

# Sustainable Silicon Recovery from Solar E-Waste: A Pathway to High-Purity Materials for Advanced Applications

P.P.Srinivasa Kumar, Ramachandra Kalubarme, R. Ratheesh<sup>†</sup>, Ajay Kaushal<sup>‡</sup>

Centre of Excellence on E-waste Management, Centre for Materials for Electronics  
Technology, Hyderabad-500051, India

## Abstract

The escalating accumulation of end-of-life solar panels presents a significant environmental challenge and an untapped resource of 4N pure silicon (99.99%). Effective recovery of this valuable material necessitates a comprehensive understanding of the heterogeneous waste composition at an atomic scale. This study details a robust methodology leveraging advanced spectroscopic and microscopic techniques to guide the recycling process of crystalline silicon (c-Si) solar panels. We employed Raman spectroscopy to profile impurities (Si, Al, Ag, B, P) across various c-Si waste phases, while Field Emission Scanning Electron Microscopy (FESEM) provided insights into morphological changes and contamination distributions post-delamination. X-ray Diffraction (XRD) identified crystalline impurities, and Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) quantified bulk metal content. Guided by these detailed characterizations, we optimized a multi-stage recovery process involving thermal pyrolysis, mechanical grinding, and selective leaching for efficient silicon liberation. The subsequent eutectic NaOH–KOH molten salt etching yielded 4N-grade silicon with minimal residual impurities, rigorously validated by ICP-OES (<10 ppm metals), XRD (confirming a pure cubic Si phase), FESEM (revealing clean surfaces), and Raman spectroscopy. This targeted characterization and recovery suite not only transforms solar e-waste into high-purity silicon wealth, contributing to sustainable supply chains, but also lays the groundwork for integrating advanced materials, such as graphene, in future recycling and sensing technologies. The insights gained are crucial for developing next-generation strategies for resource recovery and circular economy initiatives.

**Keyword:** *End-of-Life Silicon Solar Modules, 4N Pure Silicon, Sustainability, FESEM, Circular Economy*

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<sup>†</sup> Corresponding author 1: ratheesh@cmet.gov.in

<sup>‡</sup> Corresponding author 2: ajay.kaushal@cmet.gov.in