdi Hodaeiesfahani

CLEARAS WATER RECOVERY

Systems operation

Autumn Fisher

Kevin McGraw

Patrick Kelly

Elaine Hartnett

John Bond
Public Works Director

Project Advisory Committee: Representatives from 8 consulting/design firms, 1 utility, 2 regulatory agencies, and 1 national lab (ORNL).

Project Overview

This project was funded under a FOA focused on improving our ability to leverage municipal wastewater for microalgae cultivation.

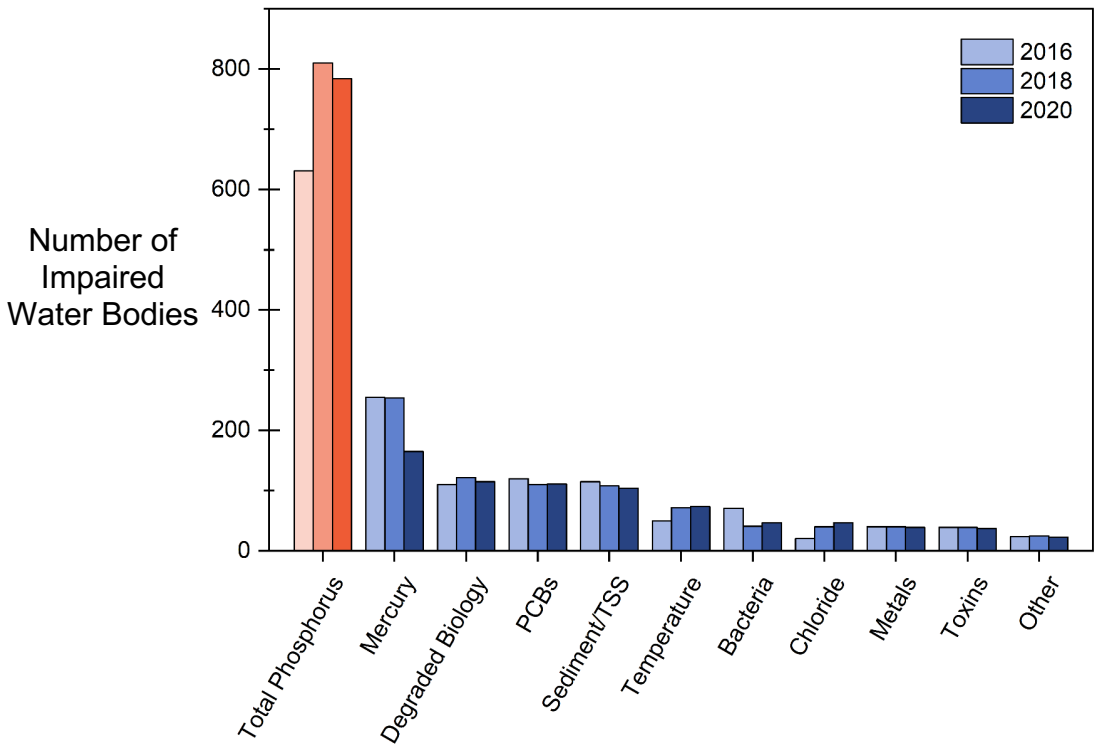
DE-FOA-0002203
Topic 2: Waste to Energy Strategies for the Bioeconomy
Sub-Topic 2c: Synergistic Wastewater Integration with Microalgae (SWIM)

objective	integrate algae biomass technologies with municipal wastewater treatment to increase energy efficiency and the costs of treatment while also enabling consistent yields of algal biomass for downstream conversion to bioenergy and/or bioproducts.
target wastewater pollutants/resources	**total phosphorus**, total nitrogen
consistency with BETO's mission	expand the domestic resource potential of the bioeconomy through low-cost supply of algae biomass.
	support lowering the cost of biofuels through low-cost feedstocks.
	reduce greenhouse gas (GHG) emissions of biofuels by offsetting wastewater treatment.

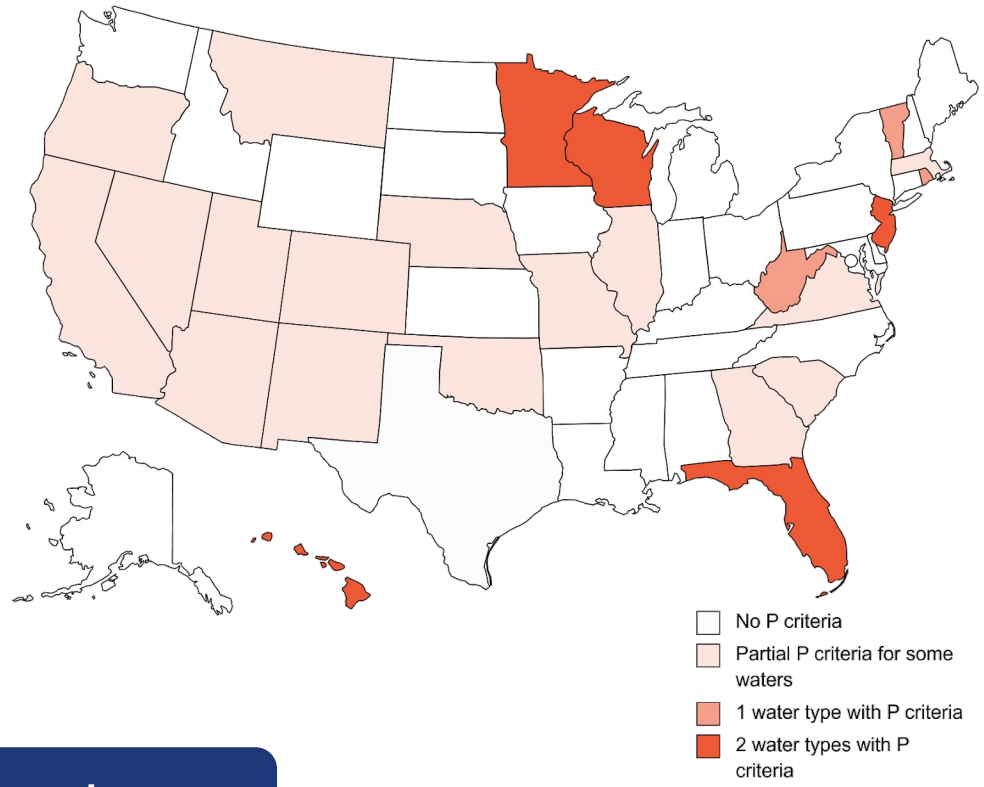
Project Overview

Effluent phosphorus (P) permits are becoming increasingly common and increasingly strict, requiring significant financial investment from utilities.

causes of water body impairment in Wisconsin



states with total phosphorus (P) criteria in 2022



Permit for Village of Roberts, Wisconsin

0.04 mg-P·L^{-1} total P annual average *(monthly average of 0.12 mg-P·L^{-1})*

[Wisconsin Department of Natural Resources (DNR). "Surface Water Impairments and Pollutants." https://dnr.wisconsin.gov/topic/SurfaceWater/Impairments.html.]

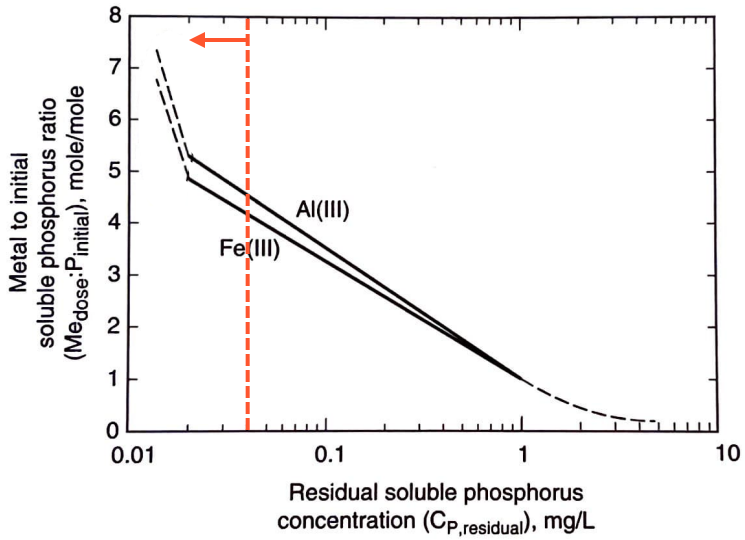
[Figure created with mapchart.net using data from U.S. Environmental Protection Agency. "State Progress Toward Adopting Numeric Nutrient Water Quality Criteria for Nitrogen and Phosphorus." htttps://www.epa.gov/nutrient-policy-data/state-progress-toward-adopting-numeric-nutrient-water-quality-criteria.]

Project Overview

The Clean Water Needs Survey (U.S. EPA) estimated a required investment of ~$50 billion for advanced wastewater treatment facilities*.

