Mitigation of persistent harmful algal bloom (HAB) in lakes using sustainable mechanical separation approaches

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Partner Organization Name: Meadowlands Environmental Research Institute (MERI), aka Meadowlands Research and &Restoration Institute (MRRI), New Jersey Sports and Exposition Authority (NJSEA)
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Industrial Partners: BRISEA Group Inc., Parsippany, NJ

Table of Content

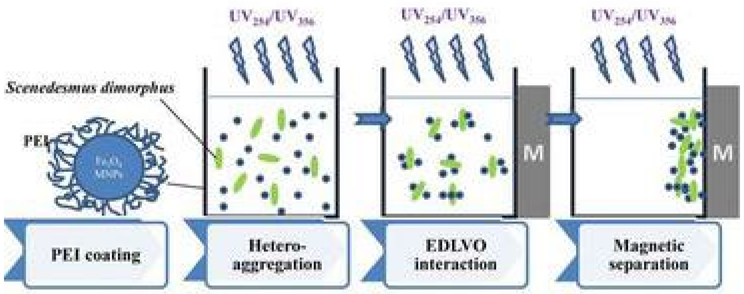
- Relevant research background and experiences
- Background-HAB and existing technologies/strength/weakness
- Technology features and principles of the presented approach
- Field results and lab results on foam fractionation
- Other relevant work- ***magnetic separation***, ***electrochemical oxidation*** and ***ozone nanobubbles***
- Acknowledgement

Relevant projects in HAB mitigation research at Zhang's group

We focused the following research on HAB mitigation and cyanotoxin removal:

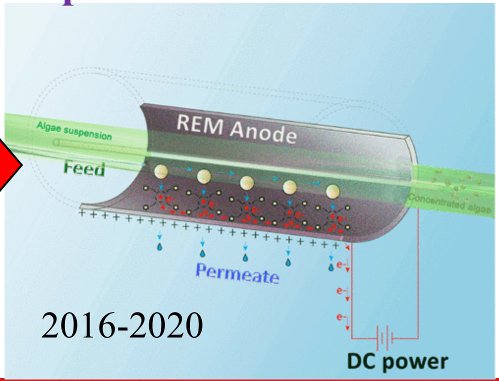
- Development of Multifunctional Reactive Electrochemical Membranes for Algal Biomass Recovery with Fouling Reduction, Water Reuse, and Cell Pretreatment. NSF Award number: 1603609 and 1836036. 09/01/2016-08/31/2020.
- Development of Reactive Nanobubble Systems for Efficient and Scalable Harmful Algae and Cyanotoxin Removal. EPA P3 Phase I Award#: 83945101 and EPA P3 phase II Award#:84001901. 7/1/2018-06/30/2021
- Analysis of the algogenic odor detection in raw water supply systems. Suez. 2018-2019

Magnetophoretic separation



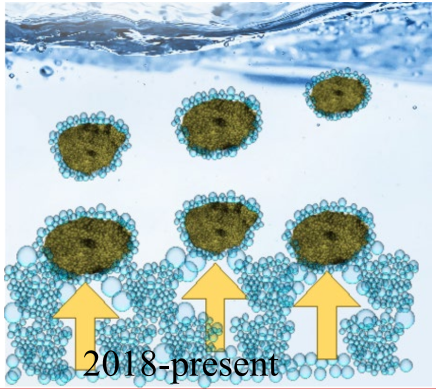
2013-2015

Electrochemical separation/oxidation



2016-2020

Air flotation/foam fractionatoin



2018-present

- **Problem with microalgal harvesting (or algal removal)**

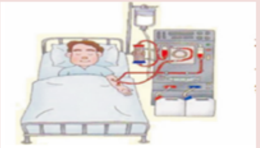
Due to the small size (typically 2–20 μm in diameter) and low concentrations in growth media (e.g., 0.5–5 g-dry weight·L^{-1}), cost efficient algal separation technologies are still lacking. Many existing ones suffer limitations in scalability or economic viability.

- **Significance of the problem and its impact.**
  - Rapid and highly efficient algal harvesting or removal is clearly critical for water treatment industries as well as for biomass engineering and biofuel production.
  - lower the operational cost and increase the economic viability of produced products (biomass or cleaned water)

Dewater! Dewater!! Dewater!!!

Current problems from HAB

Public health concerns
- ➢ Allergic reactions
- ➢ Illness caused by algal toxins



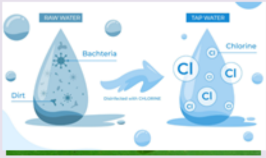
Ecological concerns
- ➢ Low dissolved oxygen concentration
- ➢ Death of aquatic animals
- ➢ Food-web disruption

Economic concerns
- ➢ Loss of recreational revenue
- ➢ Added drinking water treatment cost
- ➢ Fishery and aquaculture contamination

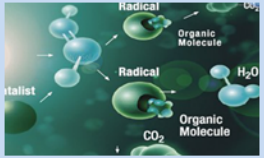
Existing technologies

Activated carbon adsorption
- ➢ Lower affinity
- ➢ Adsorption competing from NOM

Chlorination
- ➢ Algal cell damage
- ➢ Release of odor and taste
- ➢ Alter functional groups



Advanced oxidation processes
- ➢ High operational cost
- ➢ Short half-life
- ➢ Large scale limited



Ultrasonic Depression

Algicides and aquatic herbicides such as copper and barley straw

Aeration and Circulation

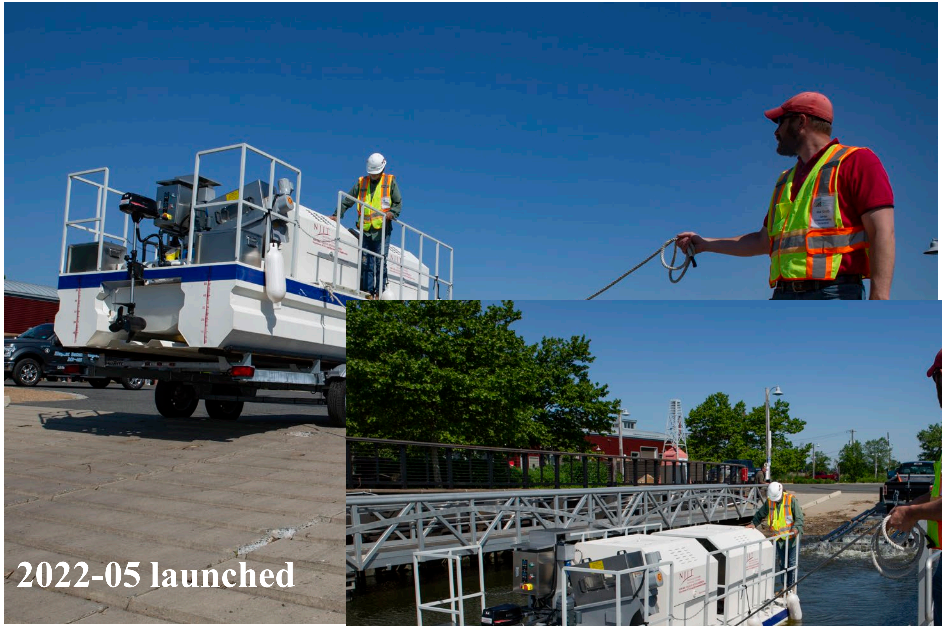
Shading – dyes or black spheres

Project Name: Mechanical removal of harmful algal bloom (HAB) in lakes using air micro-nano bubbles from a specialized floating platform

RFP Category: Grants to Prevent, Mitigate and/or Control of Freshwater Harmful Algal Blooms (HABs)

