Environment and Natural Resources Trust Fund

2025 Request for Proposal

General Information

Proposal ID: 2025-203

Proposal Title: Sustainable Nonthermal Plasma Assisted Ammonia Production

Project Manager Information

Name: Roger Ruan

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

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Project Basic Information

Project Summary: This project aims to develop a novel non-thermal plasma technology to replace the Haber-Bosch process with renewable electricity and water electrolysis for greener production of ammonia.

ENRTF Funds Requested: $850,000

Proposed Project Completion: June 30, 2028

LCCMR Funding 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 substantial dependence on non-renewable, environmentally unfriendly nitrogen fertilizers, such as anhydrous ammonia and ammonia nitrate, poses a significant challenge for both US farming and industries. In Minnesota alone, annual imports of nitrogen fertilizer range from $400 million to $800 million, underscoring the economic strain and environmental impact of current practices. Current industrial technology for nitrogen fertilizer, the dominant Haber-Bosch process, provides over 130 million tons of ammonia annually, while supporting approximately 40% of the world's population. However, it is also responsible for about 2% of global energy consumption and 1.5% of greenhouse gas (GHG) emissions. The reaction conditions of the Haber-Bosch process lie in the range of 200 to 400 atm and 400 to 600 °C, respectively. These intense temperature and pressure conditions also reflect the high capital costs in addition to the environmental challenge. Therefore, these drawbacks present an opportunity for innovation and urgent need for a more energy-efficient, cost-effective, and low GHG emission process to mitigate environmental impact and foster agricultural sustainability.

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.

This research project aims to revolutionize nitrogen fixation by proposing a novel non-thermal reactor utilizing plasma technology, offering a sustainable one-step method for nitrogen compound synthesis, which possesses three essential properties: a) utilization of sustainable raw materials and energy sources; b) acceptable energy efficiency; c) minimal or zero CO2 emissions. The proposed novel non-thermal plasma (NTP) gas-liquid nitrogen fixation process that generated plasma in situ within the liquid body using concentrated high-intensity electric field (CHIEF) aims to increase ammonia production, partially replacing the energy intensive Harbor-Bosch process. The project's objectives encompass optimizing the CHIEF reactor, integrating efficient water electrolysis for hydrogen generation, incorporating nano- or micro-bubble technology, developing catalysts, and adopting ion exchange membranes for product concentration. The ultimate goal is to produce liquid ammonium hydroxide (aqueous ammonia) in an environmentally conscious, energy-efficient manner. Through these innovative steps, we aim to address the environmental concerns associated with current nitrogen fixation methods, providing a sustainable solution for ammonia production. The research will result in a comprehensive techno-economic analysis, ensuring the viability and scalability of the proposed technology, paving the way for a more sustainable and efficient future in nitrogen compound synthesis.

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?

The project aims to revolutionize ammonia production by developing a novel non-thermal plasma technology, particially replacing the Haber-Bosch process. Key outcomes include:

1) Zero carbon emissions in ammonia production, mitigating Haber-Bosch's environmental impact;
2) Electrifying ammonia production with renewable energy, (e.g. solar, wind, etc.) reducing dependence on fossil fuels;
3) Introducing a long-term electrosynthesis strategy, minimizing the need for Haber-Bosch;
4) Providing a cost-effective, scalable process for ammonia production;
5) Enabling small-scale on-site models for localized fertilizer and water treatment, reducing costs and emissions;
6) Facilitating large-scale industrial production for diverse applications, fostering a sustainable transition in ammonia technologies.

Activities and Milestones

Activity 1: Develop and optimize non-thermal plasma reactor to synthesize ammonia

Activity Budget: $350,000

Activity Description:
In this activity, we will first develop a bench-scale synthesis system that accommodate different types of NTP reactors and various metallic catalysts. Our lab has successfully developed CHIEF reactor, capable of simulating natural lightning processes to synthesize nitrogen oxides on a laboratory scale. Consequently, we will investigate and model the relationship between the externally applied voltage and minimum breakdown discharge voltage occurring in CHIEF, and a mathematical model will be established to illustrate the relationship between the externally applied voltage and the minimum breakdown discharge voltage. As a result, the configuration and working conditions of CHIEF can be optimized based on the modeling results in term of the aperture depth in CHIEF (plasma region volume), liquid conductivity, ion concentration, power frequency and waveform, and the magnitude of externally applied voltage. Furthermore, the CHIEF system allows simultaneous and in-suit H2 production during high voltage application. The generated H2 will compensate partially for the external H2 supply, which serves as the feedstock for subsequent ammonia synthesis, and H2 generated from water this way is considered green hydrogen. Apart from the ammonia synthesis, our integrated process is expected to reduce GHG emissions, and improve the energy efficiency accordingly.

