MICROWAVE-ENHANCED PYROMETALLURGICAL PROCESSING FOR SUSTAINABLE E-SCRAP RECYCLING

Ansan Pokharel – Department of Mechanical, Materials & Aerospace Engineering, West Virginia University, Morgantown, WV, USA.
Terence Musho* – Department of Mechanical, Materials & Aerospace Engineering, West Virginia University, Morgantown, WV, USA; Elemental Genesis Technologies Inc., Morgantown, WV, USA. *Corresponding Author: tdmusho@mail.wvu.edu

Abstract:

Electronic scrap (e-scrap), particularly printed circuit boards (PCBs), represents a valuable resource for recovering transition metals and critical elements essential to modern technologies. However, conventional recycling methods typically involve high energy consumption, environmental degradation, and reliance on chemical-intensive processes. This study introduces a novel, scalable microwave-enhanced pyrometallurgical approach for recycling e-scrap. Leveraging microwave technology, the process selectively recovers high-value metals via rapid volumetric heating and optimized carbothermal reduction, eliminating traditional beneficiation steps such as plastic and carbon removal, while efficiently handling heterogeneous e-scrap mixtures.

The methodology targets transition metals including copper (Cu), cobalt (Co), aluminum (Al), tin (Sn), and zinc (Zn), with copper as the initial focus due to its high concentration in PCBs. Thermodynamic modeling using Ellingham and phase diagrams guided the determination of optimal process parameters, which were validated through bench-scale experiments. Results demonstrated the successful recovery of copper sponge material with 95% purity in a single processing stage, achieving substantial energy efficiency and cost savings.

This preliminary study highlights the potential of MW processing to significantly enhance e-scrap recycling by enabling high-purity metal recovery, reduced environmental impact, and scalability for industrial applications. Future work will focus on improving selectivity, broadening the range of recoverable materials, and scaling the technology to address wider recycling challenges, contributing to a sustainable circular economy.

Introduction and Motivation:

According to the latest report from the Global E-Waste Monitor, a record-breaking 65 million metric tons of electronic scrap (e-scrap) were generated worldwide in 2024 [1][2]. The United States is among the leading contributors, discarding between 300 million to 400 million electronic items annually, equivalent to approximately 7 million metric tons of e-scrap. Alarming statistics from the U.S. Environmental Protection Agency (EPA) reveal that while e-scrap accounts for only 2% of the trash in landfills, it represents a staggering 70% of the total toxic waste [1]. The environmental and human health implications of this toxic burden are significant, as hazardous components such as heavy metals and persistent organic pollutants can leach into ecosystems and accumulate in the food chain [3].

Despite its environmental risks, e-scrap presents vast economic and strategic potential as a secondary source for mining rare and valuable materials. When properly managed, e-scrap can become a sustainable resource for recovering critical materials and minerals, including rare earth elements (REEs). This aligns with the U.S. government's circular economy initiatives, which aim to reduce dependency on critical materials and bolster resource security [4]. The recovered materials can be reintegrated into the production of the same or different products, driving both resource efficiency and economic growth.

However, the current state of e-scrap management reveals a major gap. Globally, only 17% of e-scrap is formally documented as recycled, leading to the loss of an estimated $57 billion worth of raw materials annually [5]. This inefficiency underscores the untapped potential of e-scrap recycling to address two critical challenges: mitigating environmental damage and alleviating shortages of critical materials essential for clean energy technologies.

The reliance of the U.S. on international supply chains for critical minerals further exacerbates this issue. According to the Department of Energy (DOE), more than 80% of rare earth elements—comprising 17 strategically critical materials—are imported, a figure that was at 100% as recently as 2019. Additionally, over 50% of 43 identified critical minerals are sourced from foreign suppliers, with 15 of these having no domestic production capacity [6]. This heavy reliance on external supply chains is unsustainable and poses significant risks, including potential supply disruptions due to geopolitical and economic instability.

