Permanente's Red Mud Co-Processing Innovations for the Valuable Extraction of Critical Minerals and Rare-Earth Elements

Patent-Pending PIPE™ Reactor Co-Processing of Cellulosic Biomass with Bauxite-Process Red Mud

Permanente Corporation ("Permanente"), the Houston-based developer of the patented PIPE™ reactor platform,[1] has patents pending covering a uniquely important application of its technologies: the simultaneous, industrial-scale co-processing of waste cellulosic biomass with the highly alkaline bauxite residue known as red mud. Inside the PIPE™ reactor, biomass and red mud are processed together at high volume in a continuous manner — a combination that obsoletes every prior approach to red mud remediation and unlocks, for the first time at industrial scale, the cost-effective extraction of the rare-earth elements, including scandium, neodymium and yttrium, and the critical minerals gallium and titanium dioxide — alongside magnetite — that red mud has always contained but has stubbornly failed to yield.

The Red Mud Problem

Red mud is the waste residue of bauxite processing into alumina by the Bayer process — the industrial pathway through which virtually all of the world's aluminum is produced. For every ton of alumina refined from bauxite, approximately 1.25 tons of red mud are generated.[2] Red mud's hazard profile comes from its extreme alkalinity (pH 11.5–13+) and the heavy metals and chemicals it contains; mismanaged red mud has caused fatal industrial accidents and long-term environmental damage. Over decades, an estimated 5.2 billion tons of red mud have accumulated globally, growing by up to 190 million tons each year — the vast majority sitting in containment ponds and impoundments, with only a small fraction reclaimed or valorized.[3]

Buried inside this global waste stream is a strategic opportunity. Red mud typically contains up to 60% iron oxide by weight — principally hematite — alongside rare-earth elements, including scandium, neodymium and yttrium, and the critical minerals gallium and titanium dioxide.[4] With rare-earth elements now designated as critical minerals in the United States and prioritized

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[1] The PIPE™ reactor platform and related processing methods are protected under the Permanente Corporation patent portfolio, which includes U.S. Patent Nos. 9,758,738 B2, 10,961,459, 11,345,860, 11,674,086, and 12,595,340 B1, together with foreign and pending counterparts. See, e.g., U.S. Patent No. 9,758,738 B2 (*Green Renewable Liquid Fuel*). The co-processing methodology described herein is the subject of additional patents pending.

[2] On average, approximately 1 to 1.5 tonnes of red mud are produced per tonne of alumina refined, with a global average of approximately 1.23. See Red mud (Wikipedia summary of industry sources), and the peer-reviewed bibliometric review at Mapping the research landscape of bauxite by-products (red mud), PMC (2024).

[3] Z. Li, Toward Low-Carbon Construction: A Review of Red Mud Utilization in Cementitious Materials and Geopolymers for Sustainability and Cost Benefits, Buildings 16(2):362 (2026), reports that the global red mud stockpile exceeded 5 billion tons by the end of 2024 and grows by roughly 200 million tons per year; AL Circle Research estimates approximately 189.5 million tonnes generated in 2025 (A Comprehensive Analysis of Bauxite Residue – Red Mud), bringing the global inventory to an estimated 5.2 billion tons. Earlier sources cite approximately four billion tonnes; see Springer et al., *Green steel from red mud through climate-neutral hydrogen plasma reduction*, Nature (2024), available at https://www.nature.com/articles/s41586-023-06901-z, and Rio Tinto, Rehabilitating Red Mud, both citing approximately four billion tonnes of bauxite residue in global storage.

[4] Iron oxide (Fe_2O_3) content in red mud typically ranges from 30% to 60% by weight, depending on the source bauxite (International Aluminium Institute, via redmud.org). See Efficient utilization of red mud waste via stepwise leaching, Scientific Reports (2023), and Horizon Magazine (European Commission), The riches in Europe's mountains of metals waste.

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under national-security and critical-supply-chain policy, attention has turned decisively to red mud as a potential domestic source.[5] Yet despite decades of research and multi-year, multi-million-dollar European and U.S. programs, red mud's valuable mineral content has remained too costly to extract at scale — until now.