Activity Milestones:

Description	Approximate Completion Date
A bench-scale synthesis system will be developed.	September 30, 2025
Investigate and model the relationship between the externally applied voltage and min break discharge voltage	December 31, 2025
Establish a mathematic model describing the working mechanism of CHIEF and optimize the reactor configuration	March 31, 2026
Investigate and comprehend the relationship between the ammonia synthesis and water electrolysis in CHIEF	June 30, 2026
Optimize the working conditions (electrical potential, electrode material, the concentration of electrolytes and the configuration	September 30, 2026

Activity 2: Develop effective and energy-efficient catalysts and utilize nano-bubble technology in the ammonia production system

Activity Budget: $300,000

Activity Description:
Catalysts are pivotal in plasma-based catalytic nitrogen fixation, facilitating N2/H2 dissociation and nitrogen reduction to NH3, thereby lowering activation energy and enhancing efficiency, thus reducing energy consumption. In this activity, we will test and screen various catalyst candidates, including metals (Fe, Ru, Ni, Co), oxides (TiO2, ZrO2), carbon-based catalysts. Initially, we will try to establish the relationship between the catalyst structure and nitrogen dissociation efficiency in the non-thermal plasma system, which will help to accelerate the catalyst development. Once the effective catalyst material has been identified, its longevity will be confirmed, and the mechanisms behind its deactivation will be thoroughly investigated. Furthermore, this proposal will incorporate the nano-bubble technology, an emerging technical innovation, into ammonia production. We will examine the effects of nano-bubbles (comprising a gas mixture of N2 and H2) water on ammonia production in CHIEF, encompassing 3 aspects: a) investigate the underlying mechanism of nano-bubble plasma discharge in the liquid phase; b) explore the relationship between externally applied voltage, air bubble size, and plasma discharge occurrence within the nano-bubbles. Use regression analysis to develop a model describing

this phenomenon; c) Determine the optimal bubble size and quantify the improvement in nitrogen fixation yield when utilizing nano-bubble water.

Activity Milestones:

Description	Approximate Completion Date
Investigate the underlying mechanism of nano-bubble plasma discharge in the liquid phase	December 31, 2026
Determine the optimal bubble size and quantify the improvement in nitrogen fixation yield	March 31, 2027
Several catalysts will be prepared and characterized and the performance of catalysts will be investigated	June 30, 2027
Catalytic mechanisms will be explored and important parameters will be optimized	September 30, 2027
Catalyst energy efficiency and the economic feasibility will be evaluated	December 31, 2027

Activity 3: Integrate solar power component into the system, evaluate the energy consumption and environmental impacts, and conduct techno-economic analysis

Activity Budget: $200,000

Activity Description:
Design a solar power system based on the systematic analysis of voltage, current, and power characteristics, which includes measuring the local solar radiation, optimizing the tilt of solar collectors, setting up the transformer and inverter, and establishing an energy storage system. Integrate the solar power components into the nitrogen fixation system, test the integrated system outdoors for a reasonable length of time. Furthermore, we will communicate our findings from Activity 1-3 to primary stakeholders such as fertilizer producers and ammonia manufacturers. Based on their feedback, we will design and construct a small pilot-scale integrated system for comprehensive evaluation of the technology. Rigorous tests will be conducted in the lab and then we will move the system to the relevant sites for testing and demonstration. The mass and energy balance data, together with emission data, will be used to evaluate the environmental and economic performance using a mathematical model. At this small pilot scale, the electrical energy needed to generate the non-thermal plasma, can be better evaluated, to confirm utility costs and economic analysis. This evaluation will also provide a good assessment of the environmental impact of the proposed technology. Further R&D efforts and commercialization strategies will be recommended.

Activity Milestones:

Description	Approximate Completion Date
Design and integrate a solar power system based on the analysis of voltage and characteristics	March 31, 2028
Test the integrated system outdoors for a reasonable length of time and demonstrate the functionality	March 31, 2028
The energy efficiency, cost, and emission of this new technology will be evaluated	June 30, 2028
Environmental impacts will be assessed	June 30, 2028
Further R&D and commercialization strategy will be recommended	June 30, 2028

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?

Upon project completion, the acquired scientific knowledge on feedstock breakdown and product synthesis during plasma-based catalytic nitrogen fixation will guide implementation. Techno-economic analysis will assess the technology's financial viability. The demonstration phase is vital for proving effectiveness and attracting public interest. Collaboration with industry partners, along with securing private, state, and federal funding, is crucial for further development and commercialization. This involves seeking research grants, venture capital investments, and government initiatives supporting sustainability. By fostering partnerships and securing diverse funding, the project's outcomes can transition into practical applications, ensuring long-term impact in nitrogen fixation.