By investing in advanced e-scrap recycling technologies, the U.S. can significantly reduce its dependence on foreign suppliers, recover valuable resources domestically, and strengthen the resilience of its critical material supply chains. These initiatives are pivotal for transitioning to a clean energy economy, enhancing resource security, and minimizing the environmental impact of electronic waste. Among the promising innovations is the microwave-enhanced carbothermal reduction process, a cutting-edge technology that offers efficient, selective, and energy-saving methods for recovering critical materials and mitigating e-waste's ecological footprint.

The microwave-enhanced carbothermal reduction process utilized in this study parallels fundamental principles observed in traditional steelmaking practices, particularly those employed in blast furnace operations. Similar to the use of carbon in steel production as both a reducing agent and energy source, our method leverages carbon generated from the pyrolysis of organic materials inherent in electronic waste (plastics, adhesives) to facilitate metal oxide reduction. In conventional steelmaking, carbon acts as the reducing agent to convert iron oxide into molten iron. Analogously, our microwave-enhanced approach uses carbon to selectively reduce targeted metal oxides into metallic sponge materials at lower temperatures and shorter reaction times due to the direct volumetric heating and enhanced reaction kinetics provided by microwave energy. This approach offers substantial economic and environmental viability, enabling smaller, regionally distributed recycling operations compared to large-scale smelting plants, thereby fostering localized circular economies for electronic waste management.

Review of Related Work:

Microwave Heating and Carbothermal Reduction

Microwave heating (MWH) is a direct heating method that converts electromagnetic (EM) energy into thermal energy within materials. Microwaves, which operate in the 1 GHz to 1000 GHz frequency range, gained prominence after World War II with the development of radar technology [7]. They are generated using devices such as magnetrons and klystrons and are widely applied in fields ranging from communication to food processing [8].

MWH relies on the interaction between EM waves and materials, causing dielectric heating through polarization mechanisms. Materials respond differently based on their dielectric properties, categorized as opaque (reflecting microwaves), transparent (allowing passage), or absorbing (converting EM energy to heat) [9]. The primary heating mechanism in MWH involves dipole relaxation, where the oscillating electric field causes dipoles within the material to realign, generating heat due to energy dissipation [10]. Compared to conventional heating methods that rely on surface conduction, convection, or radiation, MWH provides volumetric heating, allowing deeper and more uniform heat penetration. This eliminates limitations such as low thermal conductivity and enables selective volumetric heating of specific compounds in mixtures. MWH is faster, more energy-efficient, and capable of achieving equivalent or superior results with lower power input, making it ideal for applications requiring rapid and controlled heating [8].

This volumetric heating capability enables selective heating of specific constituents within complex mixtures, significantly improving process control and efficiency. By precisely adjusting temperature and pressure conditions, selective absorption can be strategically exploited to sequentially stage the extractive metallurgy process. For example, specific metallic oxides within a heterogeneous e-scrap feedstock can be selectively targeted and reduced either partially to lower oxides or completely to metal sponges. Notably, the selective microwave absorption diminishes once the target reduction is thermodynamically complete, inherently resulting in a self-limiting reaction.

The reduction agent utilized in this research is carbon, facilitating a carbothermal reduction (CTR) process analogous to traditional steelmaking in a blast furnace. CTR is characterized by the reduction of

metallic oxides using carbon, an endothermic reaction typically requiring significant energy inputs. The general reaction can be expressed as $MaOb + bC \rightarrow bCO + aM$. Traditional CTR using conventional thermal heating (CTH) often involves high operating temperatures, lengthy reaction durations, and inefficient heat transfer, leading to excessive energy consumption and incomplete reductions due to temperature gradients and cold centers within the samples.