Conventional
phosphorus **removal** technologies

limit of technology **~0.3 mg-P·L^{-1}**



~0.1 mg-P·L^{-1}
(does not remove organic P)

EcoRecover
phosphorus **recovery** technology

<0.02 mg-P·L^{-1}

Permit for Village of Roberts, Wisconsin

0.04 mg-P·L^{-1} total P annual average
(monthly average of 0.12 mg-P·L^{-1})

Wastewater infrastructure projects are often eligible for
low interest loans (e.g., 0-2%) and loan forgiveness (millions of $).

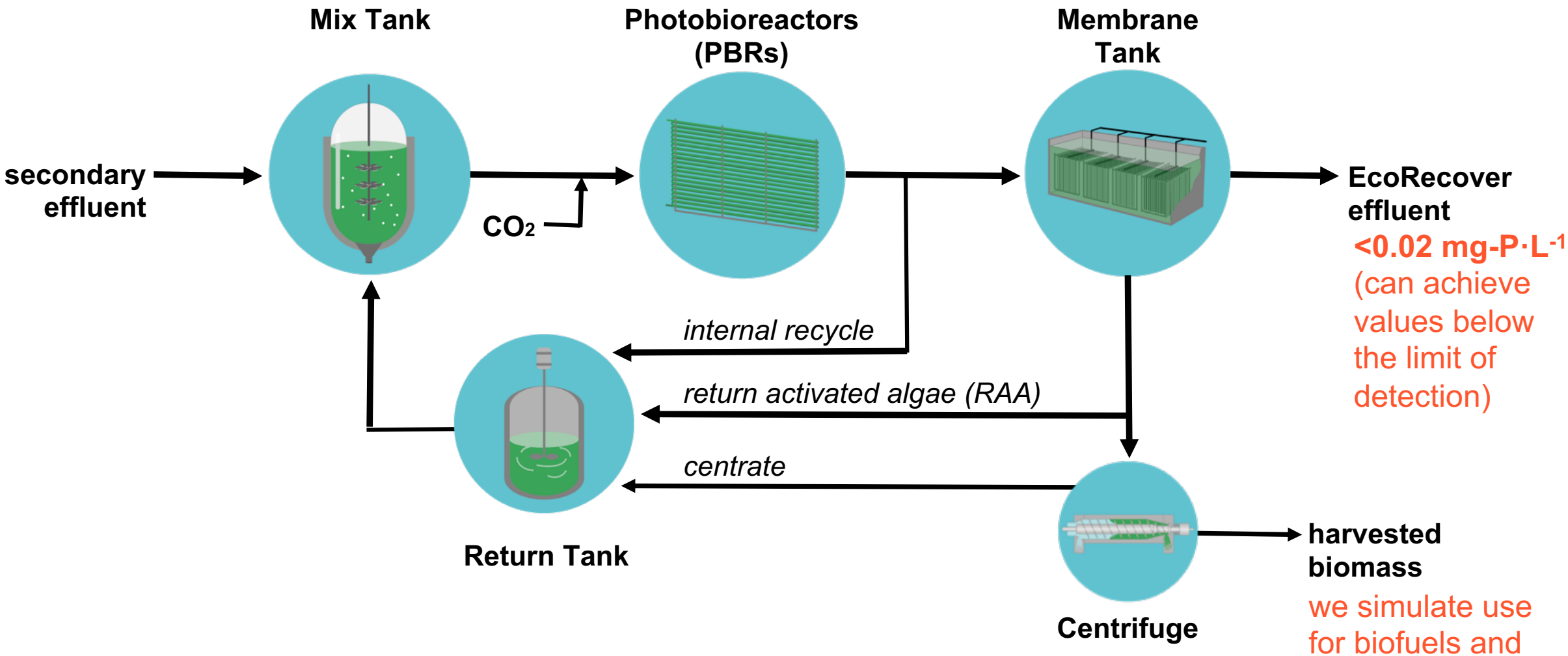
[U.S. Environmental Protection Agency. "Clean Watersheds Needs Survey." https://www.epa.gov/cwns]

[Tchobanoglous et al. *Wastewater Engineering: Treatment and Resource Recovery*; McGraw-Hill Education: New York, 2013.]

A facility is considered to have advanced wastewater treatment if it achieves one or more of the following: BOD_5 less than 20 mg·L^{-1}, nitrogen removal, **phosphorus removal, ammonia removal, metal removal, or synthetic organic removal.*

Project Overview

The EcoRecover process targets rapid and (nearly) complete phosphorus removal through an intensive suspended growth process with microalgae.



EcoRecover

Project Overview

The overarching goal is to advance our capacity for locality-specific design optimization and real-time process control of mixed community microalgal systems.

Project Objectives

1. Develop and validate an open-source algae process simulator.
2. Develop and train a low-cost system for real-time monitoring of community structure.
3. Validate optimized process design and real-time process control.

Project Outputs

Open-source process simulator

Calibrated / validated open-source process simulator with process modeling, techno-economic analysis (TEA), and life cycle assessment (LCA), for the cultivation of mixed microalgal communities.

Real-time tracking of microbial community structure

Deployable, miniaturized, low-cost (<$300) microscope for real-time monitoring of cultivation ecology for mixed microalgal communities.

Optimized EcoRecover process

Verified process with validated process simulator, locality-specific design optimization, and real-time monitoring and control system.

Approach

The first permanent EcoRecover installation was constructed in the Village of Roberts, Wisconsin (USA) and designed for 150,000 gallons·day^{-1} (680 m^3·day^{-1}).

Installations

Roberts, WI *operating*	**0.15 MGD**
Mondovi, WI *under construction*	**0.3 MGD**
Waupun, WI *under construction*	**2.8 MGD**

MGD = million gallons per day

Approach

Our approach includes robust characterization and optimization of the EcoRecover process, and advances enabling tools for other algal cultivation systems.