Contract WM #: WM20-040

2021-10-13 delivered to NJSEA

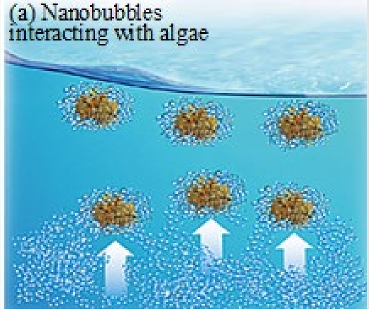


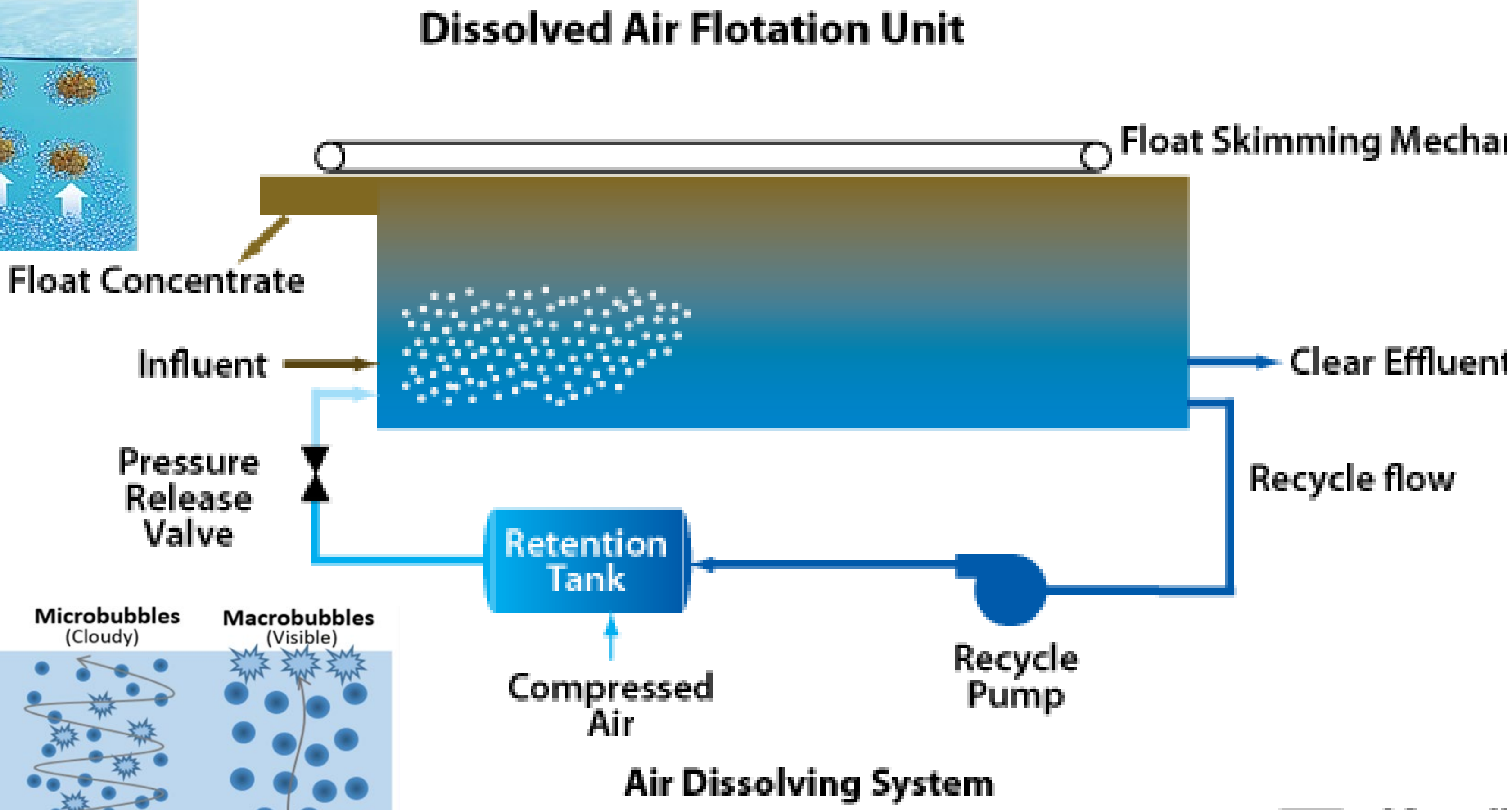
2022-05 launched

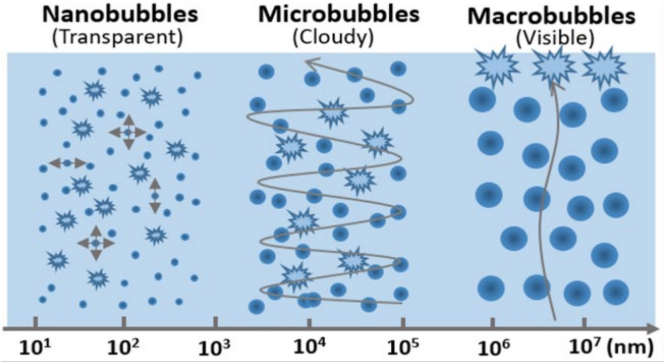
DEPARTMENT OF ENVIRONMENTAL PROTECTION NEW JERSEY

NEW JERSEY INSTITUTE OF TECHNOLOGY Founded 1881

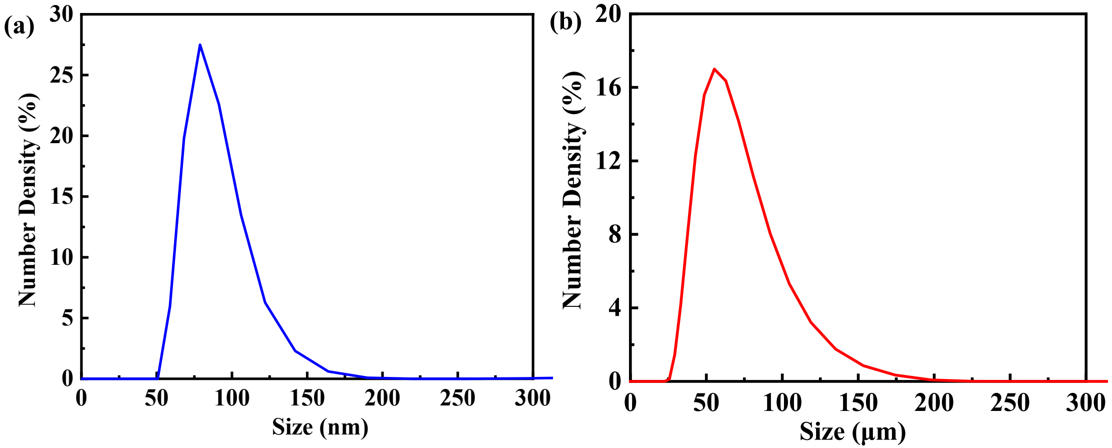
MERI

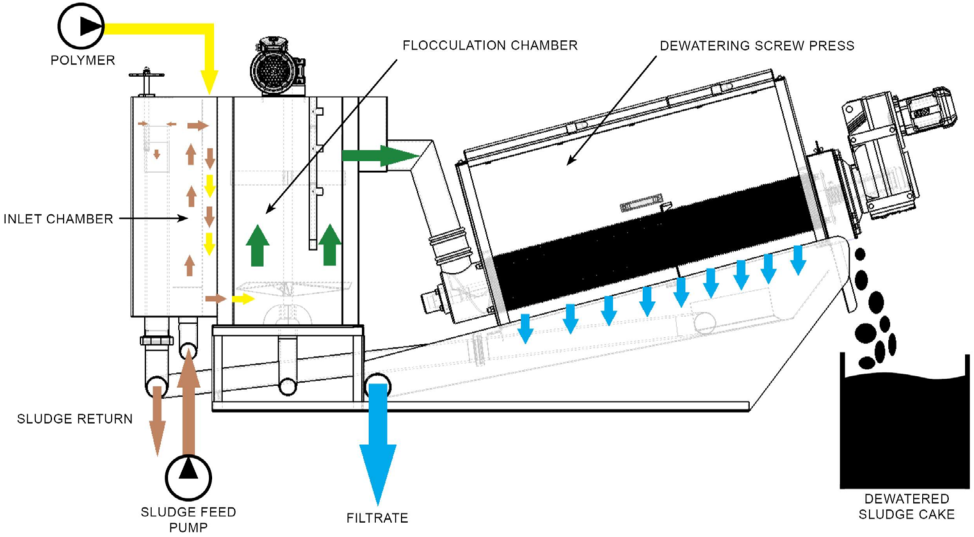

(a) Nanobubbles interacting with algae


Dissolved Air Flotation Unit
Float Skimming Mecha
Float Concentrate
Influent
Clear Effluent
Pressure Release Valve
Recycle flow
Retention Tank
Compressed Air
Recycle Pump
Air Dissolving System

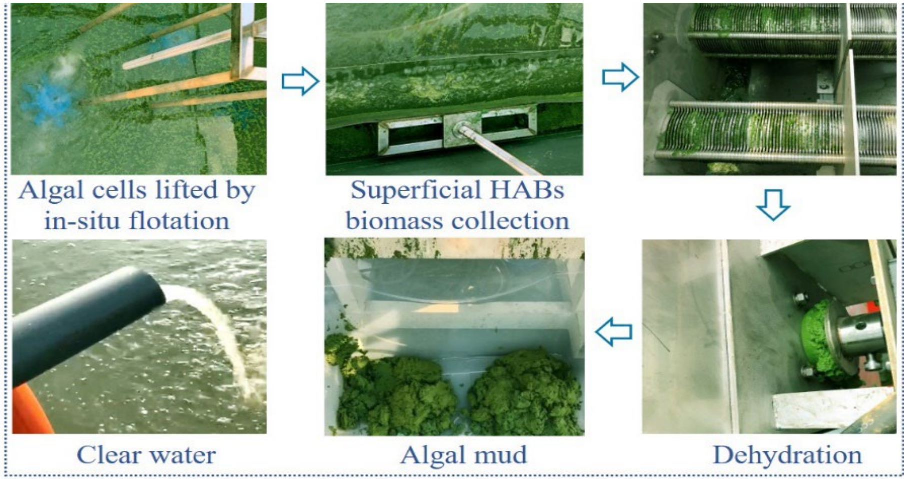

Nanobubbles
(Transparent)
Microbubbles
(Cloudy)
Macrobubbles
(Visible)
10¹ 10² 10³ 10⁴ 10⁵ 10⁶ 10⁷ (nm)