MWH, conversely, significantly enhances CTR by directly converting EM energy to thermal energy within the material volume, resulting in rapid and uniform heating. This not only reduces reaction temperatures and durations but also markedly improves energy efficiency. For example, zinc oxide reduction occurs effectively at 550°C with MWH, compared to 950°C under conventional thermal methods [11]. Prior research underscores the advantages of MWH in terms of enhanced reaction kinetics, densification, reduced grain sizes, and improved microstructural uniformity. Notably, Huang et al. [12] observed a substantial decrease in activation energy for iron oxide reduction when employing MWH. Additionally, He et al. [13] demonstrated that MWH significantly accelerated manganese ore reduction due to enhanced reaction surface area from hot cracking and facilitated gasification. Ahmed et al. [14] similarly achieved a successful selective reduction of low-grade manganese ore using MWH, obtaining products containing 97% pure iron and 84.45% pure manganese oxide.

The developed approach has been employed by our research group for the recovery of tantalum (Ta) and manganese (Mn) from tantalum capacitor (TC) e-scrap [15]. It was found that grinding the e-scrap eliminates the need for excessive flux additions beyond what is present from the ash content. This is a result of liberating the inherently phase-separated nature of the electronic scrap. This form of beneficiation is effective only when the grain size is reduced to the scale of the microstructural features.

Furthermore, the carbon derived from the pyrolysis of organic components (e.g., plastics, adhesives) serves as both a microwave sink and a reducing agent, thereby eliminating the additional beneficiation step of plastic removal. However, further research is needed to quantify the generation of potentially hazardous by-products, such as dioxins and furans, resulting from the pyrolysis of these organic materials. The carbon generated during pyrolysis significantly enhances microwave absorption and supports the selective carbothermal reduction of metal oxides. By leveraging MWH's efficiency, selectivity, and rapid heating capabilities, this approach optimizes resource recovery from complex material mixtures. Consequently, it fills an important gap left by conventional processes, which rarely facilitate the simultaneous and selective extraction of multiple metals from complex oxide mixtures.

Technology Approach:

Experimental Setup

An illustration of the microwave experimental setup is shown in Figure 1. The system utilizes a 3 kW, 2.45 GHz single-mode microwave (MW) generator (Sairem Microwave, Model GMP G4), a benchtop unit designed for small-batch processing of approximately 10-gram samples. This setup is intended for optimizing processing parameters. It is envisioned that a full-scale inline MW processing unit will feature an entirely different geometry to accommodate industrial e-scrap processing requirements.

The sample was placed in an alumina crucible positioned within the waveguide and supported by a fixed-height alumina tube for precise alignment. Both the crucible and tube were enclosed within a quartz tube to create a vacuum environment. The vacuum environment is necessary for controlling the partial pressure of oxygen. The quartz tube’s lower end was connected to a vacuum pump, while the upper end featured a KF-style vacuum fitting with a compression gasket to maintain the vacuum.

Temperature monitoring was conducted remotely using a 900 nm Williamson infrared (IR) pyrometer placed above the sample. The pyrometer measured temperature through an optical window transparent to the 900 nm wavelength, ensuring accurate readings while preserving the vacuum seal. Temperature control was managed through a custom LabVIEW program that integrated a PID controller. The preprogrammed heating profile included ramp rates, hold durations, and multiple temperature steps. Real-time temperature readings from the pyrometer were used to dynamically adjust microwave power via

a Modbus Ethernet interface. The PID controller, fine-tuned using LabVIEW's autotuning feature, ensured precise and stable temperature regulation.

The microwave system, illustrated in Figure 1, also incorporated a stub tuner and sliding short to optimize the standing wave. The stub tuner matched source and load impedance for efficient power transfer, while the sliding short adjusted the phase or peak electric field position within the waveguide. Changes to the sliding short affected the waveguide length, requiring coordinated adjustments to both components.

Optimization of the setup was conducted empirically by monitoring reflected power and further refined using COMSOL Multiphysics simulations. These simulations provided theoretical starting points for positioning the stubs and sliding short, as well as estimating peak heating rates and achievable temperatures. This integration of simulations and experimental tuning enhanced the system's efficiency and performance.

