Environment and Natural Resources Trust Fund

2026 Request for Proposal

General Information

Proposal ID: 2026-477

Proposal Title: Catalytic Microwave-Assisted Pyrolysis of Waste Printed Circuit Boards

Project Manager Information

Name: Paul Chen

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

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Project Basic Information

Project Summary: This project explores catalytic microwave-assisted pyrolysis for efficient metal recovery and non-metallic fraction decomposition from waste printed circuit boards (WPCBs), while developing multi-functional catalysts for bromine recovery from WPCBs.

ENRTF Funds Requested: $300,000

Proposed Project Completion: June 30, 2028

LCCMR Funding Category: Small Projects (G)
Secondary Category: Resiliency (A)

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.

Waste printed circuit boards (WPCBs) are a significant part of electronic waste, fueled by increasing demand for consumer electronics. In Minnesota, an estimated $3 billion worth of precious metals are contained in the annual e-waste stream, including PCBs, but only 23.7% of electronic waste is currently recycled. WPCBs contain valuable metals such as copper, gold, silver, and palladium, serving an important secondary resource for metal recovery. However, conventional recycling methods, including mechanical separation and hydrometallurgical or pyrometallurgical processes, suffer from inefficiencies, high energy consumption, and environmental concerns, such as toxic emissions and hazardous waste generation. Additionally, the non-metallic fraction (NMF) of WPCBs, primarily composed of fiberglass and epoxy resin, presents a disposal challenge due to its complex structure, resistance to degradation. This fraction often contains brominated flame retardants (BFRs), and the uncontrolled release of bromine poses environmental and health risks, yet its recovery remains underexplored. Current processes either neglect the bromine content or result in its uncontrolled release, worsening pollution. This project aims to develop a resource-efficient, scalable approach to WPCB recycling that enhances the recovery of valuable metals while safely managing hazardous components, reducing reliance on virgin metal extraction, minimizing hazardous emissions, and strengthening Minnesota's waste management infrastructure.

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 project proposes an advanced approach to waste printed circuit board (WPCB) recycling through catalytic microwave-assisted pyrolysis (MAP), addressing critical challenges in metal recovery, non-metallic fraction (NMF) decomposition, and bromine capture. By leveraging MAP's selective and localized heating of the metallic fraction of WPCBs, the project will optimize pyrolysis conditions—temperature, time, and microwave power—to enhance energy efficiency while maximizing metal recovery and controlled NMF breakdown. A key innovation lies in the development of multi-functional catalysts, which not only improve pyrolysis efficiency but also selectively capture halogenated compounds such as HBr, mitigating environmental risks associated with brominated flame retardants. Additionally, the project will explore the role of microwave-induced plasma charge in accelerating organic decomposition and metal separation, potentially enhancing process efficiency. To ensure economic and environmental feasibility, a comprehensive techno-economic and life-cycle assessment will be conducted, evaluating energy consumption, product yields, and the commercial potential of recovered materials. This project supports Minnesota's environmental resilience by reducing hazardous e-waste disposal, enabling a circular economy, and mitigating the environmental risks of bromine emissions. By integrating waste valorization, resource conservation, and pollution prevention, this approach contributes to a more sustainable and resilient electronic waste management system.

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 project supports the protection and conservation of natural resources by advancing sustainable recycling methods for waste printed circuit boards (WPCBs). By developing catalytic microwave-assisted pyrolysis, the project will enable efficient metal recovery, reduce hazardous waste, and minimize reliance on environmentally harmful disposal methods like landfilling and incineration. The integration of multi-functional catalysts will enhance bromine capture, preventing toxic emissions and safeguarding air and water quality. Additionally, the project promotes resource conservation by recovering valuable metals and transforming the non-metallic fraction into useful byproducts, contributing to a circular economy and reducing the environmental footprint of electronic waste disposal.

Activities and Milestones

Activity 1: Microwave-Assisted Pyrolysis for Metal Recovery and NMF Decomposition

Activity Budget: $150,000

Activity Description:
This activity aims to optimize the conditions for microwave-assisted pyrolysis (MAP) to maximize metal recovery and non-metallic fraction (NMF) decomposition from waste printed circuit boards (WPCBs). The first phase involves collecting and characterizing WPCBs to determine their material composition, including metal content, resin matrix, and brominated flame retardants. Controlled MAP experiments will then be conducted to assess the effects of temperature, reaction time, and microwave power on pyrolysis efficiency. The recovered metals will be analyzed for purity and recovery rates using techniques such as inductively coupled plasma (ICP) spectroscopy, while the gaseous and liquid products will be characterized via gas chromatography-mass spectrometry (GC-MS). The impact of MAP on enhancing metal liberation, reducing hazardous emissions, and improving NMF breakdown will be evaluated. The results will be used to establish optimal operating conditions and guide the scale-up of the process.