Online Monitoring

SCADA system
supervisory control and data acquisition system

CLEARAS WATER RECOVERY | Village of Roberts

On-Site Analyses

daily on-site monitoring

diel performance

kinetics

CLEARAS WATER RECOVERY | ILLINOIS | Village of Roberts

Biomass Characterization

elemental composition

storage carbon

ILLINOIS

'Omics Characterization

16S & 18S rRNA sequencing

metagenomics

transcriptomics

University at Buffalo

Process Modeling, TEA, LCA

open-source

object-oriented programming

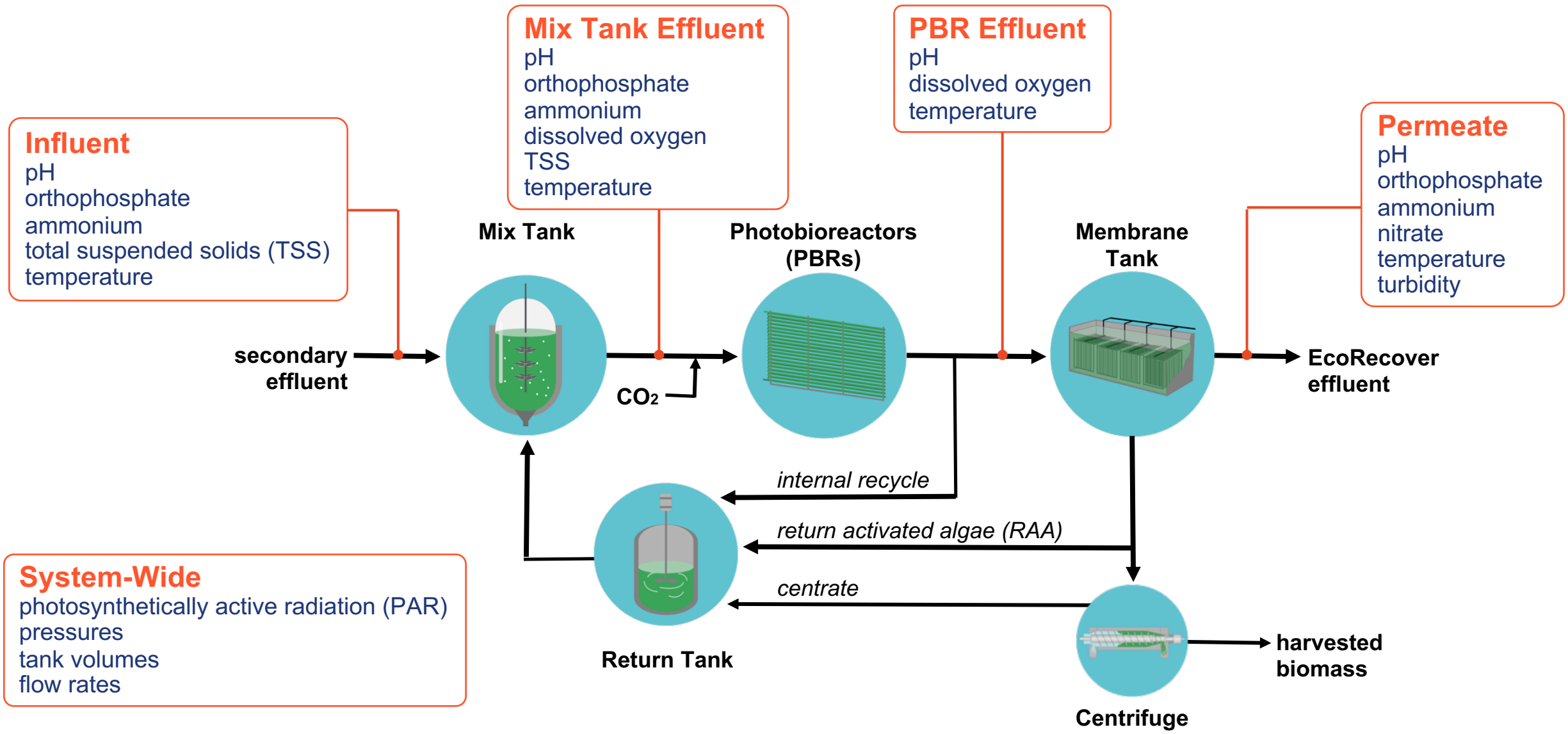
ILLINOIS

Autonomous Microscopy

ARTiMiS

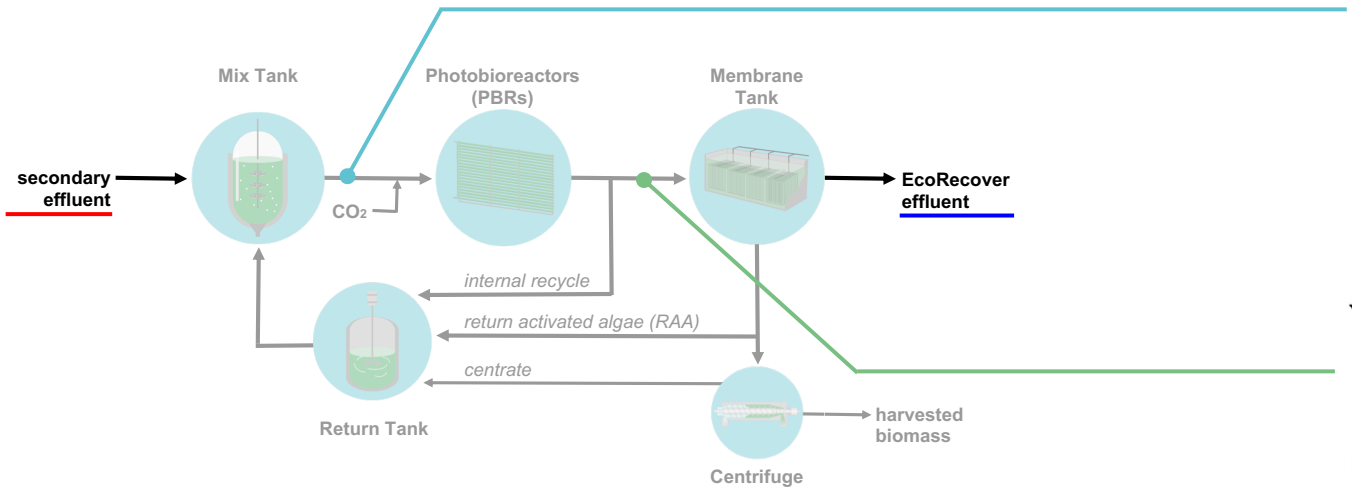
Georgia Institute of Technology

Long-term monitoring and characterization is enabled by a network of on-line sensors and analyzers that interface with a SCADA system.



Progress & Outcomes

We have intensively monitored the system for ~1.5 years (since Fall 2021) and have captured periods of excellent performance and upset events.



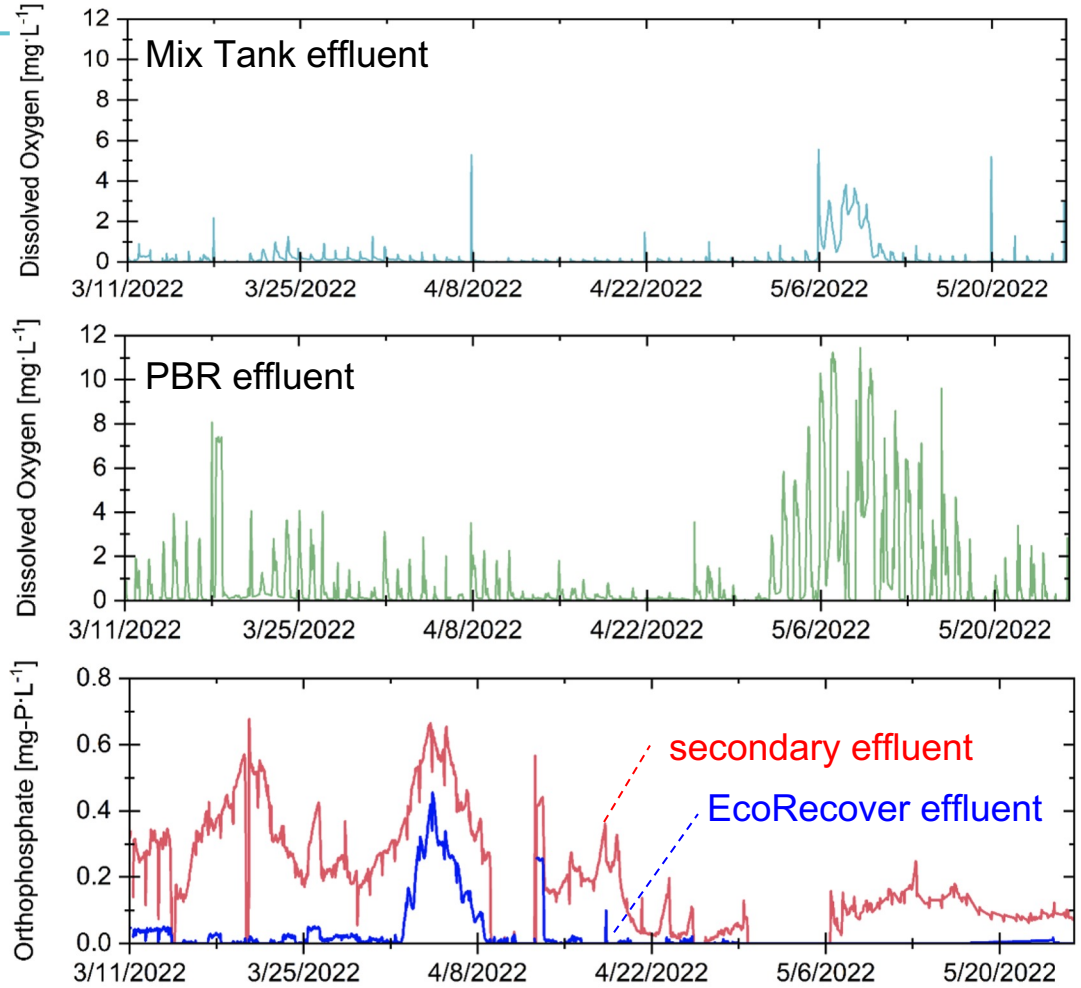
Timescale

Cloud-Hosted Relational Database

528 parameters (SCADA + AIMS)

>200,000 timepoints

	influent_nh4	…	raw_solids_final_weight_g
2021-04-25			
…			
2023-03-31			



Recent achievement from mid-November 2022 through mid-February 2023: **effluent P < 0.03 mg-P·L^{-1} for ~3 months** (100% of samples).