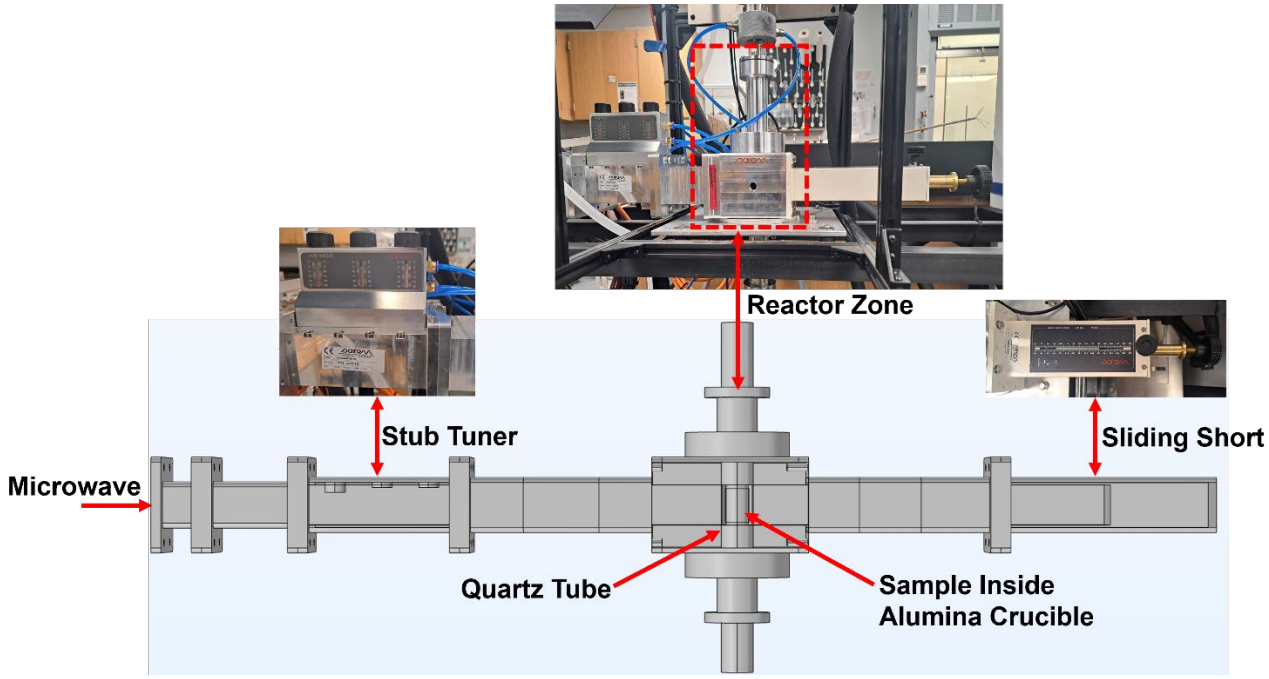

Figure 1: Benchtop 3 kW, 2.45 GHz single-mode microwave processing unit used for optimizing thermodynamic parameters (temperature, pressure, and fluxes) in bench-scale trials (~10-gram samples). A differently designed, full-scale microwave system will be developed for industrial-scale inline processing of electronic scrap.

Discussion:

Prior to conducting the microwave-assisted extraction experiments, it was crucial to determine the optimal temperature and pressure conditions for the processing steps. The number and nature of these steps depend on the composition of the elements targeted for extraction. Given the variability in feedstock composition, these calculations must be tailored to the specific material of interest to achieve the most effective recovery outcomes. In this study, a general approach was developed to facilitate the recovery of a wide range of materials, establishing that multiple processing steps are required depending on the elements involved.

To optimize the processing sequence, a thorough thermodynamic analysis was conducted using two key tools: the Ellingham diagram (ED) and the phase diagram (PD). These tools provided both

qualitative and quantitative insights into the system's thermodynamic behavior, enabling the design of an effective processing pathway for selective recovery.