Fine bubble aeration for air/algae flotation (i.e., 5 m^3/h at 1 atm and approximately an air/water ratio of 9% v/v)




POLYMER
FLOCCULATION CHAMBER
DEWATERING SCREW PRESS
INLET CHAMBER
SLUDGE RETURN
SLUDGE FEED
PUMP
FILTRATE
DEWATERED
SLUDGE CAKE


Speed up to 1 km/h


Algal cells lifted by
in-situ flotation
Superficial HABs
biomass collection
Dehydration
Algal mud
Clear water

In this project, two HAB-impaired lakes (reported on the NJDEP website), Branch Brook Park Lake (Essex County) and Deal Lake (Monmouth County) will be selected as the targeted water bodies for the c

Results/goals

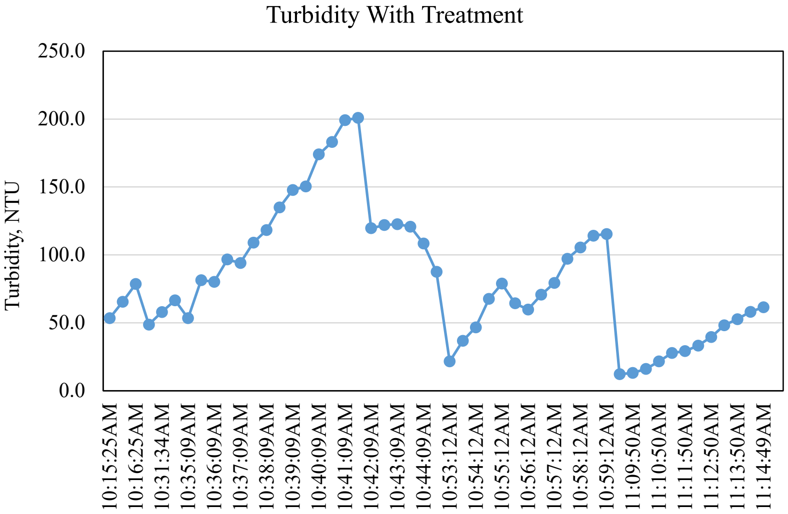
- Development a multifunctional air-flotation which not only rapidly removes HABs in situ but also increases dissolved oxygen and biodegradation activity via enhanced air transfer using the **micro-nanobubble aeration**.
- Assessment of water quality parameters includes algal concentrations, turbidity, nutrient levels, etc., before/after boat operations.
- Demonstrate a sustainable mechanical platform to rapidly remove HABs from impaired water.
- A comprehensive and smart bloom control strategy/suggestions are offered based on skills, experiences and results to be obtained onsite.

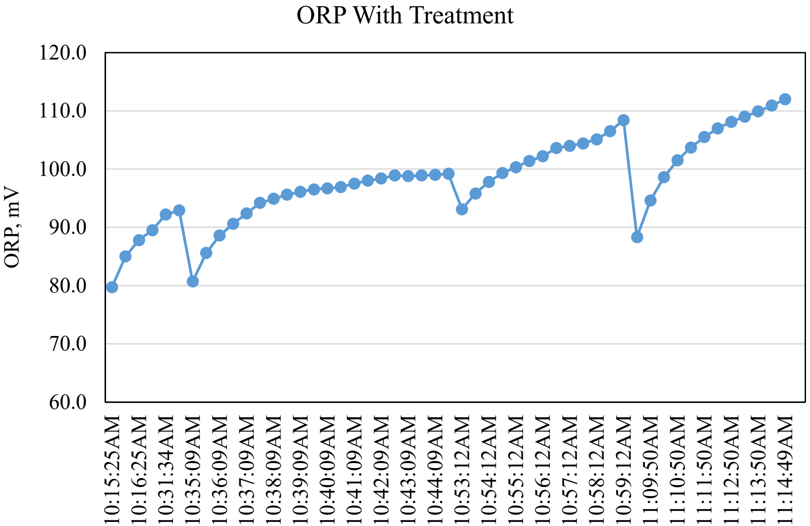
Branch Brook Lake survey-MRRI

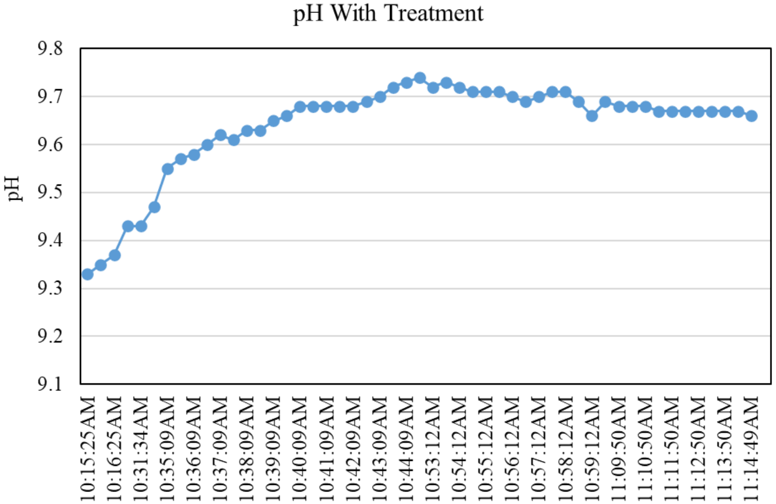
- Flied drone to capture high resolution panoramic and ortho imagery;
- Water quality parameters measured in the middle of the lake from south to north;
- Collected bathymetry data by sonar.

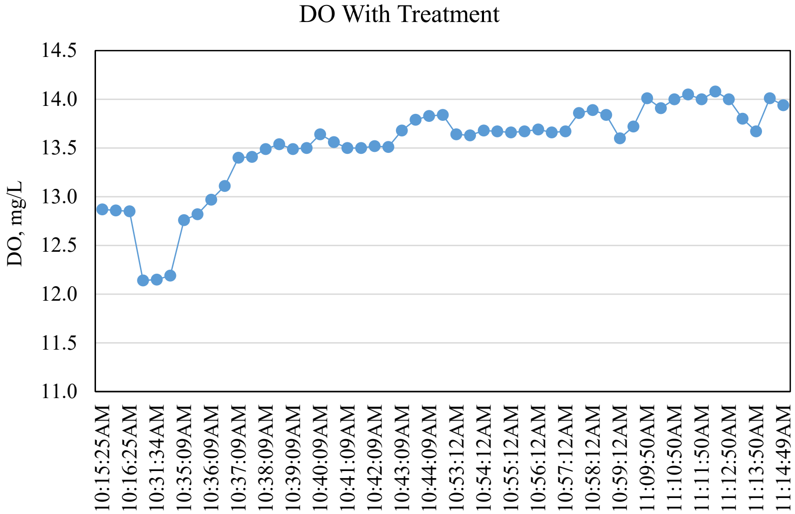
Water Quality Parameters (N=9)	
Temperature, ^{o}C	17.79±0.32
Conductivity, mS/cm	0.75±0.03
Salinity, ‰	0.37±0.01
pH	7.62±0.22
Turbidity, NTU	1.63±1.25
DO mg/L	7.93±1.41