Activity Milestones:

Description	Approximate Completion Date
Collection and characterization of WPCBs	September 30, 2026
Optimization of MAP conditions (temperature, time, power)	December 31, 2026
Metal recovery and purity assessment	June 30, 2027
Analysis of NMF decomposition and byproduct characterization	September 30, 2027

Activity 2: Development of Multi-Functional Catalysts for Halogen Capture and Enhancing NMF Degradation

Activity Budget: $100,000

Activity Description:
This activity focuses on developing and testing multi-functional catalysts that enhance non-metallic fraction (NMF) decomposition while selectively capturing halogenated compounds released during pyrolysis. The catalysts will be designed by integrating three key components: microwave-absorbent materials (e.g., SiC, Fe-based materials) to improve heating efficiency, cracking catalysts (e.g., ZSM-5, γ-Al_2O_3) to facilitate NMF breakdown and improve pyrolysis oil quality, and halogen absorbers (e.g., CaO, MgO, kaolin) to selectively capture hydrogen bromide (HBr) and mitigate toxic emissions. The synthesis process will involve blending and calcining these components to ensure optimal physicochemical properties. The materials will be characterized using scanning electron microscopy (SEM), X-ray diffraction (XRD), nitrogen adsorption-desorption (BET), and Fourier-transform infrared spectroscopy (FTIR) to analyze their structure, surface area, and chemical composition.
The synthesized catalysts will be tested in MAP experiments to evaluate their efficiency in improving pyrolysis product quality, enhancing metal recovery, and reducing bromine emissions. Performance will be assessed based on metal recovery rates, oil composition, and bromine capture efficiency. The best-performing materials will undergo further optimization for stability, recyclability, and long-term effectiveness. This work will provide a sustainable solution to minimize halogen-related environmental hazards in WPCB recycling.

Activity Milestones:

Description	Approximate Completion Date
Synthesis and characterization of multi-functional catalysts	March 31, 2027

Optimization of MAP conditions (temperature, time, power)	June 30, 2027
Optimization of catalyst performance (stability, regeneration, efficiency)	September 30, 2027

Activity 3: Techno-Economic and Environmental Analysis of CMAP for WPCB Recycling

Activity Budget: $50,000

Activity Description:

To evaluate the scalability and sustainability of the proposed MAP process, a comprehensive techno-economic and environmental analysis will be conducted. The economic assessment will estimate capital and operational costs, energy consumption, and potential revenue from recovered metals and byproducts. Sensitivity analysis will be performed to identify key cost drivers and determine financial feasibility. The environmental analysis will assess greenhouse gas emissions, energy efficiency, and pollution mitigation benefits compared to conventional WPCB recycling methods. Life-cycle assessment (LCA) methodologies will be used to quantify environmental impacts and identify opportunities for process improvement. The findings will inform industry stakeholders, policymakers, and investors on the viability of MAP technology for WPCB recycling.

Activity Milestones:

Description	Approximate Completion Date
Techno-economic feasibility analysis	December 31, 2027
Life-cycle environmental impact assessment	March 31, 2028
Final report and dissemination of results	June 30, 2028

Project Partners and Collaborators

Name	Organization	Role	Receiving Funds
Roger Ruan	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?

The project results will be implemented through collaborations with electronic waste recyclers, metal recovery firms, and environmental agencies to scale catalytic microwave-assisted pyrolysis (MAP). Findings will be disseminated via publications, conferences, and stakeholder workshops to drive adoption. Regulatory partnerships will ensure compliance with environmental standards. Additional funding will be sought from agencies like DOE and EPA, alongside private investments. The University of Minnesota's commercialization office will explore licensing and patents. These efforts will support long-term scalability, fostering a sustainable e-waste recycling model for Minnesota and beyond, reducing hazardous waste, conserving resources, and strengthening waste management infrastructure through public-private partnerships.

