Environment and Natural Resources Trust Fund

2024 Request for Proposal

General Information

Proposal ID: 2024-190

Proposal Title: Sequester Waste CO2 Using Microalgae-Based Biohybrid Semi-Artificial System

Project Manager Information

Name: Roger Ruan

Organization: U of MN - College of Food, Agricultural and Natural Resource Sciences

Office Telephone: (612) 804-2270

Email: RUANX001@UMN.EDU

Project Basic Information

Project Summary: High efficiency CO2 biosequestration for valuable microalgal biomass production using a biohybrid semi-artificial system that combines photovoltaic and microbial fuel cells with optimized algal cathode

Funds Requested: $200,000

Proposed Project Completion: June 30, 2027

LCCMR Funding Category: Small Projects (H)

Secondary Category: Air Quality, Climate Change, and Renewable Energy (E)

Project Location

What is the best scale for describing where your work will take place?

Statewide

What is the best scale to describe the area impacted by your work?

Statewide

When will the work impact occur?

During the Project and In the Future

Narrative

Describe the opportunity or problem your proposal seeks to address. Include any relevant background information.

The emission of CO2 from large point sources (e.g., power plants and industrial facilities) has led to serious global warming and climate change, which is affecting Minnesota in evident ways, including rising temperatures, extreme weather events, and changes in local ecosystems. While photosynthesis, be it biological or artificial, is a widely-used method to sequester CO2, it faces challenging limitations such as low conversation efficiency of CO2 reduction (ca. 1~2 %) [1], expensive synthetic precious-metal-based photocatalysts, and low productivity/selectivity of CO2 fixation [2].
It is imperative for photosynthetic CO2 fixation to realize high efficiency of electron generation from solar energy and strong selectivity of reduction of CO2 to valuable products [3]. An integrated semi-artificial photosynthetic system that combines biological and artificial photosynthesis for solar energy conversion and CO2 capture with microalgae is a promising technology to address the issues and limitations. However, there are still challenges and obstacles to overcome before it can be successfully implemented in commercial CO2 fixation.

What is your proposed solution to the problem or opportunity discussed above? Introduce us to the work you are seeking funding to do. You will be asked to expand on this proposed solution in Activities & Milestones.

We propose to establish a biohybrid semi-artificial system that combines photovoltaic and photosynthetic microbial fuel cells with an optimized microalgal cathode.
The photovoltaic (PV) cells in this system, which have a much higher electron generation efficiency (up to 20 %) than natural photosynthesis, can capture sunlight and generate electrons efficiently for subsequent CO2 reduction. On the other hand, the microalgae-based microbial fuel cell (MFC) is a promising method for CO2 fixation, where microalgae-based electroactive biofilms at the cathode act as electron acceptors and use the generated electrons from photovoltaic cells to reduce CO2 and produce carbon-rich microalgal biomass.
Besides, operational parameters such as electrode materials, microalgal species, CO2 nanobubbles with high gas transfer efficiency, operating conditions and cycles favoring CO2 fixation will also be systematically investigated.

What are the specific project outcomes as they relate to the public purpose of protection, conservation, preservation, and enhancement of the state's natural resources?

This proposed research aims to integrate novel semi-artificial approaches to improve the efficiency of solar energy conversion and CO2 fixation by microalgae. The anticipated outcomes of this project have the potential to advance the scaled-up utilization of solar energy for CO2 fixation and contribute to the circularity of materials and solar energy in Minnesota, thereby reducing resource consumption and environmental pollution.
Moreover, the commercial application of this technology could lead to the establishment of several companies in Minnesota focused on microalgae-based carbon fixation and carbon-neutral production. This would create job opportunities for local residents and promote sustainable economic development.

Activities and Milestones

Activity 1: Establish the biohybrid semi-artificial system for simultaneous CO2 fixation and wastewater oxidation

Activity Budget: $60,000

Activity Description:
The biohybrid photosynthetic system is made up of two major subsystems: silicon-based PV cells and microbial fuel cells with microalgal cathode.