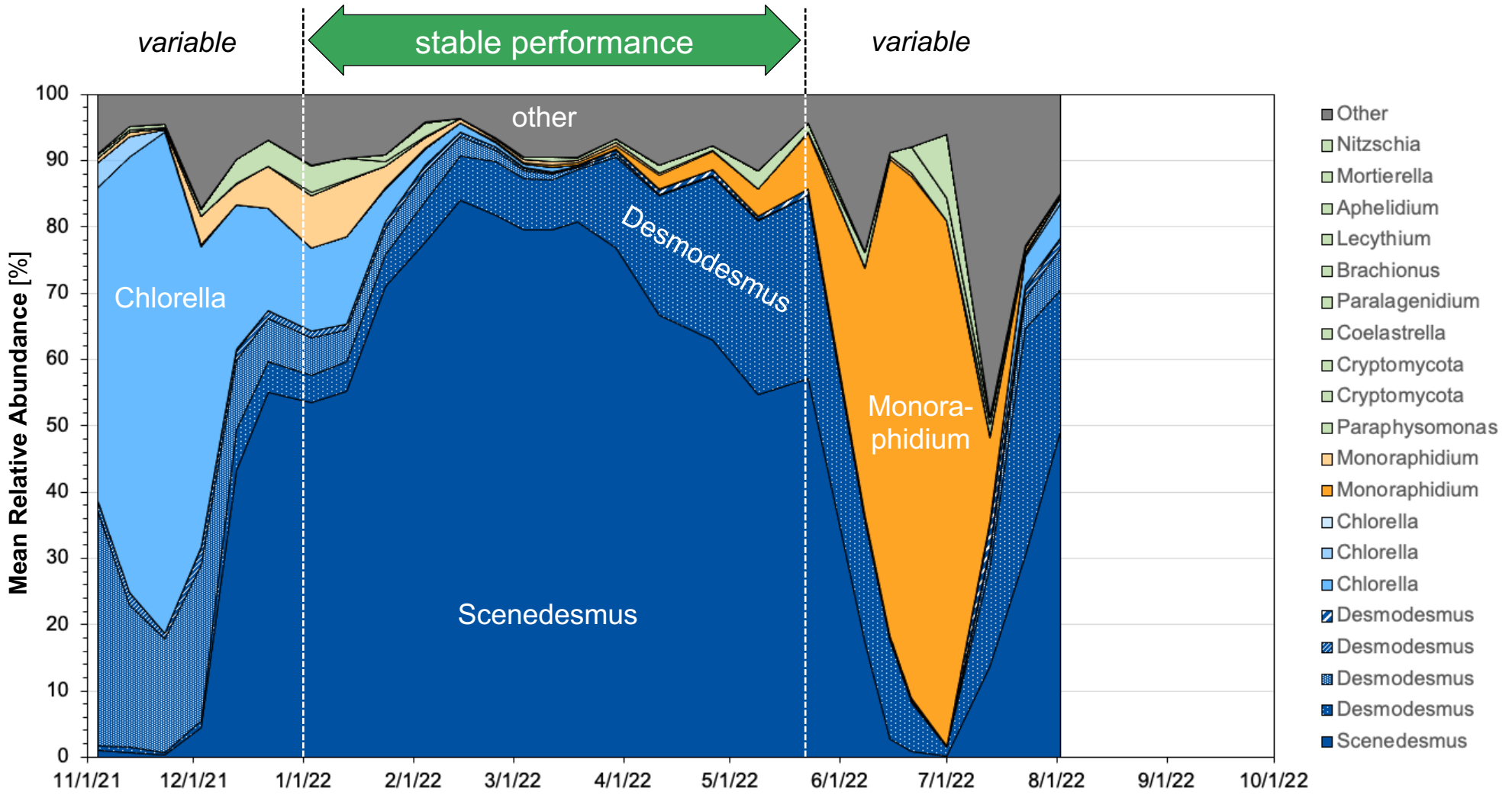
Community structure analyses complements water quality and microscopy data and identified indicators of stable performance or impending upset.

Indicators of stable performance:

- high *Scenedesmus sp.*
- balanced nitrifier community

Indicators of variable performance:

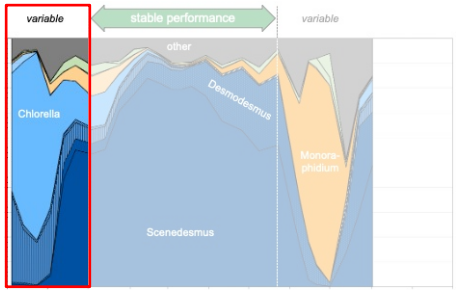
- loss of *Scenedesmus sp.*
- imbalance between ammonia oxidizing bacteria (AOB) and nitrite oxidizing bacteria (NOB)



University at Buffalo

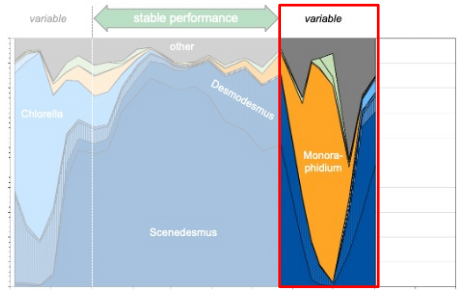
Progress & Outcomes

Process upsets were caused by (1) imbalanced nitrifying community (2) sudden influent changes which allowed **opportunistic pathogens** to increase