The ED, based on the NIST-JANAF thermochemical tables, identified temperature ranges where reduction processes are thermodynamically favorable for various materials. Subsequently, the PD was used to determine the equilibrium phases that would form at these temperatures and the pressures required to stabilize the desired phases.

Phase diagram calculations were performed using the CALculation of PHAse Diagrams (CALPHAD) methodology, implemented in FactSage software. Thermodynamic data was sourced from the built-in databases for oxides (FToxide) and pure substances (FactPS), both derived from the NIST-JANAF Thermochemical Tables. This comprehensive approach enabled the precise determination of optimal processing conditions, ensuring effective extraction and recovery across diverse materials.

The Ellingham diagram (ED) and phase diagram (PD) were employed to optimize the experimental process for the pyrolyzed e-scrap shown in Figure 2B. Based on these thermodynamic analyses, the process was divided into a series of stages, each designed to progressively reduce higher oxides to lower oxides and, ultimately, to their pure metallic states. For example, in our previous study [16], this approach enabled the successful extraction of 97% pure tantalum (Ta) and the reduction of manganese oxides to lower oxides and carbides in three stages. At each stage, the phase and purity of the extracted materials were characterized using X-ray diffraction (XRD) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) (NexION 2000 ICP Mass Spectrometer, PerkinElmer).

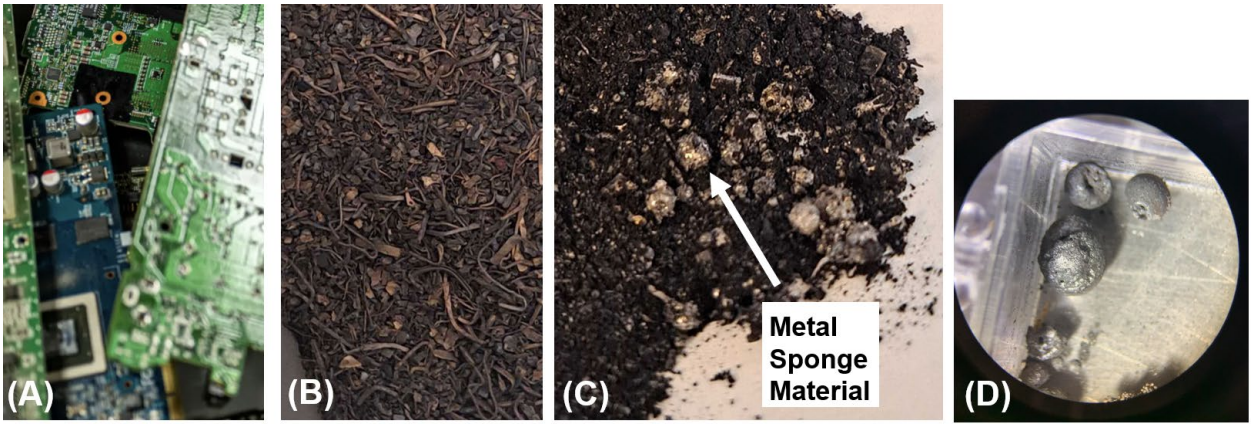

Figure 2: Stages of microwave-enhanced processing of printed circuit boards (PCBs): (A) Original PCB with attached components; (B) PCB after pyrolysis, converting organic materials to carbon; (C) Resulting metal sponge mixture following microwave-enhanced reduction; (D) Physically separated and classified metal sponge product (>95% copper purity).

Based on the analysis of pyrolyzed circuit boards shown in Figure 2B, we focused our material recovery efforts on transition metals, including cobalt (Co), copper (Cu), aluminum (Al), tin (Sn), and zinc (Zn), from discarded electronic circuit boards. The circuit boards were initially shredded and pyrolyzed, during which the polymers and organic components in the e-scrap were converted to amorphous carbon (Figure 2B). The purity of the pyrolyzed sample was analyzed using ICP-MS. The results revealed that the sample primarily consisted of 70% Cu, 14% Sn, 5% Al, and 5% Zn, with these elements being the most abundant. It should be clarified that no additional external flux was required or added for this particular study. Instead, the intrinsic ash content from the PCBs served as the natural flux during the reduction process. Using the Ellingham diagram (ED) and phase diagram (PD), the optimal reduction temperature and pressure for Cu recovery were determined to be 700°C and atmospheric pressure, respectively.

