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Phytomining as an Emerging Metal Recovery Route: A Critical Review of Plant Uptake Mechanisms, Processing Strategies, And Industrial Constraints (2020–2025)

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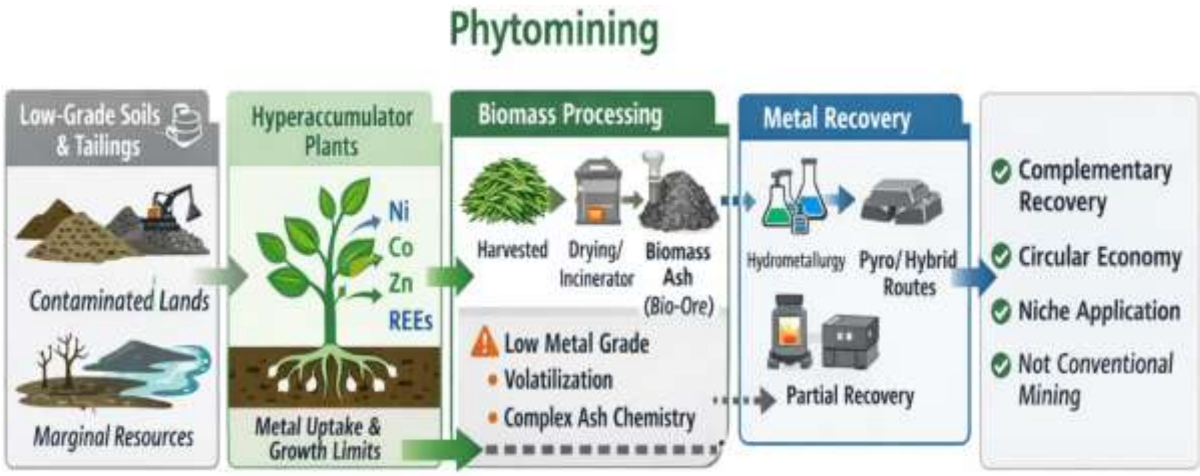
ABSTRACT: Phytomining has re-emerged as a promising strategy for the sustainable recovery of valuable and critical metals from soils, mine tailings, and industrial residues, while simultaneously contributing to environmental remediation. This critical review synthesizes advances published between 2020 and 2025, focusing on the biological, agronomic, and metallurgical foundations that govern phytomining performance and scalability. Recent progress in hyperaccumulator selection, soil amendments, plant–microbe interactions, and biomass processing has expanded the range of target metals beyond nickel to include gold, platinum-group metals, rare-earth elements, and scandium. However, field-scale deployment remains constrained by trade-offs between biomass productivity and metal concentration, as well as by the efficiency and cost of downstream ash processing and metal recovery. By integrating reported case studies, techno-economic assessments, and environmental indicators, this review positions phytomining within circular economy and nature-based remediation frameworks. Key knowledge gaps have been identified in process integration, quantitative performance metrics, and long-term sustainability, providing a roadmap for transitioning phytomining from experimental trials to industrially relevant applications.

KEYWORDS: Phytomining, Hyperaccumulator plants, Critical metals, Nickel, Rare earth elements, Biomass processing, Circular economy, Sustainable mining

Highlights

- Phytomining research expanded significantly between 2020 and 2025, with growing emphasis on critical and strategic metals.
- Nickel remains the most mature target, while REEs, scandium, and precious metals represent emerging frontiers.
- Soil amendments and plant–microbe interactions are key drivers of metal uptake and biomass productivity.
- Biomass processing and ash metallurgy remain the main technical bottlenecks for large-scale deployment.
- Phytomining aligns with circular economy and remediation goals but requires integrated techno-economic optimization.

Graphical abstract



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1. INTRODUCTION

Demand for critical metals is rising faster than supply can meet. This pressure is evident in clean-energy value chains, such as nickel, where the debate on security of supply and sustainability already includes phytomining as a complementary pathway in specific settings (Dilhara et al., 2024). At the same time, society expects lower-emission extraction methods and solutions that recover value from degraded lands and mineral residues.

Phytomining (often discussed alongside agromining) is based on a straightforward idea: grow plants that accumulate target metals, harvest the biomass, and convert it into a "bio-ore" suitable for downstream processing. Foundational work has clarified how the concept evolved and why its translation into practice is slow (Chaney et al., 2020). Recent reviews show rapid expansion of phytomining across metals and sites, but they also highlight recurring technical and economic bottlenecks (Kikis et al., 2024).

