# Cyber-Physical Sensing, Modeling, and Control for Large-Scale Wastewater Reuse and Algal Biofuel Production

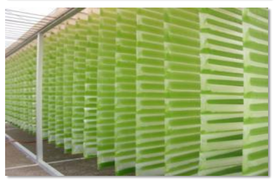
## Background

- **Wastewater Treatment**: Currently, many wastewater treatment plants are discharging treated wastewater containing significant amounts of nutrients, such as nitrogen, ammonium, and phosphate ions, directly into the water system, posing significant threats to the environment.
- **Biofuel Green Energy**: Bon-fossil green energy is very important for environment, energy security, and sustainable economic development.
- **Large-scale algal cultivation and production** has been recognized by the U.S. National Academy of Science and Department of Energy as one of the most promising and attractive solutions for simultaneous wastewater treatment and biofuel production.

## Why Large-Scale Algal Cultivation and Biofuel Production

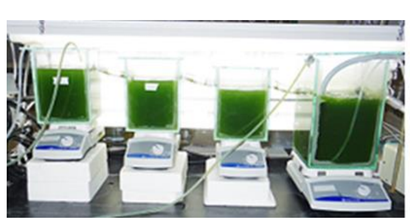
Compared to other green and renewable energy sources, algae biofuel has the following advantages:

- **Impressive productivity** - Microalgae can potentially produce 100 times more oil per acre than soybeans.
- **Non-competitive with Agriculture** - Algae can be cultivated with wastewater on non-arable land in a variety of climates.
- **Simultaneous treatment of wastewater** – It offers a highly efficient solution for wastewater treatment and polishing.
- **Mitigation of $CO_2$** - Algae uses solar energy to convert and fix carbon dioxide into biomass.



## Challenges and Opportunities

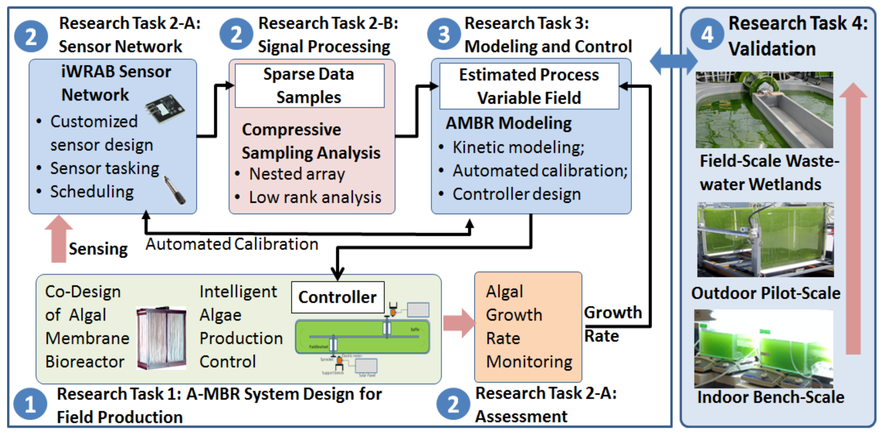
- **Scaling up the algae biomass growth** for economically and environmentally sustainable biofuel production needs still faces significant challenges. Increasing the algal biofuel productivity, lowering this cost, and minimizing the environmental impact have become an urgent task for research and development.
- Currently, algal cultivation relies on raceway ponds with low algae concentrations, resulting in low algae biomass productivities (< 20 g/m$^2$/day).
- Recently, our research team has successfully developed algae membrane bioreactor technologies to separate and concentrate algae biomass from water, and significantly improve the algae density by 5-10 times, resulting in doubled productivity **in a controlled indoor environment**.
- This new algal membrane bioreactor (A-MBR) cultivation method offers a very promising approach for algal biofuel production and wastewater reuse.



## Project Goals

- This project aims to develop an integrated set of cyber-physical sensing, modeling, and control methods and tools to support large-scale intelligent Wastewater Reuse and Algal Biomass (iWRAB) production.
- Our **project goal** is to increase the algal productivity from <20 g/m$^2$/day in current practice to >60 g/m$^2$/day using the proposed algal membrane bioreactor (A-MBR) and cyber-physical system (CPS) technologies, demonstrating a feasible pathway towards green energy production and water reuse.