2022-08-19 Deal Lake Water Quality

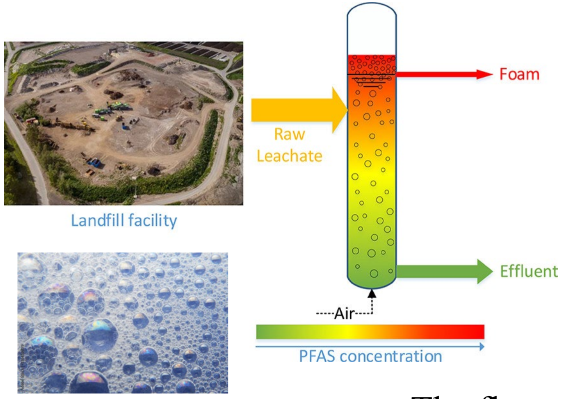


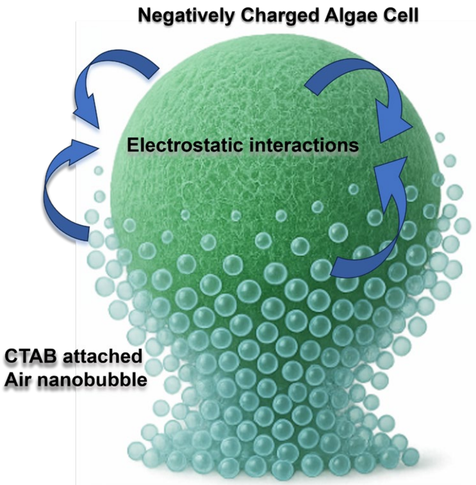




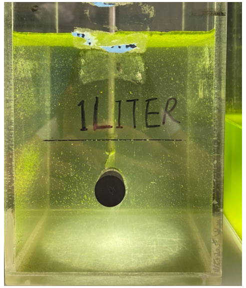


Nanobubble or ultrafine bubble-enabled air flotation and foam fracti



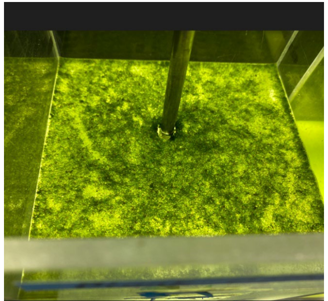


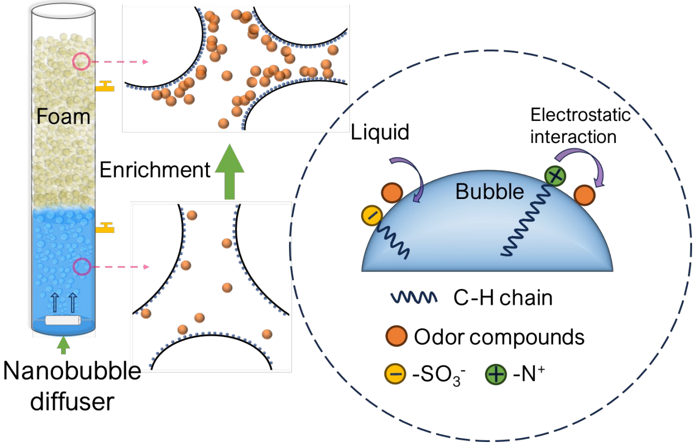
The floated algal biomass after micro/nanobubble purging



Algal suspension

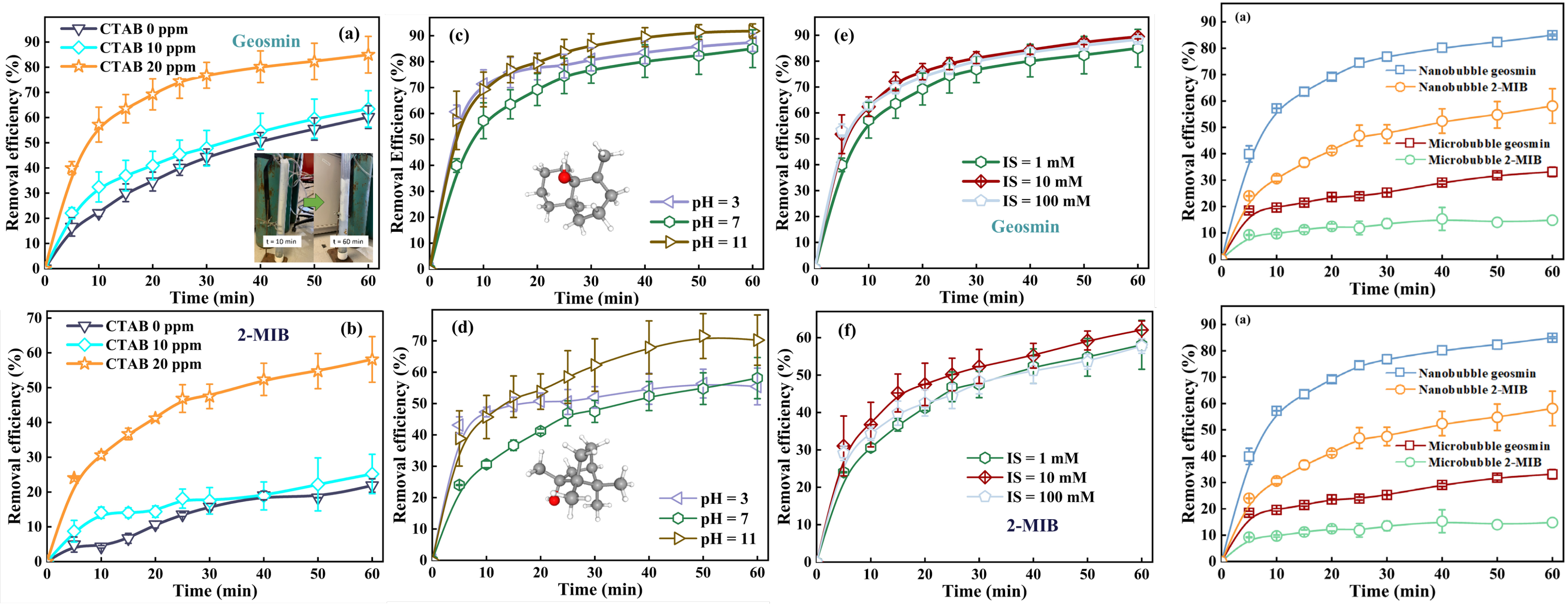
The floated algal biomass (top view photo)



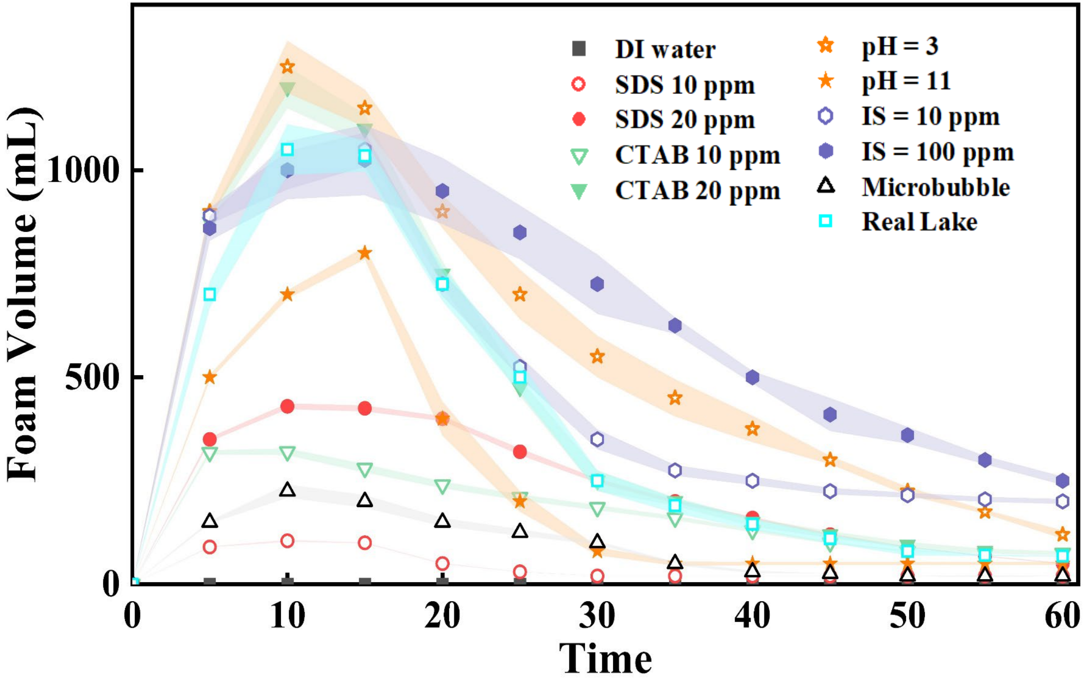


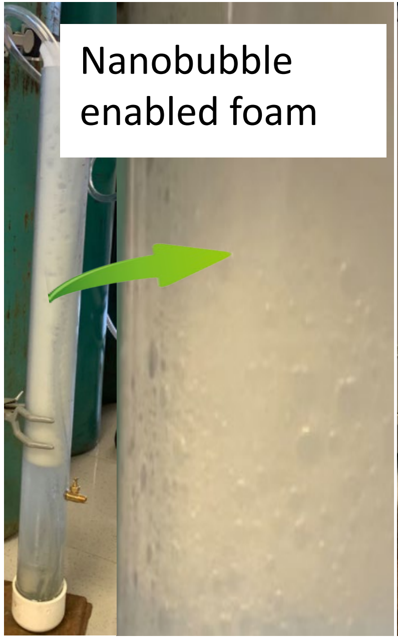
Nanobubbles-enabled foam fractionation for efficient odor compound (Geosmin and 2-MIB) removal

- A column setup with ceramic tubular membrane, aided by **surfactants (SDS & CTAB).**
- Odor compounds detection: **liquid-liquid extraction** and **gas chromatography-mass spectrometry.**
- Foam was produced under different conditions (e.g., different bubble size, surfactants, dosages, pH, and IS).



