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HARNESSING HYPERACCUMULATOR PLANTS FOR SUSTAINABLE CRITICAL MINERAL RECOVERY

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ABSTRACT

India's growing demand for critical minerals to support renewable energy, electric mobility, and advanced technologies has intensified concerns over import dependence. Phytomining, which uses hyperaccumulator plants to recover valuable metals from low-grade ores, mine wastes, and industrial residues, offers a sustainable alternative. Advances in plant biotechnology and metal recovery have expanded its potential beyond environmental remediation. In India, phytomining can complement conventional mining, restore degraded lands, enhance carbon sequestration, support rural livelihoods, and strengthen critical mineral security, contributing to a circular economy and the vision of Viksit Bharat 2047.

KEYWORDS: Circular economy, critical mineral recovery, ecological restoration, hyperaccumulator plants, phytomining

INTRODUCTION

As India advances its ambitions to become a global leader in electric mobility, renewable energy, advanced manufacturing, semiconductor production, and strategic defence technologies, ensuring a secure and sustainable supply of critical minerals has emerged as a strategic national priority. Minerals such as lithium, nickel, cobalt, vanadium, graphite, scandium, and rare earth elements are indispensable for the production of batteries, solar photovoltaic systems, wind turbines, electronic devices, and advanced defence technologies (Kumar and Bhattacharyya, 2025). However, India's continued reliance on imports for many of these resources exposes the country to supply-chain vulnerabilities, market uncertainties, and geopolitical risks, highlighting the need to diversify and strengthen domestic sources of critical minerals (Government of India, 2025; Kumar and Bhattacharyya, 2025).

In response to these challenges, researchers are increasingly exploring innovative and environmentally sustainable approaches to mineral resource recovery. Among the most promising is phytomining, a nature-based mining strategy that utilizes hyperaccumulator plants to extract and concentrate valuable metals from soils, mine wastes, and other mineral-rich substrates (Rylott and van der Ent, 2025; He et al., 2026). This emerging technology has attracted growing international interest owing to its potential to simultaneously recover critical minerals and restore degraded landscapes. Scientists suggest that India's extensive areas of mine spoils, degraded lands, industrial wastes, fly ash deposits, red mud repositories, and low-grade mineralized resources could serve as untapped reservoirs of critical minerals, accessible through biological harvesting and recovery systems (Akinbile and Mbohwa, 2025).

MINING METALS THROUGH AGRICULTURE

Unlike conventional mining, which depends on energy-intensive processes such as blasting, excavation, crushing, and chemical extraction, phytomining ((Fig 1) harnesses the natural ability of certain plants, known as hyperaccumulators, to absorb and concentrate metals from soils and mineral-rich substrates (He et al., 2026). These extraordinary plants take up unusually high concentrations of metals through their root systems and store them in their shoots, leaves, and stems (Rylott and van der Ent, 2025). Following harvest, the metal-rich biomass can be processed using metallurgical techniques to recover the accumulated metals (Pereira, 2026). To date, more than 750 hyperaccumulator species have been identified worldwide, demonstrating the remarkable diversity of plants capable of concentrating metals at exceptional levels. Studies have successfully recovered nickel, cobalt, thallium, selenium, gold, and rare earth elements from contaminated soils, mine wastes, and low-grade mineral deposits using these species (Rylott and van der Ent, 2025; Akinbile and Mbohwa, 2025). Notably, commercial-scale nickel phytomining has already been established in several regions, providing compelling evidence that plants can serve as effective biological mining tools (Rylott and van der Ent, 2025). More recently, researchers have reported that certain grasses and ferns can accumulate rare earth elements at economically significant concentrations, creating new opportunities for the sustainable recovery of strategic minerals essential for clean-energy and advanced technology applications (Richardson et al., 2025).