Project Manager and Organization Qualifications

Project Manager Name: Paul Chen

Job Title: Research Professor and Program Director

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

Dr. Paul L. Chen is a Research Professor and Program Director at the Center for Biorefining, Department of Bioproducts and Biosystems Engineering, University of Minnesota. With over 28 years of experience in biomass conversion, waste valorization, sustainable fuels, and advanced thermochemical processes, he has pioneered catalytic microwave-assisted pyrolysis, hydrodeoxygenation, and biorefining technologies. His extensive research portfolio includes 260+ peer-reviewed journal articles, 15 book chapters, and two books, amassing over 26,800 citations (h-index: 85, i10-index: 237). His expertise in microwave-assisted waste-to-fuel conversion, catalyst development, and resource-efficient recycling has driven key innovations in renewable energy. Holding 18 U.S. patents, Dr. Chen has developed novel technologies in microwave-assisted biofuel production, catalyst design, and pollutant control. His breakthroughs in hydrodeoxygenation have significantly reduced reliance on costly hydrogen and high-pressure conditions for fuel upgrading, making sustainable aviation fuel and waste-to-energy solutions more economically viable.

Dr. Chen has secured over $45 million in research funding from agencies such as USDA, DOE, DOD, and NSF, leading multi-institutional and industry-collaborative projects. His leadership has enabled the scaling of renewable energy and waste mitigation technologies, including the development of pilot-scale microwave-assisted systems for biofuel production and electronic waste recycling. His expertise in techno-economic analysis and life-cycle assessment ensures that projects are scientifically rigorous, financially viable, and environmentally sustainable.

Beyond academia, Dr. Chen actively collaborates with industry to commercialize waste-to-energy and sustainable fuel technologies. He has played a key role in technology transfer, licensing agreements, and industry partnerships, ensuring real-world applications of his research. His service as an editor, peer reviewer, and committee member in multiple scientific organizations further solidifies his influence in shaping the future of renewable energy and waste conversion research.

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 helps 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								
Lead PI - grant funds will raise FTE but still be less than 1		direct all research and personnel			36.6%	0.2		$28,562
Co-PI - summer salary only		oversee specific research component			36.6%	0.1		$29,778
Post Doc		conduct experiments and analysis			25.9%	2		$165,417
graduate student		assist post doc with experiments and analysis, education			83.6%	0.5		$29,473
							Sub Total	**$253,230**
Contracts and Services								
							Sub Total	**-**
Equipment, Tools, and Supplies								
	Equipment	components	for lab system testing and development of research					$22,770
	Tools and Supplies	lab and miscellaneous supplies, including catalysts, chemicals, consumable supplies for analytical instruments, gloves, masks	to accurately and safely conduct proposed research					$24,000
							Sub Total	**$46,770**
Capital Expenditures								
							Sub Total	**-**
Acquisitions and Stewardship								
							Sub Total	**-**

Travel In Minnesota								
							Sub Total	**-**
Travel Outside Minnesota								
							Sub Total	**-**
Printing and Publication								
							Sub Total	**-**
Other Expenses								
							Sub Total	**-**
							Grand Total	**$300,000**

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: $300,000

This amount accurately reflects total project cost?

Yes

Attachments

Required Attachments

Visual Component

File: 5dc8da84-3fa.pdf

Alternate Text for Visual Component

Illustration of the catalytic MAP process for WPCBs recycling. It includes WPCB collection and characterization, optimized pyrolysis conditions (temperature, time, power), and multi-functional catalysts for NMF decomposition and bromine capture. A feedback loop highlights improved metal recovery (copper, gold, etc), reduced toxic emissions, and enhanced environmental sustainability....

Supplemental Attachments

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

Title	File
Letter of Authorization to Submit	8064f210-79b.pdf
Audit	a1c247cd-ac0.pdf

Administrative Use

Does your project include restoration or acquisition of land rights?

No

Do you understand that travel expenses are only approved if they follow the "Commissioner's Plan" promulgated by the Commissioner of Management of Budget or, for University of Minnesota projects, the University of Minnesota plan?

N/A

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

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 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:

Wendy Moylan, Juer Liu, University of Minnesota

Do you understand that a named service contract does not constitute a funder-designated subrecipient or approval of a sole-source contract? In other words, a service contract entity is only approved if it has been selected according to the contracting rules identified in state law and policy for organizations that receive ENRTF funds through direct appropriations, or in the DNR's reimbursement manual for non-state organizations. These rules may include competitive bidding and prevailing wage requirements

N/A