Foaming ability and stability



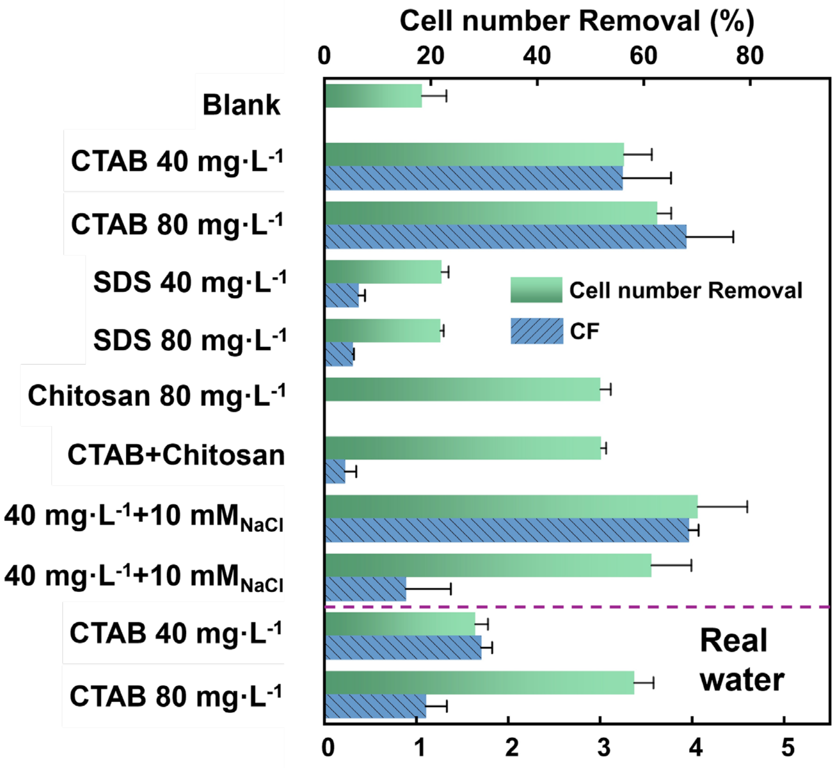


- Foam formation performance depends on the adsorption of the surfactant molecules at the air–water interface.
- The foam volume shrink reflects the **foam stability**, at low pH 3, high ionic strength (IS = 100 mM) and [CTAB] = 20 $mg \cdot L^{-1}$ stability improved (longer collapse time).

Influence of different factors on algae cells removal performance in algae suspension

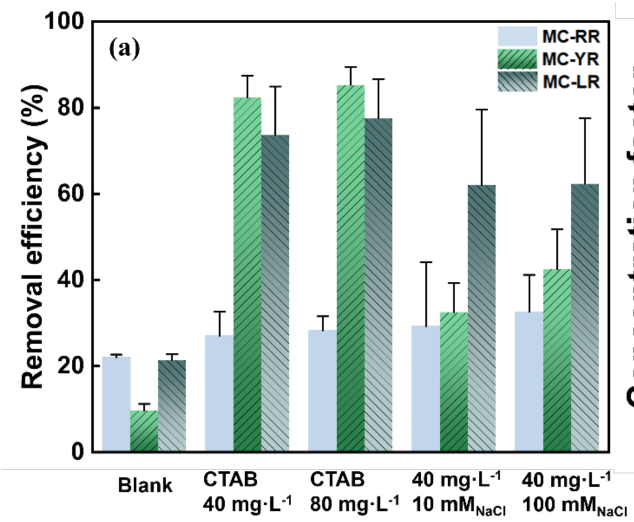
- *Microcystis aeruginosa* UTEX B 2662 was purchased from the UTEX Culture Collection of Algae and cultured to reach stock suspension (OD_{680} = 0.50×10^6 cells·mL^{-1}).
- Algal cell counts: light microscope and a modified Palmer-Maloney chamber.
- Surfactants: CTAB, SDS, and Chitosan

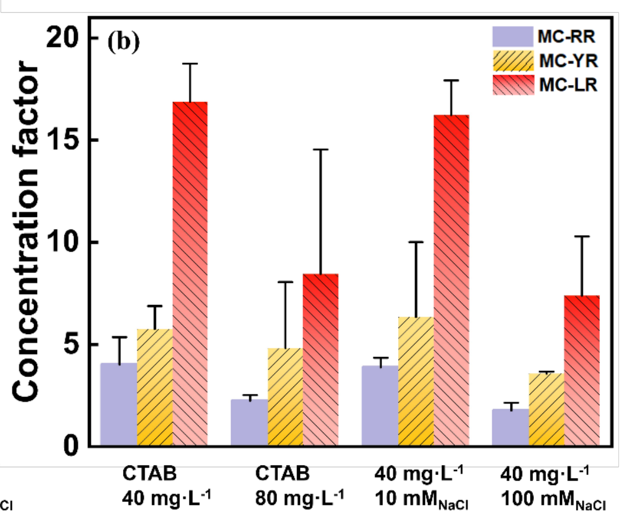
- 20% removal of algae in Blank: temporarily floated
- Salinity 10 mM to 100 mM: concentration factor 3.96 to 0.88 (frothing performance).
- Real water: DOM competition



Influence of different factors on microcystins removal performance in algae suspension

- Three kinds of microcystin (MC-LR, RR, and YR): HPLC coupled with a quadrupole mass spectrometer;
- The presence of CTAB increased MC-YR and MC-LR removal from 10% to 70%
- Raising salinity limits removal efficiency especially for MC-YR (85.29 ± 4.12% to 32.52 ± 6.73%).
- Compared to the MC-RR and MC-YR, more hydrophobic MC-LR was much more concentrated in the foam layer.
- CF lower with higher concentration of CTAB: saturate air-water interface, MC was outcompeted





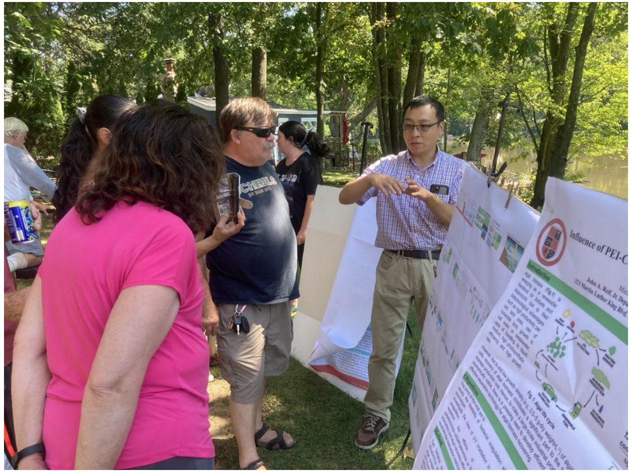
Community engagement and outreach

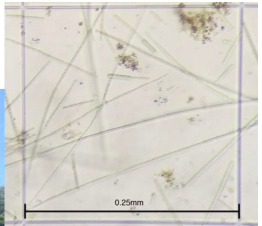
On July 22, 2021, Dr. Zhang and his team members, along with BRISEA staffs, joined the summer educational program with Kelley Forsyth, a horticulturist working for JERSEY CARES and her team at Branch Brook Lake

On November 7 2021, Dr. Zhang organized a field trip for his microbiology class (12 graduate students) and Zhang's group members (6 Ph.D. students and two undergraduate students)

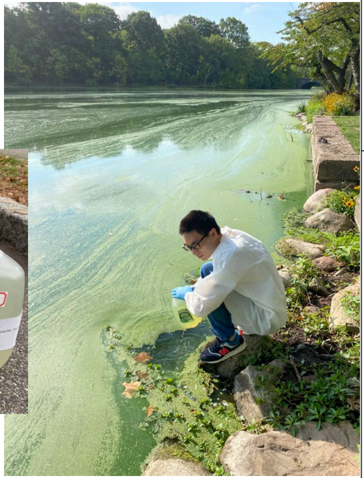
On 08/10/2022 from 10:30 am to 12:30 pm, Dr. Zhang’s group organized an outdoor workshop with Kelley Forsyth from Jersey Cares (www.jerseycares.org/careofthepark) at Branch Brook Park.