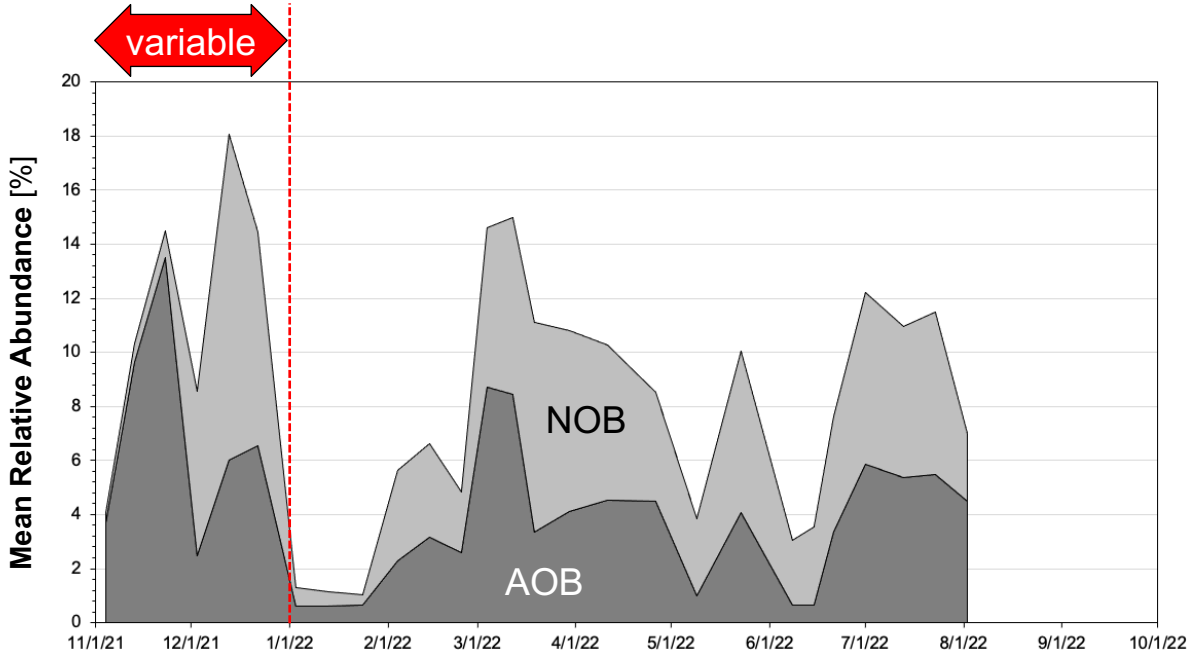


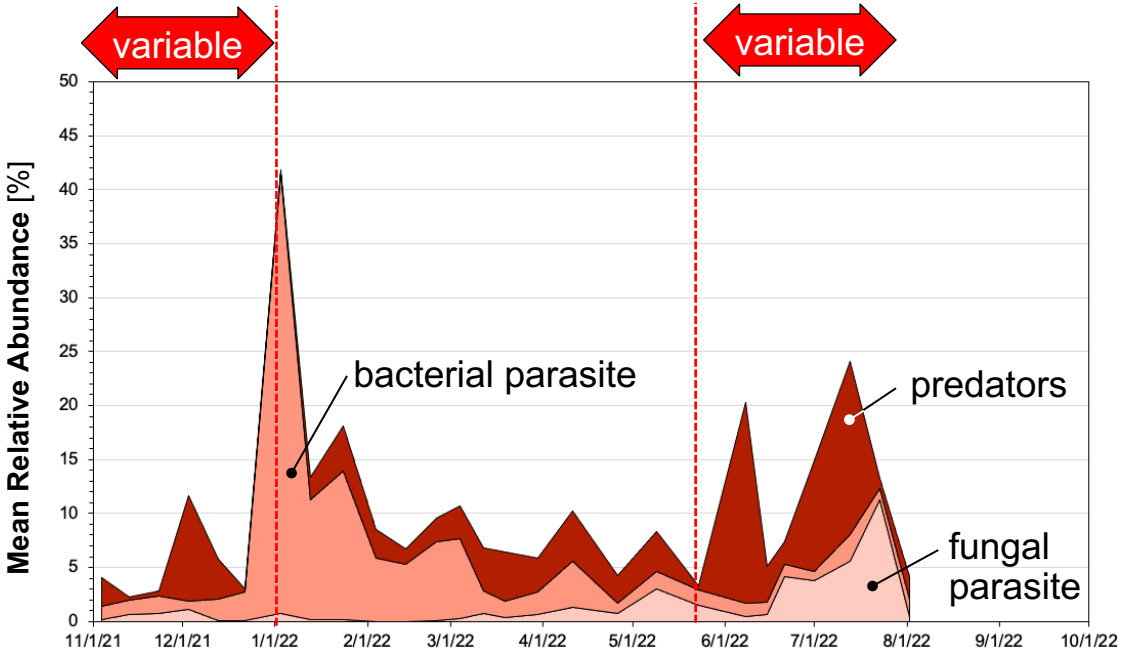
imbalance between AOB and NOB

AOB = ammonia oxidizing bacteria
NOB = nitrite oxidizing bacteria



parasites and predators





University at Buffalo

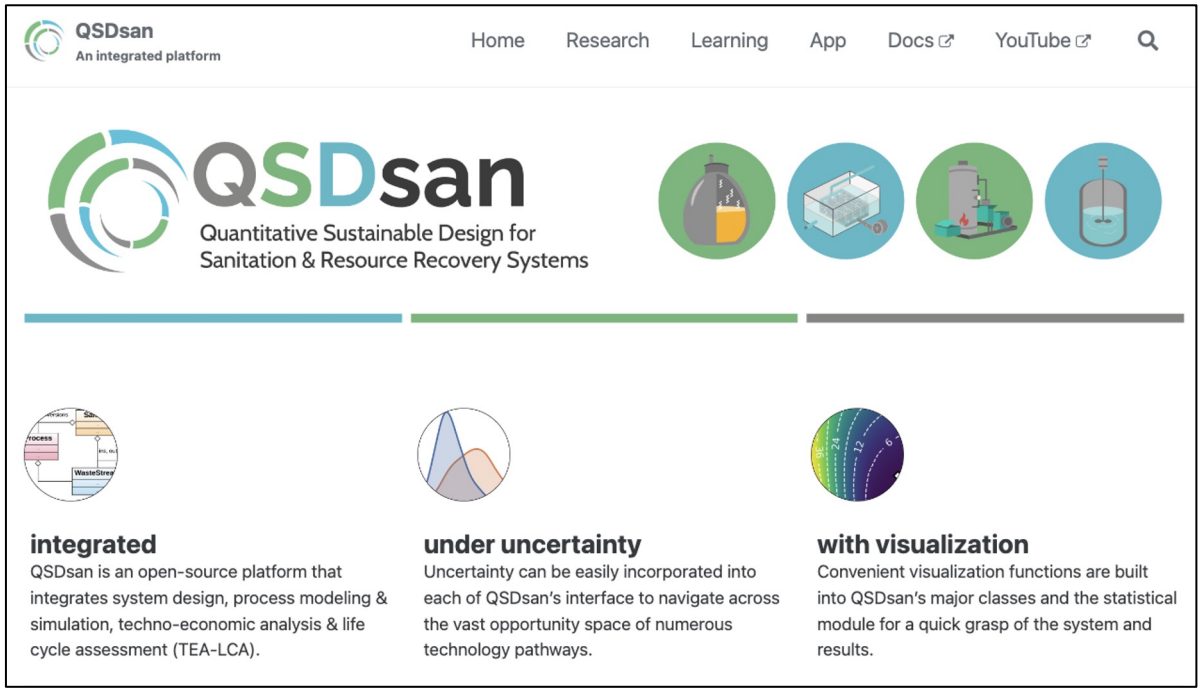
To advance our ability for design, simulation, TEA, and LCA of algal cultivation (and conversion) systems, we building open-source models in QSDsan.

QSDsan
Quantitative Sustainable Design for Sanitation & Resource Recovery Systems

[qsdsan.com/]
[https://github.com/QSD-Group]
[Li et al. QSDsan: An integrated platform for quantitative sustainable design of sanitation and resource recovery systems. *Environ. Sci.: Water Res. Technol.* 2022, 8 (10), 2289-2303. https://doi.org/10.1039/d2ew00455k]

updated mixed community microalgae process model with 13 state variables and 30 processes

calibration and validation with batch and continuous datasets



BioSTEAM

CABBI
CENTER FOR ADVANCED BIOENERGY AND BIOPRODUCTS INNOVATION

developed through our work with **CABBI**, a DOE Bioenergy Research Center (BRC)

includes downstream separations, conversions, TEA, LCA, uncertainty and sensitivity analyses

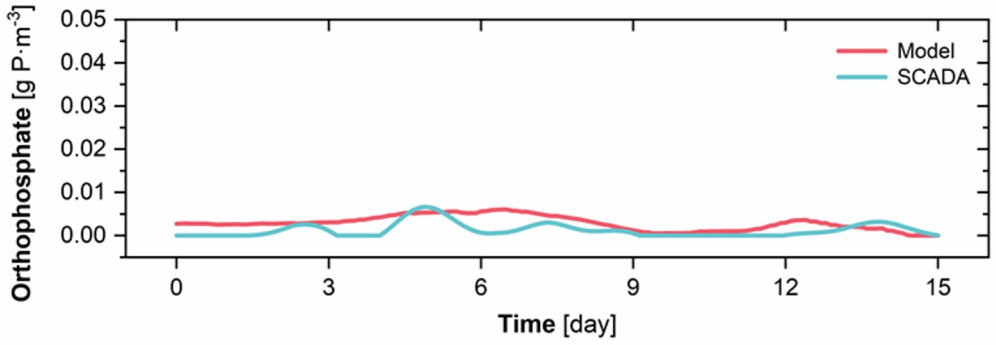
[biosteam.readthedocs.io]
[https://github.com/BioSTEAMDevelopmentGroup]
[Cortes-Peña et al. BioSTEAM: A Fast and Flexible Platform for the Design, Simulation, and Techno-Economic Analysis of Biorefineries under Uncertainty. *ACS Sustainable Chemistry & Engineering*. 2020, 8 (8), 3302–3310. https://doi.org/10.1021/acssuschemeng.9b07040]

Progress & Outcomes

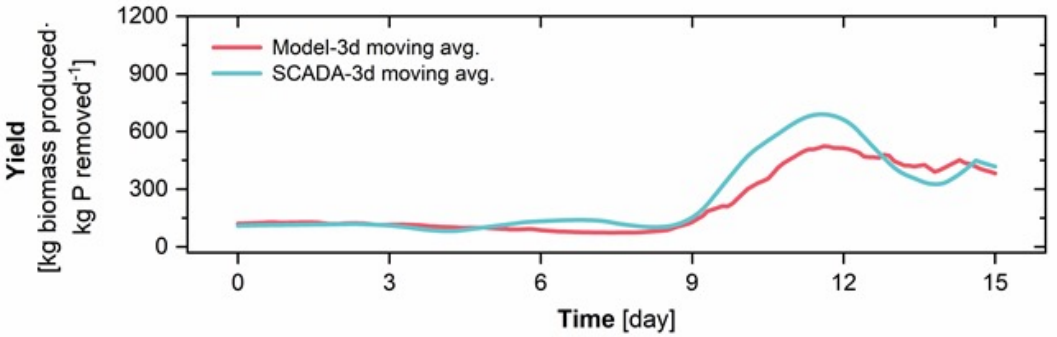
The process simulator met our go/no-go milestone for predicting effluent phosphorus, energy consumption, and biomass yield (i.e., amount of algae produced).

example validation

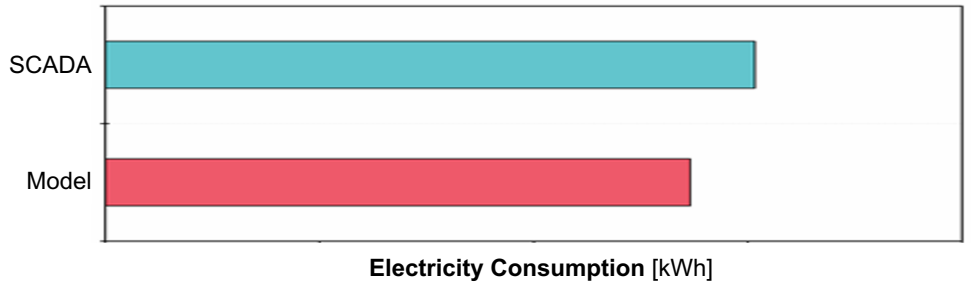
(the model was calibrated using data from a preceding time period)



*predict **avg effluent P** within **0.05 mg-P·L^{-1}***
achieved **within 0.01 mg-P·L^{-1}**



*predict **yield** within **25%***
achieved **within 20%**



*predict **energy** within **25%***
achieved **within 10%**

on-going validation

(calibration and validation is being performed across 5 periods of performance each lasting ~2+ months)

November 2021

S	M	T	W	T	F	S
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30				

December 2021

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12	13	14	15	16	17	18
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26	27	28	29	30	31	

January 2022

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16	17	18	19	20	21	22
23	24	25	26	27	28	29
30	31					

February 2022

S	M	T	W	T	F	S
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20	21	22	23	24	25	26
27	28					

March 2022

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13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30	31		

April 2022

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17	18	19	20	21	22	23
24	25	26	27	28	29	30

May 2022

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15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	31				

June 2022

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26	27	28	29	30		

July 2022

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17	18	19	20	21	22	23
24	25	26	27	28	29	30
31						

August 2022

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28	29	30	31			

September 2022

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25	26	27	28	29	30	

October 2022

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23	24	25	26	27	28	29
30	31					

November 2022

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		1	2	3	4	5
6	7	8	9	10	11	12
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20	21	22	23	24	25	26
27	28	29	30			

December 2022

S	M	T	W	T	F	S
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4	5	6	7	8	9	10
11	12	13	14	15	16	17
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January 2023

S	M	T	W	T	F	S
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8	9	10	11	12	13	14
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29	30	31				