(1) Silicon-based PV cells are used to harvest outdoor sunlight and generate electrons. PV cells are connected in a closed-loop manner to MFCs via an appropriate power converter and batteries to control the voltage and level the electricity [3]. To achieve the maximum conversion efficiency, parameters such as solar panel area, energy conversion efficiency, suitable voltage and current density, and battery capacity should be considered and optimized according to the intended CO2 fixation rate.
(2) Microalgae-based MFC utilizes whole microalgae as biocatalysts for CO2 conversion at the cathode in conjunction with wastewater oxidation at the cell anode [5]. This device consists of electrodes, microalgae-based electroactive biofilms, ion exchange membrane, and other components like electrochemical reactors. A variety of factors may affect the performance of MFCs, including electrode materials, formation of microalgal biofilms attached to the cathode, extracellular electron transfer (EET) capability of microalgal biofilms, different types of proton exchange membranes, suitable composition of wastewater, etc. It is necessary to systematically optimize the aforementioned factors and parameters to develop the MFC system successfully for CO2 fixation.

Activity Milestones:

Description	Approximate Completion Date
A biohybrid semi-artificial system will be developed and operational	September 30, 2024
Key factors are identified and optimized for the high efficiency of photon-to-electron conversion	December 31, 2024
Crucial promoters for high performance of microalgae-based MFC system evaluated and optimized for CO2 fixation	March 31, 2025

Activity 2: Promote the formation of microalgal-based cathode biofilms for CO2 fixation

Activity Budget: $70,000

Activity Description:
The cathodic chamber is mainly made up of the cathode, electroactive biofilms, dissolved CO2, and redox mediators. The efficiency of CO2 fixation highly depends on the EET capability of electroactive microalgal biofilms. To enhance the processes, different strategies will be investigated:

(1) Different innovative nanomaterials (e.g., carbon paper with reduced graphene oxide – silver nanoparticle scaffolds) will be compared and used as the cathode to improve EET capability [6].
(2) Different microalgal species with superior capabilities of synthesizing redox cytochrome proteins and secreting extracellular polymeric substances (EPS) will be tested to improve extracellular electron transfer for CO2 conversion [7, 8].
(3) CO2 in nanobubble aqueous form is reported to improve the growth and photosynthetic efficiency of plants. Thus, the application of a nanobubble generation system will be explored to inject CO2 gas into the cathodic chamber and examine its effects on CO2 fixation efficiency.
(4) Magnetic fields can affect various biochemical processes, including photosynthesis, due to their interaction with

unpaired electrons and radicals. External magnetic fields with different intensities (0-300 mT) and exposure times (0-24 h) will also be investigated to explore their positive effects on CO2 fixation.

Activity Milestones:

Description	Approximate Completion Date
The effects of different innovative nanomaterials on the capability of extracellular electron transfer of microalgal	March 31, 2025
Different microalgal species will be compared and identified to be used for the formation of	June 30, 2025
Develop techniques to generate CO2 nanobubbles to enhance CO2 fixation efficiency	September 30, 2025
Effect of external magnetic fields effects on CO2 fixation will be evaluated	December 31, 2025

Activity 3: Optimize anode materials and other parameters at the anode component for wastewater oxidation

Activity Budget: $70,000

Activity Description:
Photo-bioelectrochemical CO2 conversion at the cathode is commonly paired with the oxygen-evolution reaction (OER) at the anode. However, considering the undesirable cross-over of O2 generated from OER, the half-cell reaction at the anode would be used for wastewater oxidation. There are several strategies that could be employed to improve the efficiency.

(1) Biochar as the anode: Compared with traditional expensive and harmful electrocatalysts, biochar electrodes have a stable structure, large surface area, low cost, and high energy output. Thus, the biochar electrodes produced from different raw materials will be compared and applied for wastewater oxidation.
(2) Wastewater as the anolyte: MFC can oxidize organic materials in wastewater for bioelectricity generation and simultaneously separate electrons from protons. Thus, different types of wastewater with specific physicochemical properties will be tested as anolytes in the anodic chamber to investigate their effects on COD removal efficiency.
(3) Optimization of operation conditions: Operation conditions in the anode chamber are essential for energy conversion efficiency. For example, CO2 reduction is generally performed under alkaline conditions, while neutral pH conditions are more favorable for water oxidation. Therefore, different operation parameters such as pH, temperature, and operating cycles will be optimized for wastewater treatment.