HAB monitoring work conducted in 2022 in Cozy lake (Morris County)



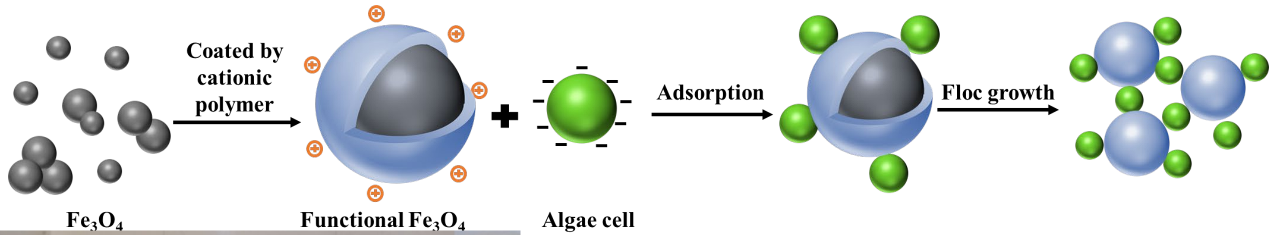


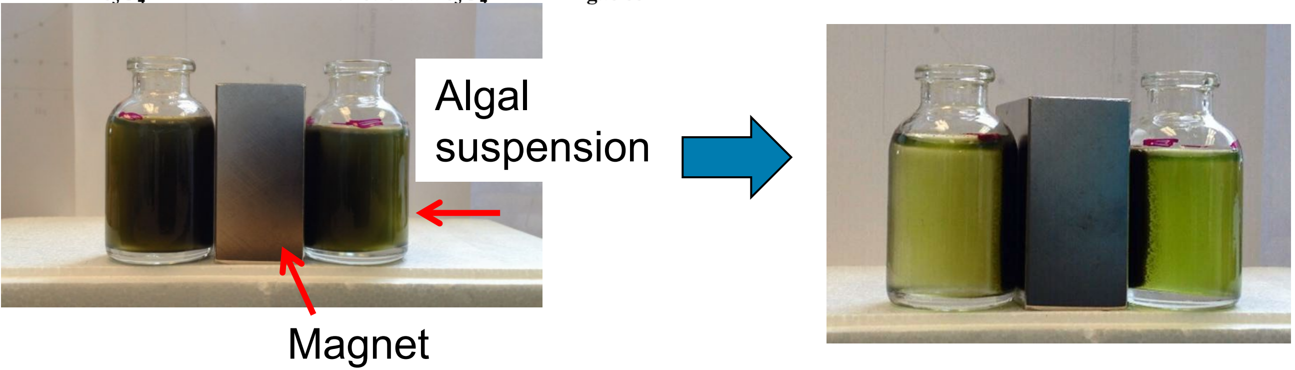
Categories	Parameters
1) Algal species and concentration	Algae number concentration distribution
	Algal genus and species analysis
	Algae dry biomass concentration
	Chlorophyll a
	EEM to detect lake water and biomass derived liquid*
2) Water quality	pH, redox, turbidity, and dissolved oxygen levels
	HPC, *E. coli*
	TOC
	TN, NH_4-N, NO_3-N, TP
	Microcystin-LR, Cylindrospermopsin, Anatoxin-a
	Geosmin and MIB

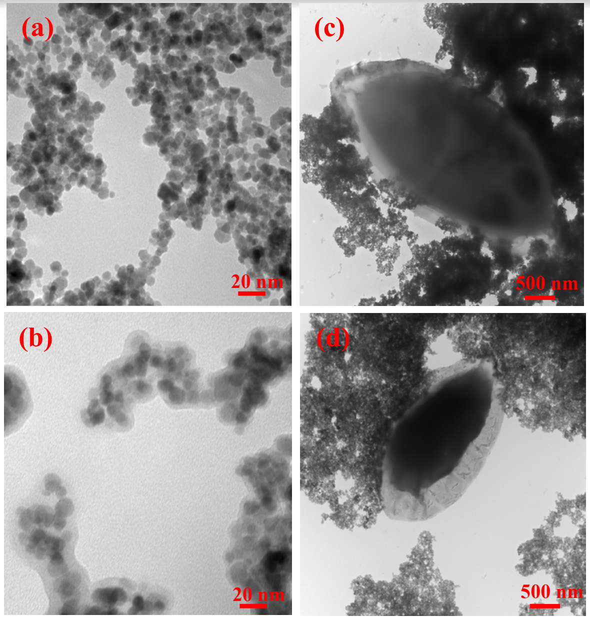


More field work photos are shown here:
https://drive.google.com/drive/folders/1VKn9me7UpmuSES125-DZVBX43WLpFyue