A STRATEGIC OPPORTUNITY FOR INDIA

India's heavy reliance on imports of lithium, cobalt, nickel, and several rare earth elements has emerged as a significant strategic and policy concern (Government of India, 2025). In response, the Government of India launched the National Critical Mineral Mission (NCMM), with an allocation of ₹16,300 crore to strengthen domestic capabilities in mineral exploration, mining, processing, recycling, and resource recovery (Government of India, 2025). The mission seeks to build resilient supply chains and enhance the country's long-term critical mineral security. Within this framework, phytomining is increasingly being recognized as a promising complementary approach to conventional mining (He et al., 2026). India possesses extensive areas of abandoned mines, coal overburden dumps, chromite mine wastes, graphite-bearing formations, and industrial waste repositories that remain largely underutilized. Although these sites often contain metal concentrations too low for economically viable conventional extraction, they may offer significant opportunities for recovery through phytomining (Akinbile and Mbohwa, 2025).

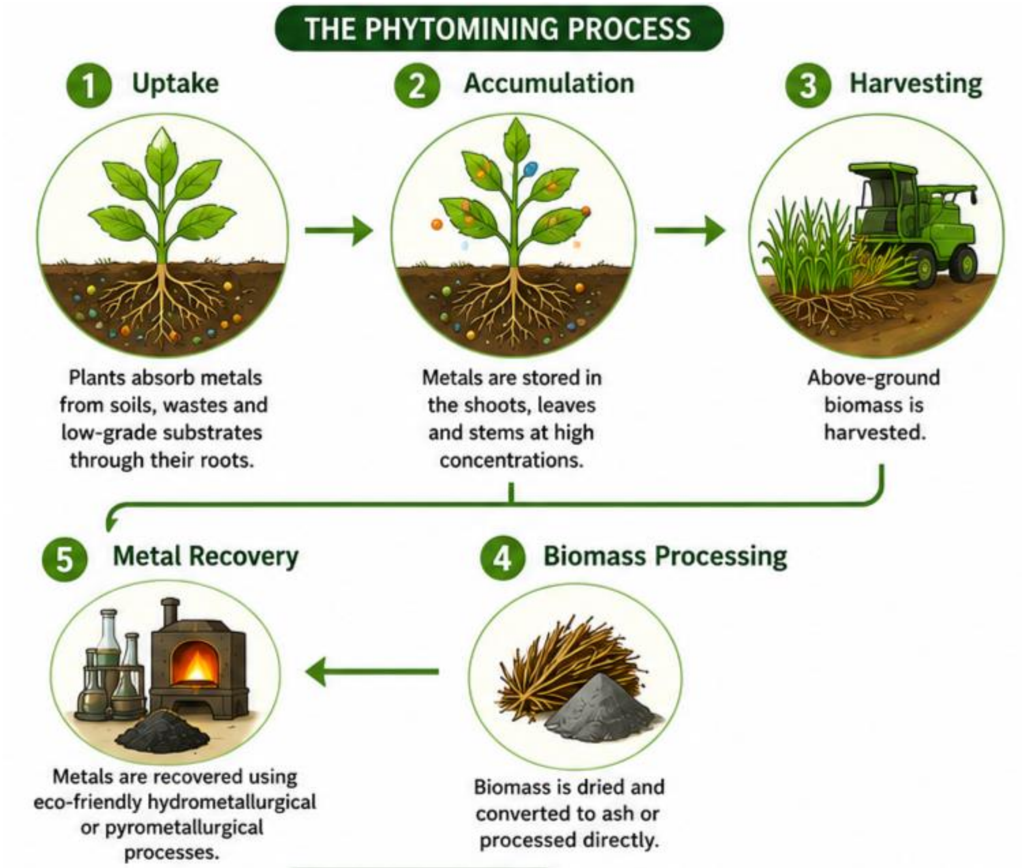

Figure 1. Conceptual framework of phytomining using hyperaccumulator plants for sustainable critical mineral recovery