Activity Milestones:

Description	Approximate Completion Date
Low-cost biochar electrodes for COD removal from wastewater will be developed	September 30, 2026
Different wastewaters will be tested for their effects on COD removal efficiency	December 31, 2026
Operation parameters such as pH, temperature, and operating cycles will be optimized	March 31, 2027
Energy balances and preliminary economic and environmental impacts will be estimated with further R&D recommendation.	June 30, 2027

Project Partners and Collaborators

Name	Organization	Role	Receiving Funds
Paul Chen	University of Minnesota	Co-PI	No

Long-Term Implementation and Funding

Describe how the results will be implemented and how any ongoing effort will be funded. If not already addressed as part of the project, how will findings, results, and products developed be implemented after project completion? If additional work is needed, how will this work be funded?

This project will develop an efficient biohybrid system that can significantly improve microalgae-based CO2 fixation for commercial applications. The results will help guide the transition to a bio-based carbon-neutral economy, and attract more public funding for further research development and implementation. We believe that this research will create opportunities for the usage of this technology at full-scale installations for capturing CO2 from large point sources such as power plants and industrial facilities. We are hopeful that our research will help mitigate CO2 emissions in Minnesota and statewide, which will better reconcile environmental protection and socio-economic development in the state.

Other ENRTF Appropriations Awarded in the Last Six Years

Name	Appropriation	Amount Awarded
Methods to Destroy PFAS in Landfill Leachates	M.L. 2022, , Chp. 94, Art. , Sec. 2, Subd. 04a	$200,000

Project Manager and Organization Qualifications

Project Manager Name: Roger Ruan

Job Title: Professor and Director

Provide description of the project manager's qualifications to manage the proposed project.

Dr. Ruan, Professor and Director of Graduate Studies of Bioproducts and Biosystems Engineering Department, and Director of Center for Biorefining at University of Minnesota, is a Fellow of ASABE, IFT, Vebleo, and IAAM, and has received many other awards, including CAFS Professional Achievement and Scientist of IAAM, etc. He is a top cited author in engineering and technology with an h-index of 88, i10-index of 443, and has over 30,000 citations. Dr. Ruan's research include renewable energy and environment technologies for sustainable development. He has published over 500 referred journal articles, two books, 24 book chapters, and holds 20 US patents in the areas of municipal, agricultural, and industrial liquid and solid waste including biomass and waste plastics treatment and utilization through novel anaerobic digestion, microalgae and hydroponic cultivation, pyrolysis and gasification, airborne and other pathogen disinfection and pollutant control, catalysis, non-thermal plasma, and nitrogen fixation, etc. He has received over 200 grants totaling over $45 million in various funding for research, including major grants from USDA, DOE, DOT, DOD, LCCMR, and industries. He has served as guest editor or editorial board member of Bioresource Technology, Renewable Energy, Engineering, Applied Catalysis and Chemical Engineering, Journal of Food Process Engineering, The Open Plasma Physics Journal, and Associate Editor of Transactions of ASABE, Engineering Applications in Agriculture, and Transactions of CSAE, and Chairman of Editorial Board and Editor-in-Chief of International Journal of Agricultural and Biological Engineering, etc. He has supervised over 75 graduate students, 140 post-doctors, research fellows, and other engineers and scientists. He has given over 300 keynote lectures, invited symposium presentations, and short courses. His earlier LCCMR funded projects have resulted in several patented technologies which have been successfully licensed to the industry. He has the technical expertise and project management experience to ensure the execution of proposed projects.