The Permanente Solution — How It Works

Permanente's newly patented PIPE™ reactor technologies for cellulosic biomass carbonization, combined with the proprietary co-processing methodology now patent-pending, have produced the first practical, cost-effective solution to the longstanding red mud problem — and a new rare-earth-element revenue opportunity that did not exist before.

Inside the closed-loop, oxygen-free torrefaction and pyrolysis environment of the PIPE™ reactor, carbonizing biomass is initially acidic. When biomass and red mud are introduced together, that acidity offsets red mud's extreme alkalinity, and both extremes are neutralized in the course of the process itself. Simultaneously, under engineered time and temperature exposure in the pyrolysis stage, carbon monoxide and hydrogen released by the carbonizing biomass draw oxygen from the hematite in the red mud, converting it to magnetite.[6] Magnetite, unlike hematite, can be quickly and cost-effectively removed from the red mud matrix by magnetic separation — creating an immediate revenue stream and, crucially, leaving behind a dramatically cleaner substrate from which rare-earth elements, including scandium, neodymium and yttrium, and the critical minerals gallium and titanium dioxide can be extracted by conventional means.

The result is a mutually beneficial process: careful management of time and temperature works in favor of both co-processed streams simultaneously, improving the quality of the carbonized cellulosic biomass products, neutralizing the red mud, and making its valuable mineral content faster and cheaper to extract. Alternative methods of creating magnetite from hematite in red mud are costly, chemically hazardous, dependent on a separate reductant and furnace, and largely ineffective at commercial scale. Permanente's approach obsoletes them.

The Double Revenue Stream

The new means of waste management for both co-processed feedstocks produces a double revenue stream that extends well beyond the conversion of low-value waste cellulosic biomass into valuable green-energy fuels and sustainable decarbonization activity. Rare-earth elements, including scandium, neodymium and yttrium, and the critical minerals gallium and titanium

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[5] Red mud is a recognized secondary source of rare-earth elements, including scandium and yttrium, as well as titanium dioxide and residual alumina. The European Union has funded multi-year programs (ETN, RemovAL, and ReActiv) specifically targeting REE recovery from bauxite residue. See Scientific Reports (2023) and Horizon Magazine (European Commission). In the United States, rare-earth elements are designated as critical minerals under Executive Order and Department of the Interior determinations; see U.S. Geological Survey, 2022 List of Critical Minerals.

[6] Competing processes for producing magnetite from red mud typically require high-temperature pyrometallurgical treatment (above 600°C) or pure-grade precursor materials, resulting in high operational and capital costs. See the NSF Industry-University Cooperative Research Center achievement summary, An Economically Viable Process to Recover High-Value Products from Red Mud. Permanente's co-processing approach in the PIPE™ reactor leverages the acidity of carbonizing cellulosic biomass to offset red mud alkalinity and to reduce hematite with the carbon monoxide and hydrogen released by the carbonizing biomass — enabling magnetite formation at materially lower cost than conventional thermal or chemical routes.

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dioxide — alongside magnetite — become, for the first time, extractable and commercially beneficial at industrial scale.

On the biomass side, the economic uplift from waste cellulosic feedstock to finished green-energy product is projected at more than 10X processing cost. On the red mud side, the transformation is more dramatic still: what has historically been a perpetual, uncapped waste-management expense for alumina refiners becomes instead a vital and valuable perpetual revenue stream projected at not less than 10X, and as much as 20X, the ongoing waste-management cost.[7] For the aluminum industry, red mud converts from liability to asset. For the United States and its allies, a strategic stockpile of critical minerals — long considered economically inaccessible — becomes economically accessible at last.

[7]Value-multiple projections (approximately 10X on biomass feedstock cost and 10X to 20X on ongoing red mud waste-management cost) are drawn from Permanente Corporation internal economic analysis and process modeling. Directional support for the economics of red mud valorization is also provided by the NSF/CR3 study referenced above, which reports operational costs approximately 46% lower and capital costs approximately 52% lower than competing magnetite-recovery processes, with additional upside from the recovery of scandium, yttrium, aluminum, and titanium. See NSF IUCRC red mud achievement summary.

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