Reflecting the growing scientific interest in this emerging field, researchers aimed at evaluating the potential of hyperaccumulator plants for the sustainable recovery of critical minerals from mineralised rocks, mine wastes, and degraded landscapes. Particular attention is being directed toward mineral rich states such as Odisha, Jharkhand, Chhattisgarh, Karnataka, Rajasthan, and Arunachal Pradesh, where phytomining could simultaneously contribute to critical mineral recovery and ecological restoration. By harnessing hyperaccumulator plants, these landscapes may become sources of nickel, cobalt, vanadium, and rare earth elements while supporting the rehabilitation of degraded ecosystems (Rylott and van der Ent, 2025; He et al., 2026).

TURNING WASTELANDS INTO "GREEN MINES"

One of the most compelling features of phytomining is its potential to convert environmental liabilities into valuable economic resources (Akinbile and Mbohwa, 2025). Mining operations frequently leave behind degraded landscapes characterized by soil erosion, contamination, biodiversity loss, and reduced land productivity. Conventional rehabilitation measures are often costly and provide limited economic returns. In contrast, hyperaccumulator plants offer a multifunctional solution by extracting valuable metals while simultaneously stabilizing soils, enhancing vegetation cover, reducing dust emissions, and promoting carbon sequestration (He et al., 2026; Akinbile and Mbohwa, 2025).

This integrated approach has led researchers to describe phytomining systems as "green mines" living, self-sustaining systems capable of producing strategic minerals while contributing to environmental restoration and ecosystem recovery (Akinbile and Mbohwa, 2025). Beyond mineral recovery, phytomining may also provide an additional source of renewable biomass. Following harvest, the biomass can be utilized for energy production, and the resulting ash, enriched with concentrated metals, can be processed through hydrometallurgical or pyrometallurgical methods to recover valuable elements, thereby enhancing the overall economic viability of the technology (He et al., 2026; Pereira, 2026).

NEW LIVELIHOOD OPPORTUNITIES FOR RURAL INDIA

Beyond its potential for critical mineral recovery, phytomining may create novel livelihood opportunities for rural and tribal communities, particularly in regions characterized by degraded lands and limited agricultural productivity (He et al., 2026). Unlike conventional mining, which typically requires substantial capital investment, intensive infrastructure, and centralized operations, phytomining can be integrated with landscape restoration initiatives and community based natural resource management programs. The cultivation of hyperaccumulator species on marginal, contaminated, or otherwise unproductive lands offers a means of generating economic value from areas unsuitable for conventional food production. By harvesting metal-enriched biomass, local communities could potentially derive additional income streams while contributing to the recovery of strategically important minerals (He et al., 2026). Such systems may be particularly relevant in mining-affected regions, where land degradation often constrains agricultural livelihoods and limits economic opportunities.

Importantly, phytomining aligns with several national priorities, including the promotion of circular economy principles, sustainable rural development, tribal empowerment, ecological restoration, and climate-resilient livelihood strategies. By linking environmental rehabilitation with resource recovery, phytomining offers a multifunctional approach that simultaneously addresses economic, social, and ecological objectives. In areas where conventional agriculture is challenged by poor soil quality, metal contamination, or recurrent climatic stresses, the cultivation of hyperaccumulator plants could provide a viable alternative land-use option and contribute to the diversification of rural economies (He et al., 2026).

INNOVATION AT THE INTERFACE OF AGRICULTURE AND MINING

Phytomining is increasingly being recognized as a multidisciplinary approach that integrates principles of agriculture, biotechnology, ecology, and mineral resource recovery, thereby redefining the conventional boundaries between biological production systems and extractive industries (Pereira, 2026). As global demand for critical minerals continues to rise, researchers are exploring ways to enhance the efficiency and scalability of phytomining through advances in plant science and environmental biotechnology.