February 2023

S	M	T	W	T	F	S
			1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28				

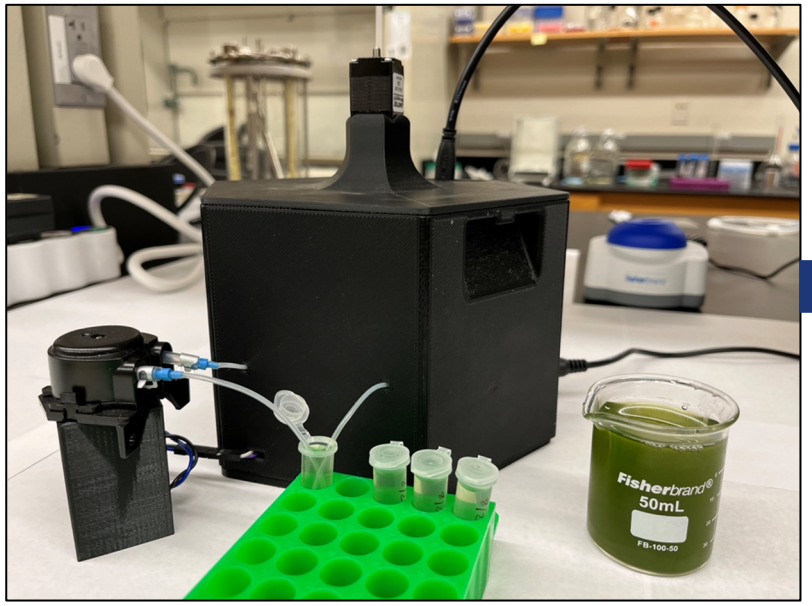
March 2023

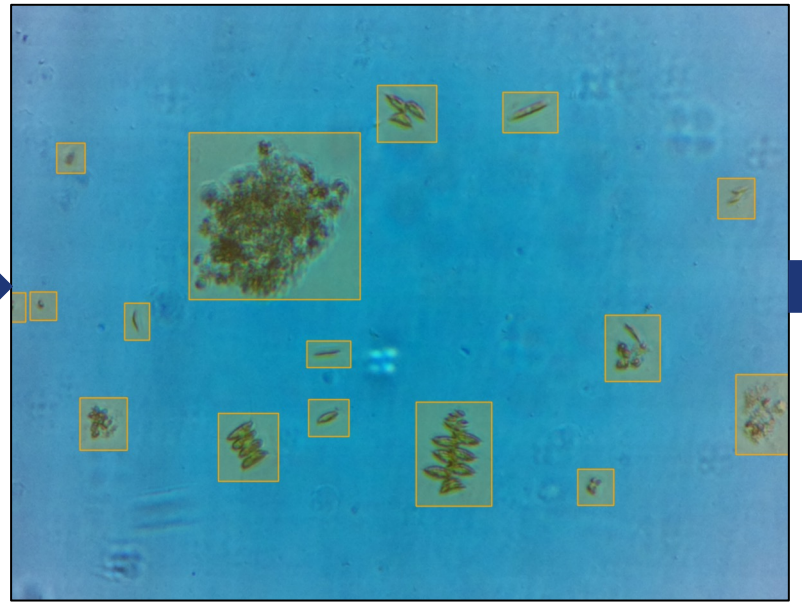
S	M	T	W	T	F	S
			1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30	31	

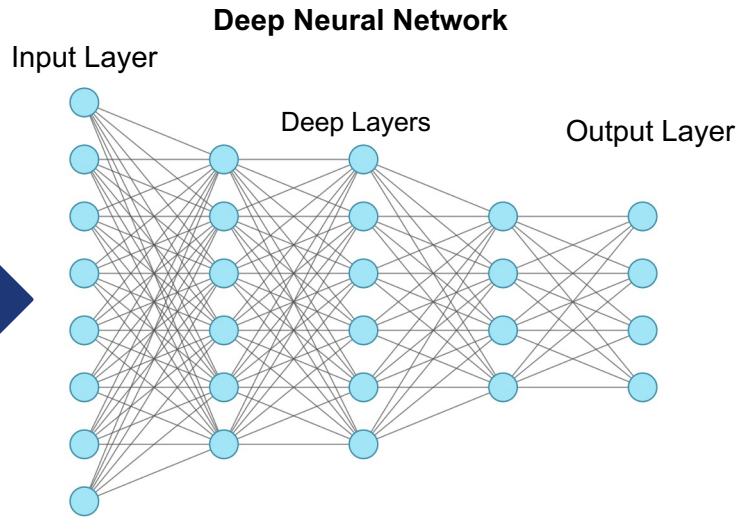
April 2023

S	M	T	W	T	F	S
						1
2	3	4	5	6	7	8
9	10	11	12	13	14	15
16	17	18	19	20	21	22
23	24	25	26	27	28	29
30						

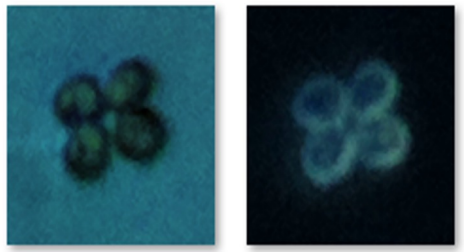
The **ARTiMiS** is an autonomous multimodal imaging platform that leverages deep learning to identify, classify, and count algal species in (near) real-time.



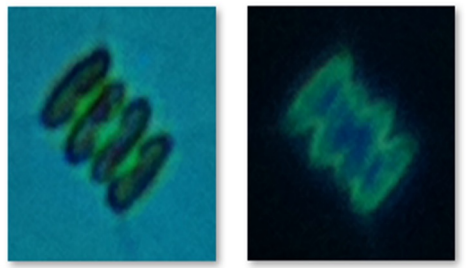




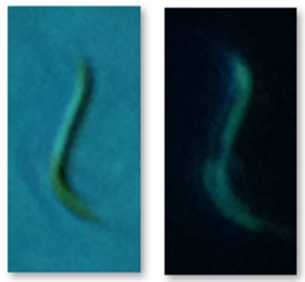
Chlorella



Scenedesmus



Monoraphidium

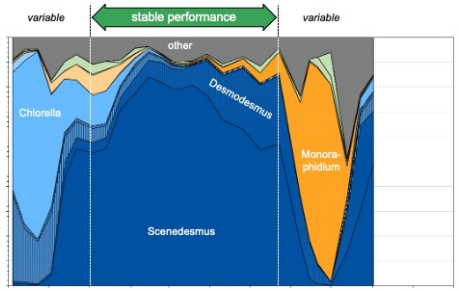


Georgia Institute of Technology

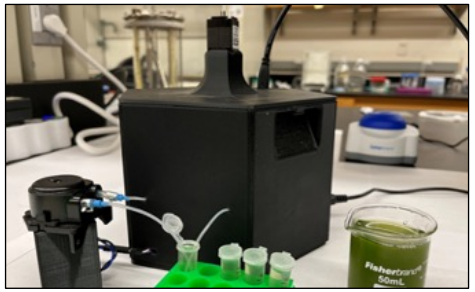
Progress & Outcomes

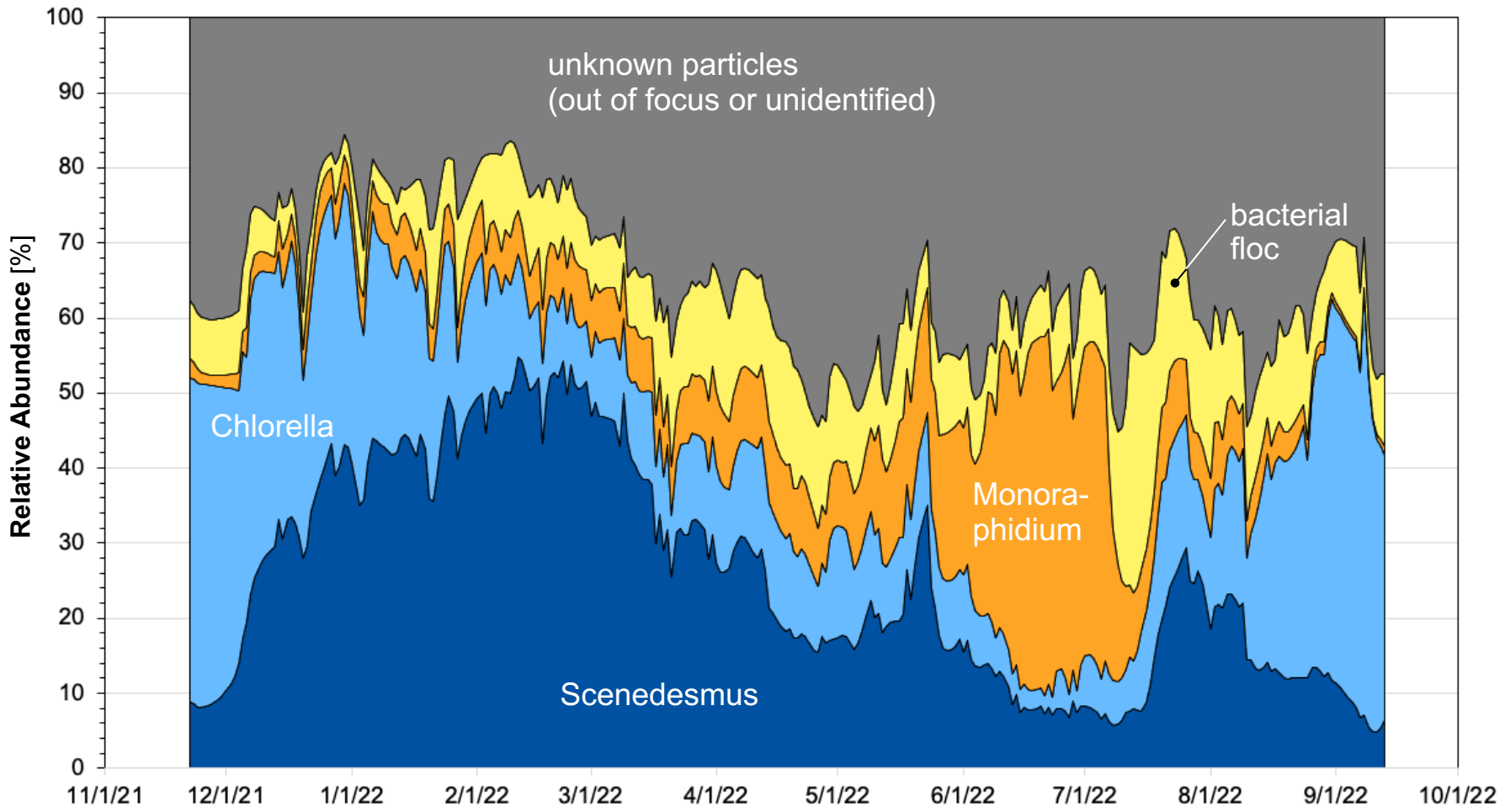
Software developed in this project have allowed the **ARTiMiS** to approach **86% accuracy for species level classification** of industrially relevant microalgae.