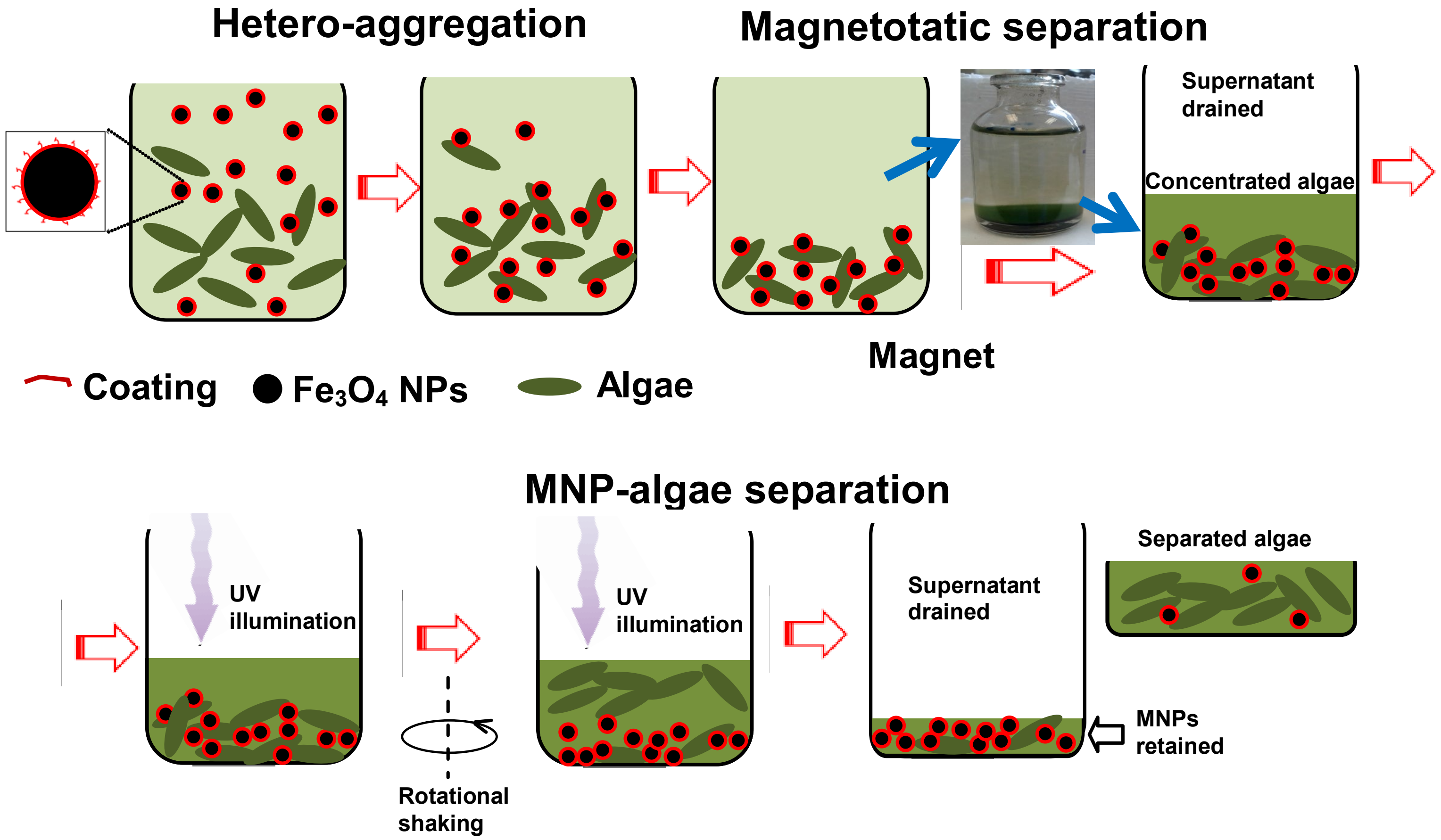
Magnetophoretic separation





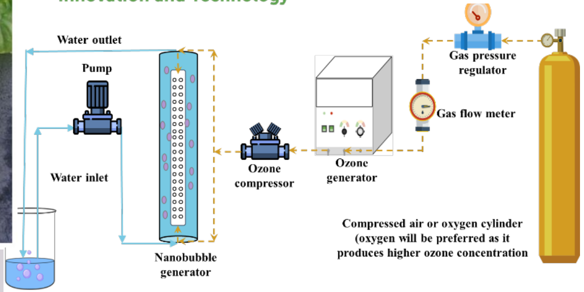


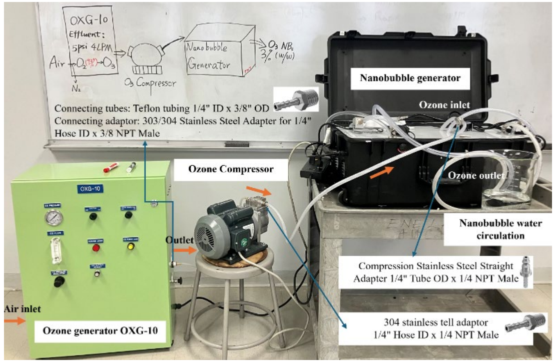
1. Li, Lili, Shan Xue, Yihan Zhang, Yunpeng Gao, Junjie Yang, Xuezhi Zhang, and Wen Zhang. "A chemical-free magnetophoretic approach for recovering magnetic particles in microalgae removal through magnetic separation." Journal of Cleaner Production 467 (2024): 143025.
2. Shijian Ge, Michael Agbakpe, Zhiyi Wu, Liyuan Kuang, **Wen Zhang***, Xianqin Wang. Influences of Surface Coating, UV Irradiation and Magnetic Field on the Algae Removal Using Magnetite Nanoparticles. ***Environmental Science and Technology***. 2015. 49 (2), pp 1190–1196 DOI: 10.1021/es5049573.
3. Shijian Ge, Michael Agbakpe, **Wen Zhang***, Liyuan Kuang, Heteroaggregation between PEI-coated Magnetic Nanoparticles and Algae: Effect of Particle Size on Algal Harvesting Efficiency. ***ACS Applied Materials & Interfaces***. 2015. DOI: 10.1021/acsami.5b00572.
4. Shijian Ge, Michael Agbakpe, **Wen Zhang***, L Kuang, Z Wu, X Wang Recovering Magnetic Fe_3O_4-ZnO Nanocomposites from Algal Biomass Based on Hydrophobicity Shift under UV Irradiation. ***ACS Applied Materials & Interfaces***, 2015, 7 (21), pp 11677–11682



Wen Zhang, et al.,. *Environmental Science and Technology*. 2014; Wen Zhang, et al., *ACS Applied Materials & Interfaces* . 2015;

Ozone Nanobubble Technology





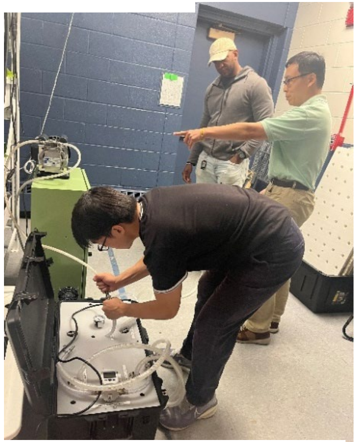


Fig. 1. Ozone nanobubble generation system developed at NJIT, showing (a) schematic of the integrated process and (b) pilot-scale unit tested in the collaborating farm.

Competitive Advantages

Consistent Performance — Repeatable CT with low variability ensures reliable microbial control.

Superior Mass Transfer — More dissolved ozone per gas input, maximizing oxidation efficiency.

Reduced Off-Gassing — Safer operation, lower ventilation and infrastructure costs.

Modular & Retrofit-Ready Design — Integrates easily into existing treatment systems.

Field-Validated — Proven operability in NJIT–EPA–CSIT pilot farms (Geogreen) beyond the lab.

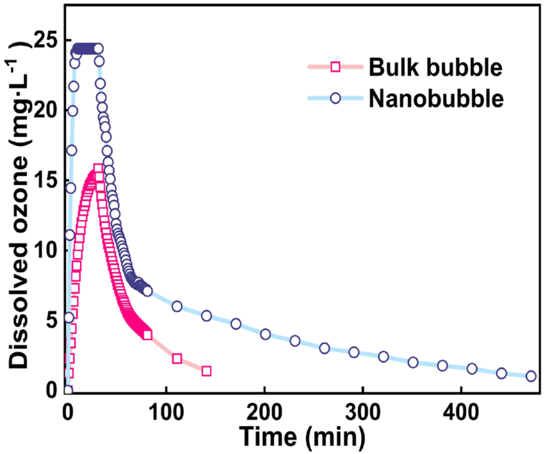
Commercial Readiness

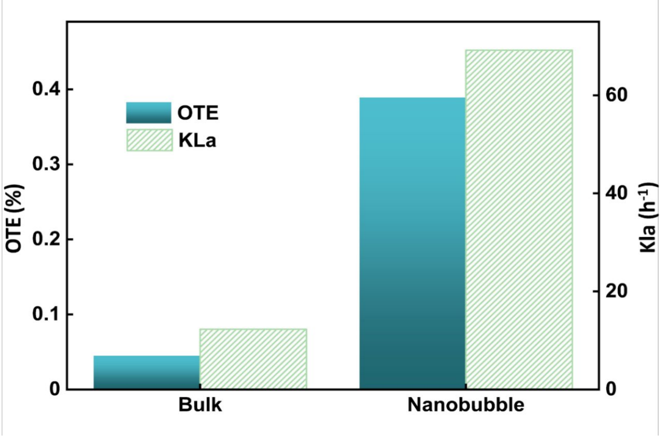
Early-stage commercialization aims to capture **1–5% of the U.S. SAM (~$20–100M)**, with scalability to global markets.

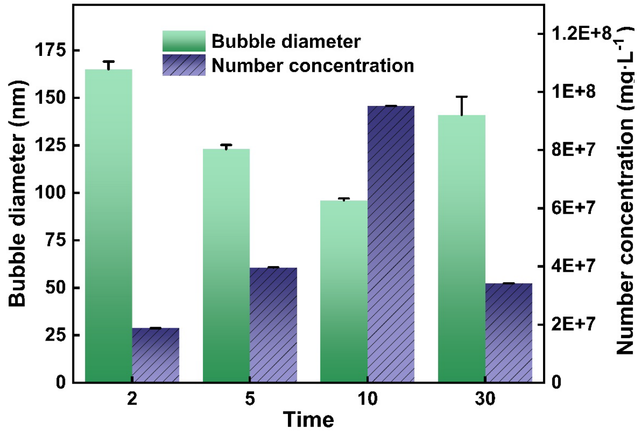
These field trials are built on proof-of-concept studies supported by CSIT grant and EPA P2 grants, which funded the initial assembly and pilot testing of an ozone nanobubble generator at our partner farm (Geogreen).

Ozone Nanobubble Technology

- Ozone nanobubbles rapidly increased dissolved ozone to 24.4 mg·L^{-1} within 10 min and maintained elevated levels for over 7 hours.
- Ozone nanobubbles exhibited higher OTE and KLa, proving superior mass transfer.







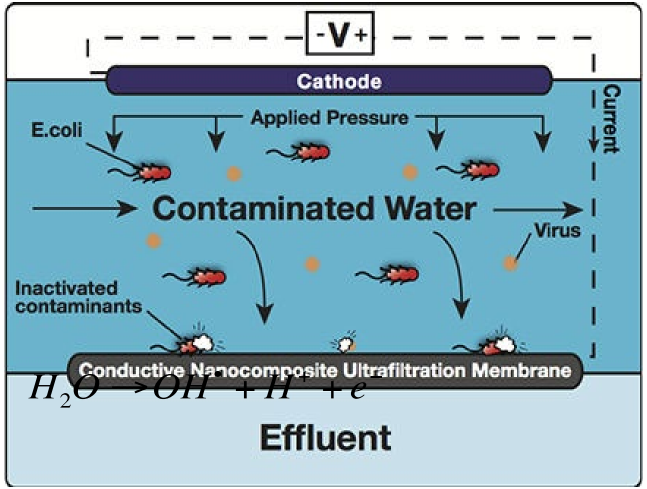
Electrochemical oxidation Technology

Benefits

1. Fully electrified and chemical free
2. Enhanced oxidation
3. Scalable and viable

Principles

- Anodic reactions with pollutants or water to produce radicals
- Forced convection to enhance mass transfer and reaction rate



$H_2O \rightarrow OH^{\cdot} + H^+ + e^-$

https://users.encs.concordia.ca/~rahaman/research.html

Environmental Science & Technology

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Microalgae Filtration Using an Electrochemically Reactive Ceramic Membrane: Filtration Performances, Fouling Kinetics, and Foulant Layer Characteristics

Likun Hua, Han Cao, Qingquan Ma, Xiaonan Shi, Xuezhi Zhang, and Wen Zhang*

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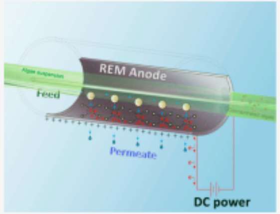
ABSTRACT: Electrochemical membrane filtration has proven to be successful for microbial removal and separation from water. In addition, membrane fouling could be mitigated by electrochemical reactions and electrostatic repulsion on a reactive membrane surface. This study assessed the filtration performances and fouling characteristics of electrochemically reactive ceramic membranes (a Magneli phase suboxide of TiO_2) when filtering algal suspension under different dc currents to achieve anodic or cathodic polarization. The critical flux results indicate that when applying positive or negative dc currents (e.g., 1.25–2.5 $mA \cdot cm^{-2}$) to the membrane, both significantly mitigated membrane fouling and thus maintained higher critical fluxes (up to $14.6 \times 10^{-5} \cdot m^3 \cdot m^{-2} \cdot s^{-1}$ or 526 LMH) compared to the critical flux without dc currents. Moreover, applying dc currents also enhanced membrane defouling processes and recovered high permeate flux better than hydraulic and chemical backwash methods. Moreover, fouling kinetics and the cake layer formation were further analyzed with a resistance-in-series model that revealed many important but underexamined parameters (e.g., cake layer resistance and cake layer thickness). The cake layer structures (e.g., compressibility) were shown to vary with the electrochemical activity, which provide new insight into the biofouling mechanisms. Finally, the algogenic odor, geosmin, was shown to be effectively removed by this reactive membrane under positive dc currents (2.5 $mA \cdot cm^{-2}$), which highlights the multifunctional capabilities of electrochemically reactive membrane filtration in biomass separation, fouling prevention, and pollutant degradation.