Organization: U of MN - College of Food, Agricultural and Natural Resource Sciences

Organization Description:
The Center for Biorefining is a University of Minnesota research center affiliated with the College of Food, Agricultural and Natural Sciences and help coordinate the University efforts and resources to conduct exploratory fundamental and applied research and provide education on science and technology for environment protection and circular economy; stimulate collaboration among the University researchers, other public sector investigators, and private investigators involved in biobased production technology development; promote technology transfer to industries; and foster economic development in rural areas. The Center's research programs are founded by DOE, USDA, DOT, DOD, LCCMR, IREE, Xcel Energy, and other federal and state agencies, NGOs, and private companies. The Center is equipped with state of the arts analytical instruments, and processing facilities ranging from bench to pilot scale.

Budget Summary

Category / Name	Subcategory or Type	Description	Purpose	Gen. Ineligible	% Benefits	# FTE	Classified Staff?	$ Amount
Personnel								
Professor/faculty		Primary Investigator - project lead, advises researchers, plans and directs research, oversees budget, monitors and reports progress			36.8%	0.03		$8,274
Professor/faculty		Co-Primary Investigator - advises researchers, designs and directs experiments, conducts data analysis, writes reports and publications			36.8%	0.15		$22,318
1 Graduate Research Assistant		Researcher - carries out experiments, collects and analyzes data, prepares reports and manuscripts, education			46.5%	3		$162,681
							Sub Total	**$193,273**
Contracts and Services								
							Sub Total	**-**
Equipment, Tools, and Supplies								
	Tools and Supplies	Purchase of lab and miscellaneous supplies, including algae strains, culture media supplements, chemicals, consumable supplies for analytical instruments, photovoltaic (PV) cells, microalgae-based microbial fuel cell (MFC), and other parts and components for fabricating experimental apparatuses	For running experiments and operating systems, chemical, physical, and biological analyses					$6,117
							Sub Total	**$6,117**
Capital Expenditures								
							Sub Total	**-**
Acquisitions and Stewardship								
							Sub Total	**-**

Travel In Minnesota								
	Miles/ Meals/ Lodging	8 one-day 1-person trips, 40 miles each round trip ($0.655/mile), meals @$50/person	Visits to CO2 emission sites, collect samples, conduct experiments on site.					$610
							Sub Total	**$610**
Travel Outside Minnesota								
							Sub Total	**-**
Printing and Publication								
							Sub Total	**-**
Other Expenses								
							Sub Total	**-**
							Grand Total	**$200,000**

Classified Staff or Generally Ineligible Expenses

Category/Name	Subcategory or Type	Description	Justification Ineligible Expense or Classified Staff Request

Non ENRTF Funds

Category	Specific Source	Use	Status	Amount
State				
			State Sub Total	**-**
Non-State				
			Non State Sub Total	**-**
			Funds Total	**-**

Attachments

Required Attachments

Visual Component

File: 9b06fc4f-cf1.pdf

Alternate Text for Visual Component

The proposed semi-artificial photosynthetic system integrates biological and artificial photosynthesis for efficient solar energy transfer and CO2 fixation. Specifically, the biohybrid system includes silicon-based photovoltaic cells and photosynthetic microbial fuel cells with optimized microalgal cathode which are connected and optimized for high efficiency CO2 biosequestration and wastewater oxidation....

Optional Attachments

Support Letter, Photos, Media, Other

Title	File
2022 Audit	37a4114e-a64.pdf
Letter of Authorization	91eef248-df7.pdf

Administrative Use

Does your project include restoration or acquisition of land rights?

No

Does your project have potential for royalties, copyrights, patents, or sale of products and assets?

Yes

Do you understand and acknowledge IP and revenue-return and sharing requirements in 116P.10?

Yes

Do you wish to request reinvestment of any revenues into your project instead of returning revenue to the ENRTF?

No

Does your project include original, hypothesis-driven research?

Yes

Does the organization have a fiscal agent for this project?

No

Does your project include the design, construction, or renovation of a building, trail, campground, or other capital asset costing $10,000 or more?

No

Do you propose using an appropriation from the Environment and Natural Resources Trust Fund to conduct a project that provides children's services, as defined in Minnesota Statutes section 299C.61 Subd.7?

No