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. Roger Ruan is a Fellow of the National Academy of Inventors, the American Society of Agricultural and Biological Engineers, the Institute of Food Technologists, the International Association of Advanced Materials, and Vebleo, and have received many other awards, including International Bioprocessing Association's Pandey Award, CAFS Professional Achievement, Scientist of IAAM, etc. Dr. Ruan's research areas include renewable energy and environment technologies for sustainable development and circular economy. His research has focused on biomass and solid wastes such as plastic wastes pyrolysis and gasification for chemicals, materials, fuels, and energy production; wastewater treatment and utilization through novel anaerobic digestion, microalgae cultivation; airborne and other pathogen disinfection and pollutant control; innovative catalytic non-thermal plasma, low temperature microwave and pulse microwave, photocatalytic intensive pulse light, and NMR/MRI technologies development and applications in nitrogen fixation, food safety assurance, and food quality improvement; and food engineering and various value-added processing. Dr. Ruan has published over 600 papers in refereed journals, two books, and 28 book chapters, and holds 19 US patents. He is also a top-cited author in engineering and technologies, with an h-index of 96, i10-index of 480, and over 37,000 citations. He has received over 200 projects totaling over $45 million in various funding for research, including major funding from USDA, DOE, DOT, DOD, LCCMR, and industries. He was the project manager of several earlier LCCMR funded projects which resulted in the issuance of US patents and licensing of technologies. He has the technical expertise and project management experience to ensure the execution of proposed project.

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 and help coordinate University efforts and resources to conduct exploratory fundamental and applied research; provide education on bioenergy, biochemicals and biomaterials; stimulate collaboration among the University researchers, other public sector investigators, and private investigators in biobased production technology development; promote technology transfer to industries; and foster economic development in rural areas. The Center's research programs have been 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.

The Department of Bioproducts and Biosystems Engineering, in CFANS, discovers and teaches solutions for the sustainable use of renewable resources and the enhancement of the environment. We discover innovative solutions to address challenges in the sustainable production and consumption of food, feed, fiber, materials, and chemicals by integrating engineering, science, technology, and management into all degree programs.

https://bbe.umn.edu/biobrief

Budget Summary

Category / Name	Subcategory or Type	Description	Purpose	Gen. Ineli gible	% Bene fits	# FTE	Class ified Staff?	$ Amount
Personnel								
Roger Ruan		Principal Investigator			37.1%	0.3		$83,916
Part time Researcher		Manage lab, conduct research and analysis			37.1%	1.5		$134,266
Graduate Research Assistant		Research Assistant			46%	3		$173,637
Post doctoral student		Conduct research and analysis and prepare manuscripts/reports			27.1%	3		$233,386
							Sub Total	**$625,205**
Contracts and Services								
							Sub Total	-
Equipment, Tools, and Supplies								
	Tools and Supplies	Purchase of lab and miscellaneous supplies, including feedstock, catalysts, chemicals, consumable supplies for analytical instruments, PPE including gloves and masks.	For running experiments and operating conversion systems					$24,795
	Equipment	Components for building demonstration system for ammonia production, including plasma reactor vessel, powder supplies with high voltage, control, motors, mixer, feeder, valves, etc.	To fabricate a small pilot system for extensive testing, cost and emission analysis, and demonsration of microwave assisted hydrodeoxygenation					$150,000
	Tools and Supplies	Up tp 2 units computer hardware	Data storage, run analytics, interface with manufactured equipment					$3,000
	Tools and Supplies	non-capital components of lab system	For testing and development of lab system					$43,000
							Sub Total	**$220,795**
Capital Expenditures								
							Sub Total	-

Acquisitions and Stewardship								
							Sub Total	**-**
Travel In Minnesota								
	Miles/ Meals/ Lodging	Mileage, per diem for trips for up to the whole team	Local outreach and community engagement					$4,000
							Sub Total	**$4,000**
Travel Outside Minnesota								
							Sub Total	**-**
Printing and Publication								
							Sub Total	**-**
Other Expenses								
							Sub Total	**-**
							Grand Total	**$850,000**

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	-

Total Project Cost: $850,000

This amount accurately reflects total project cost?

Yes

Attachments

Required Attachments

Visual Component

File: 1f2c30b8-9b2.pdf

Alternate Text for Visual Component

a) Schematic diagram of the plasma nitrogen fixation system using the concentrated high-intensity electric field.
b) Solar panel power system...

Supplemental Attachments

Capital Project Questionnaire, Budget Supplements, Support Letter, Photos, Media, Other

Title	File
Plasma nitrogen fixation system	e1f48f4e-c6b.pdf
SPA Cover Letter - Ammonia Production	34e7e526-35b.pdf

Administrative Use

Does your project include restoration or acquisition of land rights?

No

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

No

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

N/A

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

N/A

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 pre-design, design, construction, or renovation of a building, trail, campground, or other fixed capital asset costing $10,000 or more or large-scale stream or wetland restoration?

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 as "the provision of care, treatment, education, training, instruction, or recreation to children")?

No

Provide the name(s) and organization(s) of additional individuals assisting in the completion of this proposal:

Paul Chen, Juer Liu, Wendy Moylan, University of Minnesota