As this study represents the initial phase of the investigation, it focuses on a single processing stage, unlike our previous studies [16], which employed multiple stages. The single-stage process was

targeted at Cu recovery due to its significantly higher initial concentration compared to other metals. The microwave experiment was conducted under inert conditions to prevent oxidation at elevated temperatures.

Following the experiment, the metal sponge material (Figure 2C) was observed in the crucible along with residual carbon and unreduced materials. The metal sponge phases were physically separated, and subsequent ICP-MS analysis revealed that they consisted of 95% pure copper. This represents a significant increase in purity from the original feedstock, yielding a high-grade, ore-equivalent material suitable for further refining processes. The remaining metals in the crucible, including tin (Sn), aluminum (Al), and zinc (Zn), primarily remained in their oxidized states and did not undergo substantial reduction. These residual metal oxides remained as fine powders, easily separable from the metallic sponge by physical methods such as electrostatic or mechanical separation techniques.

Importantly, extending the microwave process beyond the 5-minute duration employed here can further enhance copper purity, as indicated by our earlier studies [16]. Additionally, the current study utilized only the carbon derived from the pyrolysis of circuit boards. Introducing pure carbon black, known for its superior microwave absorption capability, could further improve the efficiency of the carbothermal reduction process, leading to enhanced purity of the recovered metals and reduced overall processing times. Future investigations will systematically evaluate the effect of additional carbon sources on product purity and process efficiency.

To address the advantage of our microwave-enhanced pyrometallurgical process relative to conventional smelter operations, it is important to highlight the significantly lower energy demands and the economic viability of smaller-scale operations. Traditional smelting methods typically require large-scale infrastructure and substantial energy input due to prolonged reaction times and inefficient heat transfer. In contrast, our proposed method leverages volumetric microwave heating, resulting in rapid and uniform heating and substantially reduced energy consumption. Additionally, the targeted selective reduction simplifies downstream refining processes by significantly lowering contaminant levels, thus reducing operational complexity and associated refining costs. This approach supports regional implementation, offering economic viability for decentralized, smaller-scale recycling facilities. Consequently, our method facilitates both environmental sustainability and regional economic benefits by promoting localized e-scrap recycling operations.

Conclusion & Recommendations:

This study demonstrates the feasibility and advantages of using microwave-enhanced carbothermal reduction for sustainable recycling of electronic scrap, specifically targeting copper from printed circuit boards due to its abundance. Through optimized thermodynamic conditions guided by Ellingham and phase diagrams, the method successfully yielded copper sponge material with 95% purity in a single-stage experiment. The findings clearly highlight the precision, efficiency, and scalability advantages offered by microwave heating, including rapid volumetric heating, accelerated reaction kinetics, and selective metal recovery.

Previous work [15] by our research group further illustrates the versatility of microwave-assisted methods, successfully recovering tantalum and reducing manganese oxides from electronic capacitors with minimal energy inputs. These combined results strongly indicate that microwave-enhanced recycling can effectively handle diverse and complex electronic waste streams, achieving substantial purity and resource recovery benefits.

The current study marks a significant advancement toward commercially viable microwave-based recycling technologies. By eliminating traditional beneficiation steps such as plastic and carbon removal, this approach significantly reduces processing costs and energy consumption, thereby promoting decentralized, economically viable recycling facilities. Future research will focus on improving reaction selectivity, extending the method to other critical materials, and scaling the process toward industrial

implementation. Ultimately, this technology offers a promising pathway toward an environmentally sustainable, economically feasible, and scalable solution for global electronic waste recycling.

