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From Smelting to Recycling: Isotopic Insights into Lead Exposure Pathways in Slovenian Children

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Stable lead (Pb) isotopes provide a powerful tracer for resolving geochemical sources and tracking contaminant transfer across environmental and biological systems. The Meža Valley (northern Slovenia) represents a long-term anthropogenically impacted system shaped by historical Pb mining and smelting, extensive waste deposits, and ongoing battery production and recycling activities. Despite substantial reductions in blood Pb concentrations since the 1970s, measurable exposure persists among children living in the upper valley communities.

To investigate source-to-organism transfer of Pb, we established a comprehensive isotopic database ($^{206}Pb/^{207}Pb$, $^{208}Pb/^{206}Pb$) for key environmental compartments, including PM10, soils, and legacy mining materials, and compared these signatures with isotopic compositions measured in blood of school-age children who were part of national human biomonitoring program and were sampled in 2019. By integrating high-precision Pb isotope ratio measurements with end-member mixing models, we quantified the relative contributions of geogenic, legacy metallurgical, and contemporary industrial sources to airborne particulates and biological uptake.

PM10 isotope signatures indicate temporally variable but dominant anthropogenic contributions (53.4–68.5%), particularly in proximity to active battery production facilities. Distinct isotopic fields allow separation of historical ore-derived Pb from present-day industrial emissions. Importantly, Pb isotope ratios in children's blood, to some extent, overlap with those of PM10, demonstrating a direct geochemical link between atmospheric particulates and biological incorporation. The isotopic coherence between environmental and human samples confirms inhalation of contaminated air as an important exposure pathway, alongside soil and dust ingestion.

This study highlights the utility of stable Pb isotope systematics for coupling geochemical processes with human biomonitoring data.