18S rRNA sequencing



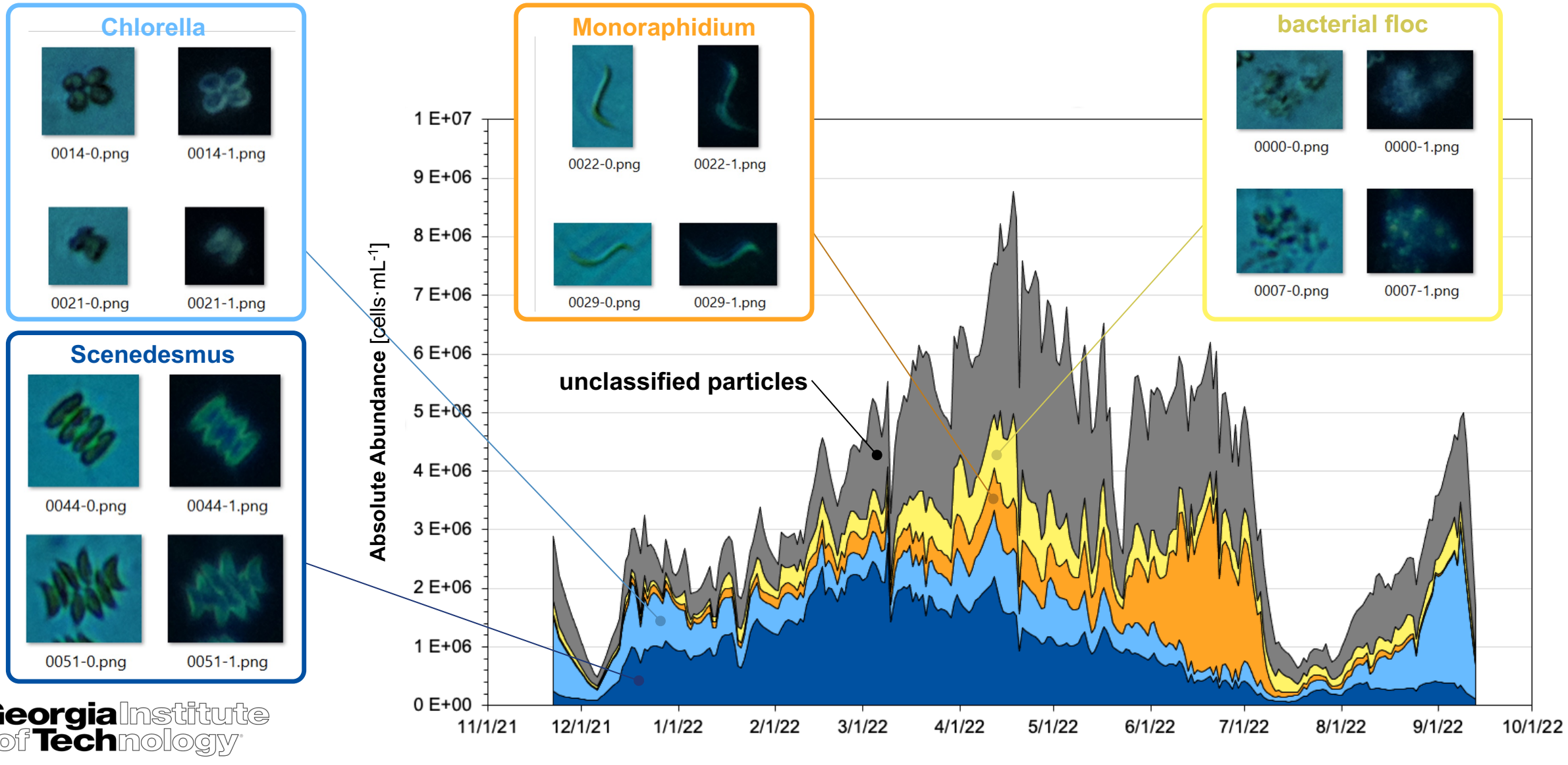
ARTiMiS





Georgia Institute of Technology

The **ARTiMiS** was advanced to accurately estimate absolute abundance of algal species providing quantitative resolution at the similar hardware cost of a TSS probe.



Georgia Institute of Technology

Impact

This project advances the EcoRecover process and two enabling technologies to help drive down costs of algae cultivation and biofuels/bioproducts.

Project Outputs

Open-source simulator
Calibrated / validated open-source process simulator with process modeling, TEA, and LCA, for the cultivation of mixed communities.

Microbial community structure tracking
Deployable, miniaturized, low-cost (<$300) microscope for real-time monitoring of cultivation ecology for mixed microalgal communities.

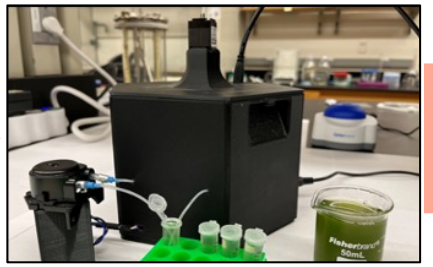
Optimized EcoRecover
Verified process with validated process simulator, locality-specific design optimization, and real-time monitoring and control system.

Contributions

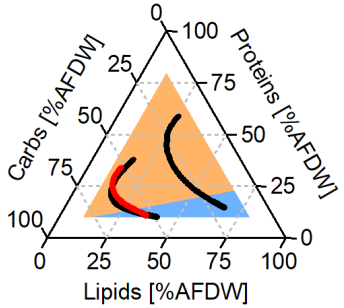
QSDsan
Quantitative Sustainable Design for Sanitation & Resource Recovery Systems

BioSTEAM

ARTiMiS



Impacts on BETO Portfolio



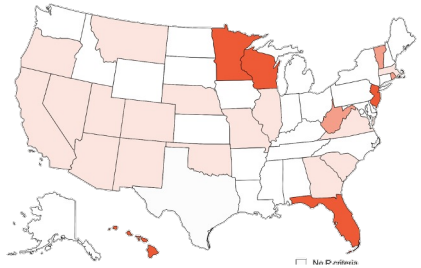
Open-source modeling to **reduce costs and GHG emissions** from mixed community and pure culture algae cultivation and downstream processing to biofuels and bioproducts.

[Leow et al. A unified modeling framework to advance biofuel production from microalgae. *Environmental Science & Technology*. 2018, 52(22): 13591-13599.]

[AzCATI]

Reduce algae biomass costs and GHG emissions through a deployable low-cost system to track pests, to track microbial community structure, and to improve cultivation efficiency and reliability.

EcoRecover

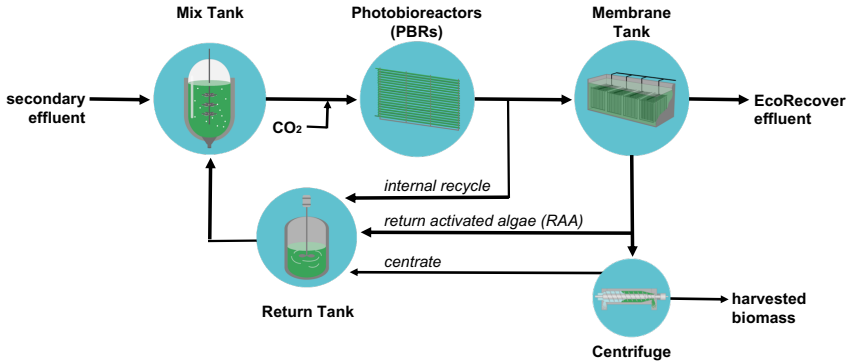


Validated EcoRecover process to leverage wastewater infrastructure investment and wastewater resources to recover resources and produce **low-cost, low-GHG algae biomass** for biofuels/bioproducts.