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Clarkson University Researchers Develop New Technology to Help Combat Harmful Algae Blooms

Clarkson University and SUNY ESF Step Up to the State's Challenge from Gov. Cuomo

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August 03, 2020 13:49 ET | **Source:** Clarkson University

photo-release

Potsdam, NY, Aug. 03, 2020 (GLOBE NEWSWIRE) -- Water quality issues have plagued some New York State lakes for decades, and recently, Governor Andrew M. Cuomo challenged Clarkson University and SUNY ESF to develop new technologies to try to reduce harmful algal blooms, or "HABs", in Lake Neatahwanta this summer. In 2019, Governor Cuomo challenged these premier research institutions to use their scientific expertise in water quality to develop new and innovative technologies to reduce the impact of HABs. SUNY ESF and Clarkson University will demonstrate the effectiveness of their experimental inventions this summer. The New York State Department of Environmental Conservation will host a virtual public information session about the deployment of the experimental projects on Wednesday, August 12, from 6 to 8 p.m.

"New York is home to some of the nation's best research institutions, so I challenged SUNY ESF and Clarkson University to develop new, nation-leading technologies to address the algal blooms that plague our waterways," Governor Cuomo said. "Protecting our state's precious water is a top priority, and this summer Lake Neatahwanta will serve as the testing ground for inventions that have the potential to be put to use across the state to reduce the threat of these harmful algal blooms."

Clarkson students and Professor Yang Yang

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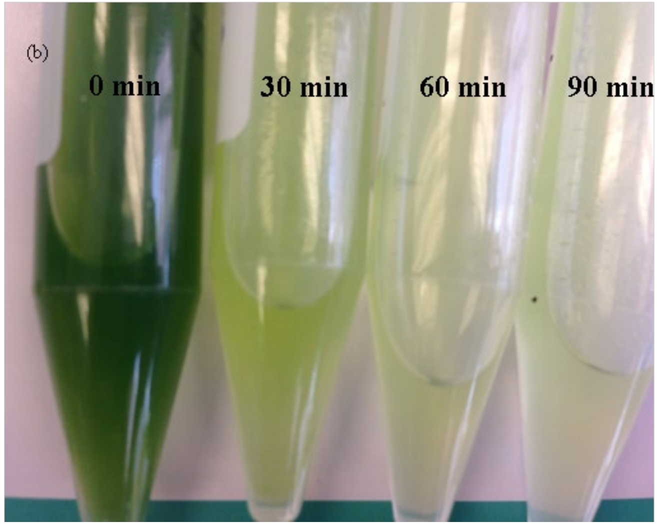
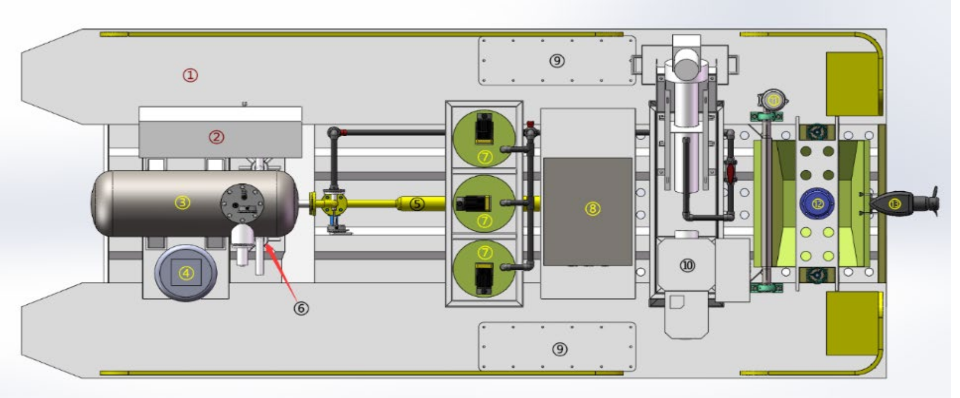
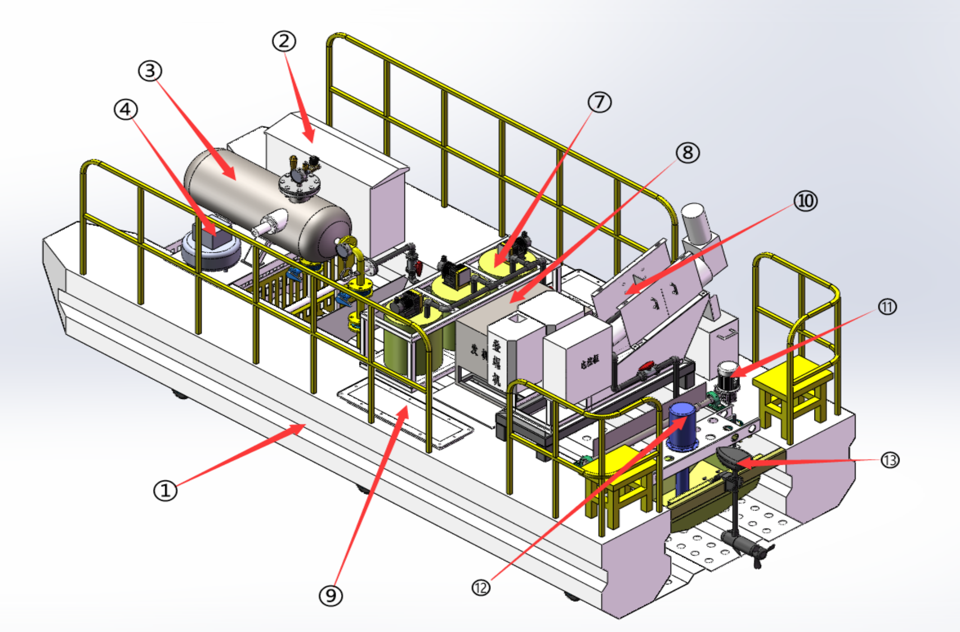


Take-home message

- Physically or mechanical remove biomass and remove the nutrient content/residuals
- Leave low chemical residuals or no harmful products (e.g., algicide, disinfection byproducts like bromated/chlorinated compounds)
- Depending on the treatment efficiency/capabilities/functionalities, many tailorable, scalable and modular equipment/instruments could be installed such as membrane filtration modules.





Acknowledgement

- **NJDEP Grants to Prevent, Mitigate and/or Control of Freshwater Harmful Algal Blooms (HABs) Contract WM #: WM20-040**:
- **NOAA Prevention, Control and Mitigation of HABs (PCMHAB)** award (NA22NOS4780172) to the University of Maryland Center for Environmental Studies (UMCES) through the US HAB Control Technologies Incubator (US HAB-CTI), a partnership between the National Oceanic and Atmospheric Administration (NOAA), UMCES and Mote Marine Laboratory
- Russell Rader (NJDEP/Water Resource Management), Heidi O'Neill (Division of Science and Research), David McPartland (319 Coordinator, Division of Water Monitoring & Standards), Deborah Kratzer (Division of Water Monitoring & Standards), and many other scientists/staff members
- **Branch Brook**: Maya Lordo, Dan Salvante, Kate Hartwyk, Gary Arlio, Tara Casella, Tomas Dougherty (Jersey Cares)
- **Deal Lake**: Donald Brockel (Chariman Deal Lake Commission), Stephen Souza (Princeton Hydro LLC)
- **MRRI Team**: Francisco Artigas, Sandy Speers, Cheryl Yao, Joe Grzy, Ildiko Pechmann, Brian Wlodawski
- **BRISEA Team**: Likun Hua (Director of Technology Concept Validation & Prototype Development), Dr. Xuezhi Zhang (CAS) and other staff members
- **NJIT**: Justin Samolewicz (Director of sponsored research office) and Deidra Slough (Assistant Director) and other supporting team members