Recent developments in plant breeding, rhizosphere engineering, microbial inoculants, genetic improvement, and soil management have shown considerable potential for increasing both metal accumulation and biomass productivity in hyperaccumulator species (He et al., 2026). These innovations are improving the economic feasibility of phytomining and expanding its applicability to a wider range of mineral resources. In parallel, researchers are investigating engineered and enhanced hyperaccumulator systems capable of recovering a broader spectrum of technology-critical elements, including rare earth elements, lithium, cobalt, nickel, and other battery minerals essential for the clean-energy transition (Rylott and van der Ent, 2025).

Looking ahead, international experts envisage the emergence of dedicated "bio-ore farms" managed production systems specifically designed for the cultivation of metal-accumulating plants and the sustainable recovery of strategic minerals (Rylott and van der Ent, 2025). Such systems could complement conventional mining by providing an environmentally benign and low carbon pathway for resource extraction. Consequently, phytomining is increasingly viewed not as a replacement for traditional mining, but as a complementary technology capable of enhancing resource efficiency, recovering metals from low-grade or secondary resources, and contributing to the development of resilient and sustainable mineral supply chains (Akinbile and Mbohwa, 2025).

A VISION FOR VIKSIT BHARAT 2047

As India advances towards its vision of becoming a developed nation by 2047, ensuring a secure and resilient supply of critical minerals will be as fundamental to national development as energy security and food security (Government of India, 2025). The growing demand for minerals required in renewable energy systems, electric mobility, advanced manufacturing, electronics, and strategic technologies underscores the need for innovative and sustainable approaches to resource security.

In this context, phytomining offers a unique opportunity to simultaneously address multiple national priorities. By harnessing the metal-accumulating capacity of hyperaccumulator plants, phytomining has the potential to contribute to domestic critical mineral production while supporting ecological restoration, reducing import dependence, creating rural livelihood opportunities, and advancing climate and sustainability goals (Rylott and van der Ent, 2025; He et al., 2026). Such multifunctional benefits make phytomining particularly relevant for a country with extensive areas of degraded lands, mine spoils, and industrial waste repositories.

Areas once regarded as unproductive wastelands could potentially be transformed into productive landscapes that generate both ecological and economic value. Strategic investments in research, pilot-scale demonstrations, technology development, and policy support under initiatives such as the National Critical Mineral Mission could help unlock this potential and establish phytomining as a complementary component of India's critical mineral strategy (Government of India, 2025). While conventional mining will continue to play a central role in meeting future mineral demand, phytomining offers an environmentally responsible pathway for recovering metals from low-grade resources, mine wastes, and degraded ecosystems. The mines of the future may therefore extend beyond conventional underground and open-cast operations to include carefully managed landscapes where plants function as biological extractors of strategic minerals. Such systems could contribute to building a more sustainable, resilient, and self-reliant mineral economy in support of the broader vision of Viksit Bharat 2047.

CONCLUSION

Phytomining offers a transformative opportunity to reshape how India secures the critical minerals required for a clean energy and technology-driven future. By harnessing the remarkable metal-accumulating capacity of hyperaccumulator plants, degraded mine lands, industrial waste sites, and other marginal landscapes can be transformed into productive "green mines" that simultaneously recover valuable minerals, restore ecosystems, and create sustainable livelihood opportunities. While phytomining is not a substitute for conventional mining, it provides a complementary, low-carbon, and environmentally responsible approach for recovering strategic minerals from low-grade resources and mine wastes that are often uneconomical to exploit using traditional methods. Realizing this potential will require sustained investments in scientific research, the discovery and domestication of indigenous hyperaccumulator species, pilot-scale demonstrations, advances in biotechnology and metallurgical processing, and enabling policy support under the National Critical Mineral Mission. As India advances towards the vision of Viksit Bharat 2047, integrating agriculture, ecology, and mineral resource management through phytomining can strengthen mineral self-reliance, accelerate ecological restoration, promote circular economy principles, and build a more resilient, sustainable, and resource-secure future.

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