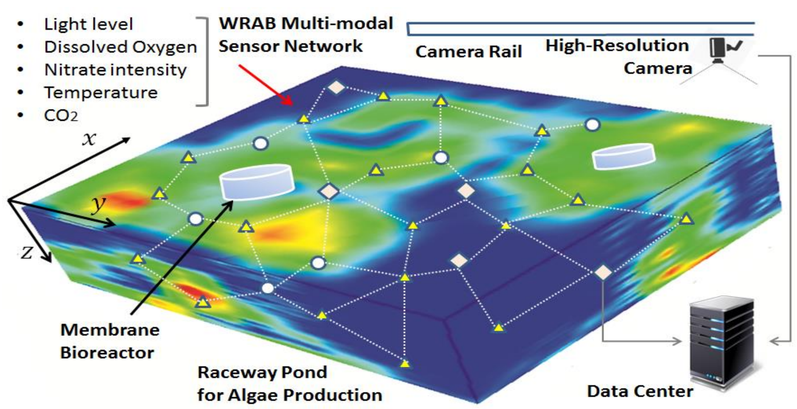
## Overview




### *Research Task 1: New design of algal membrane bioreactor for high-density field cultivation.*

To move the A-MBR technology to outdoor dynamic environments, we need to address a set of unique and challenging issues.

- Investigate special membrane materials for A-MBR operation using nano $TiO_2$ modified membranes with self-cleaning and photo-catalytic properties.
- Characterize the A-MBR process for optimal selection of short solids and hydraulic retention times (SRTs and HRTs) to improve algal biomass productivity.
- Explore a tank-in-series A-MBR design to create nutrient concentration gradients across the tanks for more efficient nutrient removal from wastewater.




### *Research Task 2: iWRAB sensor network design and Signal Processing*

- Design a network of multi-modal sensors for real-time in-situ monitoring of key environmental variables and assessment of the health conditions of algal cultures in the harsh and dynamic outdoor environments.
- Investigate compressive sampling and nested array methods for accurate reconstruction of the variable field with fine resolutions in space and time from a minimum number of active sensors.
- Driven by these signal processing results, we will develop advanced sensor network tasking, scheduling, and resource allocation methods to minimize the network resource consumption and system cost.

## Research Team

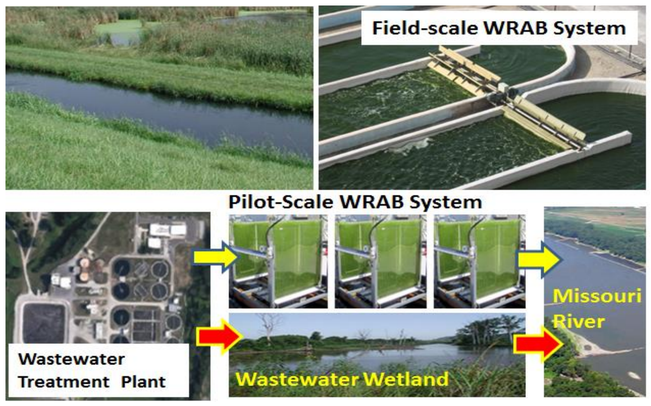

**University of Missouri (Lead)**
Zhihai HE (PI), ECE; Baolin DENG, ChE;Zhiqiang HU: CivilEng; Tony HAN, ECE
**University of Maryland:** Piya PAL: ECE


### *Research Task 3: Data-driven knowledge-assisted modeling and control of iWRAB.*

- Construct data-driven knowledge-based kinetic models for high-density algae cultivation using the A-MBR technology.
- To handle large spatiotemporal variations, driven by the compressive sampling analysis, we will develop layered and compartment models for algal cultivation in the field.
- Based on the large-scale datasets collected by the iWRAB sensor network, we will also explore advanced deep learning methods to learn and model complex the A-MBR process.
- We will design methods for automated model calibration by querying the sensor network and adaptive methods for iWRAB process control.

### *Research Task 4: Field Validation of the iWRAB System.*

- We will follow a tiered plan, namely, bench-scale, pilot scale, and field scale, to deploy and evaluate the proposed technologies and examine our performance goals.
- We expect that the proposed CPS sensing, modeling, and control technologies will further improve the algal productivity by another 50-70% to achieve >60 g/m$^2$/day.




## Broader Impact

- This project will demonstrate a new pathway toward green and sustainable algae cultivation and biofuel production using wastewater.
- The proposed CPS methods and technologies, if successfully developed, can also be extended to other application domains for intelligent production and manufacture.
- It will provide unique and exciting opportunities for mentoring graduate students with interdisciplinary training opportunities, involving K-12 students, women and minority students.
- With web-based access and control, we will convert the bench-scale and pilot scale algae cultivation systems into an exciting interactive online learning platform to educate undergraduate and high-school students about cyber-physical system design, process control, and renewable biofuel production