Summary This project advances the EcoRecover process and two enabling technologies that will support other activities in the BETO portfolio: QSDsan and ARTiMiS.

EcoRecover

phosphorus as a value proposition to access wastewater resources



process simulator

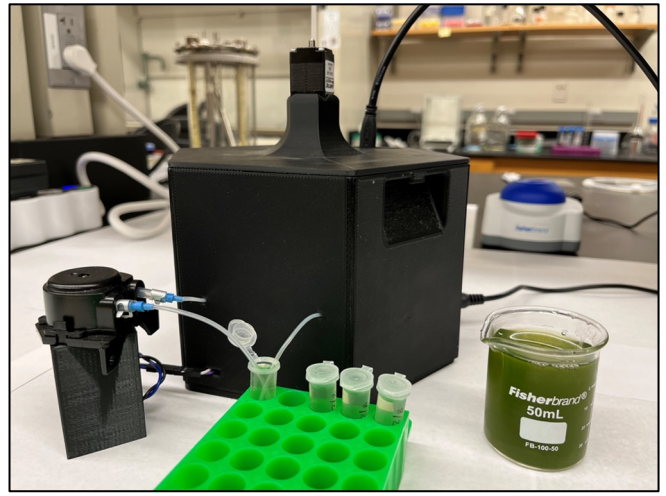
open-source process simulator for design, simulation, TEA, and LCA of cultivation and downstream processing

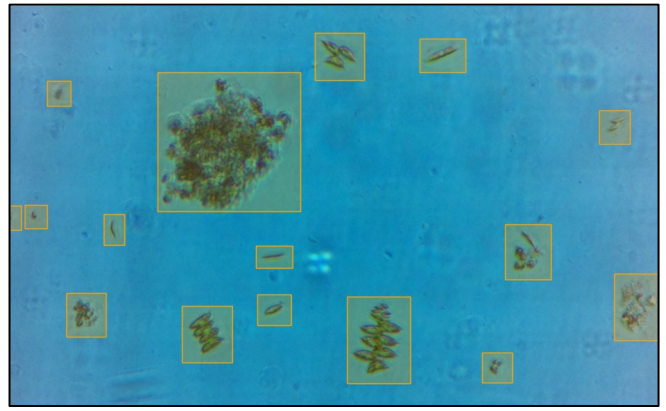
QSDsan
Quantitative Sustainable Design for Sanitation & Resource Recovery Systems

BioSTEAM

ARTiMiS

low-cost, real-time (2-5 min) community structure and pest monitoring





Quad Chart Overview

Timeline

Project start date: January 1, 2021
Project end date: June 30, 2024

	FY22 Costed	Total Award
DOE Funding	$580,334	$2,000,000
Project Cost Share *	$146,000 (estimated)	$509,062

Project Goal

The overarching goal is to advance our capacity for locality-specific design optimization and real-time process control of mixed community microalgal systems.

End of Project Milestone

- *achieve effluent ≤ 0.04 mg-P·L^{-1} for >90% of operating time*
- *operation at ≤ 126 kWh·kg-P^{-1}*
- *yield of ≥ 79 g-AFDW·g-P^{-1}*

Funding Mechanism

DE-FOA-0002203
Topic 2: Waste to Energy Strategies for the Bioeconomy
Sub-Topic 2c: Synergistic Wastewater Integration with Microalgae (SWIM)

TRL at Project Start: 5 (QSDsan & ARTiMiS)
TRL at Project End: 7

Project Partners*

Partner 1
Partner 2

*Only fill out if applicable.

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Highlights from past reviews and Go/No-Go review.

No previous reviews.

No available report from recent go/no-go evaluation.

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Publications, Patents, Presentations, Awards, and Commercialization

Lind, Jordan."Construction, commissioning, and startup of the world'sfirst advanced biological nutrient recovery (ABNRTM) facility at the Village of Roberts, WI." *2021 Algae Biomass Summit*. Algae Biomass Organization. 19 October 2021. Oral Presentation.

Gincley, Benjaminand Pinto, Ameet."Low-cost automated imaging-based monitoring of algal community structure in industry and the environment." *2021 Algae Biomass Summit*. Algae Biomass Organization. 13 Oct 2021. Oral Presentation.

Gincley, Benjamin and Pinto, Ameet. "Autonomous in situ monitoring of complex microalgal communities." *The 9th Microbial Ecology & Water Engineering Specialist Conference*. International Water Association. 18 October 2021. Oral Presentation.

Molitor, H.R.; Kim, G.-Y.; Avila, N.M.; Guest, J.S. Intensive Microalgal Cultivation for Phosphorus and Nitrogen Removal from Wastewaters. *17th International Water Association Leading Edge Conference on Water and Wastewater Technologies*, Reno, NV, March 2022. Lightning talk.

Alam, M.M; Hodaei, M.; Molitor, H.R.; Kim, G.-Y.; Gincley, B.; Avila, N.M.; Pinto, A.J.; Guest, J.S.; Bradley, I.M. (Abstract, Poster Presentation) Temporal variation in community structure and function of a mixed microalgal community from a full-scale municipal wastewater treatment plant. *Association of Environmental Engineering and Science Professors (AEESP) Research and Education Conference*; St. Louis, Missouri; June 2022.

Hodaei, M.; Alam, M.M.; Gallimore-Repole, S.; Benson, M.; Molitor, H.R.; Kim, G.-Y.; Gincley, B.; Avila, N.M.; Pinto, A.J.; Guest, J.S.; Bradley, I.M. (Abstract, Poster Presentation) Effects of algal community diversity on wastewater treatment performance and stability during environmental perturbations. *Association of Environmental Engineering and Science Professors (AEESP) Research and Education Conference*; St. Louis, Missouri; June 2022.

Molitor, H.R.; Kim, G.-Y.; Avila, N.M.; Gincley, B.; Alam, M.M; Hodaei, M.; Pinto, A.J.; Bradley, I.M.; Guest, J.S. (Abstract, Oral Presentation) Intensive mixed community microalgal cultivation for nutrient recovery from municipal wastewater. *Association of Environmental Engineering and Science Professors (AEESP) Research and Education Conference*; St. Louis, Missouri; June 2022.

Gincley, B., Khan, F., and Pinto, A.J. (Abstract, Poster Presentation) Characterizing microalgal community structure with ARTIMiS. *Association of Environmental Engineering and Science Professors (AEESP) Research and Education Conference*; St. Louis, Missouri; June 2022.

Guest, J.S. (Abstract, Invited Oral Presentation) Characterization of an Intensive Microalgal Treatment Process for Phosphorus Recovery from Wastewater. *International Water Association (IWA) Wastewater, Water, and Resource Recovery Conference*. Virtual (and in Poznan, Poland); April 2022.

Kim, G.-Y.; Molitor, H.R.; Zhang, X.; Li, Y.; Avila, N.M.; Shoener, B.D.; Schramm, S.M.; Morgenroth, E.; Snowling, S.D.; Guest, J.S. Development of a Phototrophic-Mixotrophic Process Model (PM2) and a Process Simulator for Algae-Based Wastewater Treatment, *13th IWA Specialist Conference on Wastewater Ponds and Algal Technologies*, Melbourne, Australia, July 2022.

Gincley, B.; Khan, F.; Hartnett, E.; Kelly, P.; Guest, J.S.; Molitor, H.R.; Bradley, I.M.; Pinto, A.J. Monitoring microalgal community structure dynamics at a wastewater nutrient recovery facility in real time with ARTiMiS. *Algae Biomass Summit Virtual Conference*, October 2022.

Molitor, H.R.; Kim, G.-Y.; Avila, N.M.; Li, Y; Alam, M.M; Hodaei, M.; Gincley, B.; Hartnett, E.; Pinto, A.J.; Bradley, I.M.; Guest, J.S. Intensive mixed community microalgal cultivation for phosphorus and nitrogen recovery from municipal wastewater. *Algae Biomass Summit Virtual Conference*, October 2022.

Molitor, H.R.; Kim, G.-Y.; Avila, N.M.; Li, Y; Alam, M.M; Hodaei, M.; Gincley, B.; Hartnett, E.; Pinto, A.J.; Bradley, I.M.; Guest, J.S. Intensive mixed community microalgal cultivation for phosphorus and nitrogen recovery from municipal wastewater. *Water Environment Federation (WEF) Research and Innovation for Strengthening Engagement (RISE) Algae-based Treatment Processes Meeting*, Virtual, December 2022.

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