Acknowledgement:

A.P. and T.M. would like to acknowledge the funding supported by the Defense Advanced Research Projects Agency (DARPA) under Agreement No. HR00112290123. This research is approved for public release; distribution is unlimited.

References:

[1] Althaf, S., et al. (2024). The Global E-Waste Monitor 2024. UNITAR – United Nations Institute for Training and Research, pp. 120–135.

[2] Grandhi, S. P., Dagwar, P. P., & Dutta, D. (2024). Policy pathways to sustainable e-waste management: A global review. Journal of Hazardous Materials Advances, vol. 11, Article 100473.

[3] Rautela, R., et al. (2021). E-waste management and its effects on the environment and human health. Science of the Total Environment, 773, 145623.

[4] Vuppaladadiyam, S.S.V., et al. (2024). Can e-waste recycling provide a solution to the scarcity of rare earth metals? An overview of e-waste recycling methods. Science of the Total Environment, 924, 171453.

[5] Pan, X., Wong, C.W., & Li, C. (2022). Circular economy practices in the Waste Electrical and Electronic Equipment (WEEE) industry: A systematic review and future research agendas. Journal of Cleaner Production, 365, 132671.

[5] Tracy, B.S. (2020). An Overview of Rare Earth Elements and Related Issues for Congress, Vol. 16, Congressional Research Service.

[6] Ohring, M., & Kasprzak, L. (2014). Reliability and Failure of Electronic Materials and Devices. Academic Press.

[7] Klinger, H.H. (1953). Applications of microwaves in scientific research. Journal of the Franklin Institute, 256, 129–146.

[8] Tang, J., & Resurreccion Jr., F. (2009). Electromagnetic basis of microwave heating. In: Development of Packaging and Products for Use in Microwave Ovens, pp. 3–38.

[9] Shanmugasundram, H.P.P.V., Jayamani, E., & Soon, K.H. (2022). A comprehensive review on dielectric composites: Classification of dielectric composites. Renewable and Sustainable Energy Reviews, 157, 112075.

[10] Thostenson, E., & Chou, T.W. (1999). Microwave processing: fundamentals and applications. Composites Part A: Applied Science and Manufacturing, 30, 1055–1071.

[11] Omran, M., et al. (2020). Microwave catalyzed carbothermic reduction of zinc oxide and zinc ferrite: Effect of microwave energy on the reaction activation energy. RSC Advances, 10, 23959–23968.

[12] Huang, Z.C., Wu, K., Hu, B., Peng, H., & Jiang, T. (2012). Non-isothermal kinetics of reduction reaction of oxidized pellet under microwave irradiation. Journal of Iron and Steel Research International, 19, 1–4.

[13] He, Y., Liu, J., Liu, J.H., Chen, C.L., & Zhuang, C.L. (2021). Carbothermal reduction characteristics of oxidized Mn ore through conventional heating and microwave heating. International Journal of Minerals, Metallurgy and Materials, 28, 221–230.

[14] Ahmed, A. (2023). Optimization of carbothermal reduction of low-grade manganese ore utilizing microwave heating. Journal of Alloys and Metallurgical Systems, 3, 100019.

[15] Pokharel, A., Jayasekera, S.J., Sabolsky, E., & Musho, T. (2025). Microwave-assisted recycling of tantalum and manganese from end-of-life tantalum capacitors. Scientific Reports (Under review).

About the Authors:

Ansan Pokharel: Ansan is a Ph.D. candidate in the Department of Mechanical, Materials, and Aerospace Engineering at West Virginia University (WVU). His research focuses on the development of advanced Multiphysics finite element models, with a particular emphasis on microwave processing applications. (Presenter)

Dr. Terence Musho, PE: Dr. Musho is an Associate Professor in the Department of Mechanical, Materials, and Aerospace Engineering at WVU. His expertise lies in computational materials science, particularly in the area of materials processing. Dr. Musho teaches both undergraduate and graduate courses in finite element analysis and heat transfer.