From 2020 to 2025, progress focused on three fronts. The first is agronomy. Studies focus on increasing biomass yield and metal concentration through fertilization, soil conditioning, and cultivation protocols, particularly in ultramafic systems relevant to nickel (Hipfinger et al., 2021). Work on organic amendments also aims to improve nickel phytomining efficiency and operational stability (Alves et al., 2025). The second is biology. There is greater attention to bacteria and mycorrhizal fungi as drivers of metal availability, plant tolerance, and overall uptake performance (Alves et al., 2021). The third is process integration and full-chain evaluation, which ultimately determines whether bio-ore can be converted into a product under realistic constraints. For rare earth elements, for instance, recent contributions combine cultivation concepts with techno-economic framing and proposals for accelerated biomass processing (Struhs & Mirkouei, 2024; Deng et al., 2025).

Despite these advances, a gap remains between proof-of-concept and deployment. Critical reviews emphasize that feasibility depends less on whether a plant can accumulate a metal and more on system outcomes: annual yield, stability of metal grade, cultivation and harvesting costs, biomass logistics, conversion route, and by-product management (Dinh et al., 2025). This is particularly evident for high-value metals, such as noble metals and PGMs, where selectivity and bio-ore processing dominate the discussion (Dinh et al., 2022a; Abdullahi et al., 2025). In parallel, phytomining has been extended to residues and tailings, including red mud systems targeting scandium. These studies are important, but their technological maturity is uneven and often limited to short trials and site-specific conditions (Tangahu et al., 2025; Arafi et al., 2025).

A second recurring issue is overgeneralization. Phytomining is not a universal substitute for conventional mining. It is better understood as a niche strategy for diffuse mineralization, low-grade deposits, legacy contamination, or locations where social or environmental constraints limit traditional extraction (Bani et al., 2024). Evidence also shows that promising laboratory results do not automatically translate into field performance, reinforcing the need for careful interpretation and comparable reporting metrics (Wang et al., 2020). A useful critical review must therefore distinguish: (i) what is technically reproducible; (ii) what is conditional on narrow site- or management-specific factors; and (iii) what remains speculative.

Objective of this review. This paper provides a critical review of phytomining research published from 2020 to 2025. We synthesize advances, limitations, and feasibility conditions by explicitly linking plant/soil biology, agronomic management, bio-ore conversion, and techno-economic performance. We also highlight reporting practices that enable cross-study comparisons and identify the most actionable research gaps by metal group (Ni, REEs, Au/PGMs, and residue-derived targets such as Sc).

The next section outlines the review's methodology, including the search strategy, inclusion and exclusion criteria, study classification by metal and evidence type (field, greenhouse, laboratory, techno-economic assessment), and the approach to generating a structured critical synthesis.

2. METHODOLOGY

This review was conducted in accordance with the PRISMA 2020 guidelines for transparent and reproducible reporting of systematic reviews (Page et al., 2021). The methodology was adapted to the scope of a critical narrative review, prioritizing conceptual integration and feasibility assessment over quantitative meta-analysis.

2.1. Literature search strategy

A structured literature search was conducted covering the period from January 2020 to December 2025. The databases Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar were queried using combinations of the keywords phytomining, agromining, phytoextraction, hyperaccumulator plants, critical metals, nickel, rare earth elements, gold, PGM, red mud, and mine tailings. Reference lists of key review articles were also screened to identify additional relevant studies.

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2.2. Eligibility criteria and study selection

Studies were included if they:

(i) explicitly addressed phytomining or agromining;
(ii) focused on metals of economic or strategic relevance; and
(iii) provided experimental, field-based, process-oriented, or techno-economic insights.

Studies limited to phytoremediation without intent to recover metals, purely speculative perspectives without data, or publications outside the defined period were excluded. Conference papers, book chapters, and theses were included if they contributed original data or methodological advances not duplicated in journal articles.

2.3. Data extraction and synthesis

From each eligible study, information was extracted on: target metal(s), plant species, substrate type (soil, tailings, residue), scale (laboratory, greenhouse, field), agronomic or biological enhancement strategies, biomass yield, metal concentration, and downstream processing considerations. Rather than aggregating results statistically, findings were synthesized critically to identify consistent trends, performance limits, and system-level constraints across metal groups.

2.4. Reporting and transparency

To ensure transparency, reproducibility, and methodological rigor, the literature selection process followed the PRISMA 2020 guidelines. The identification, screening, eligibility, and inclusion steps used in this critical review are summarized in the flow diagram in Figure 1.

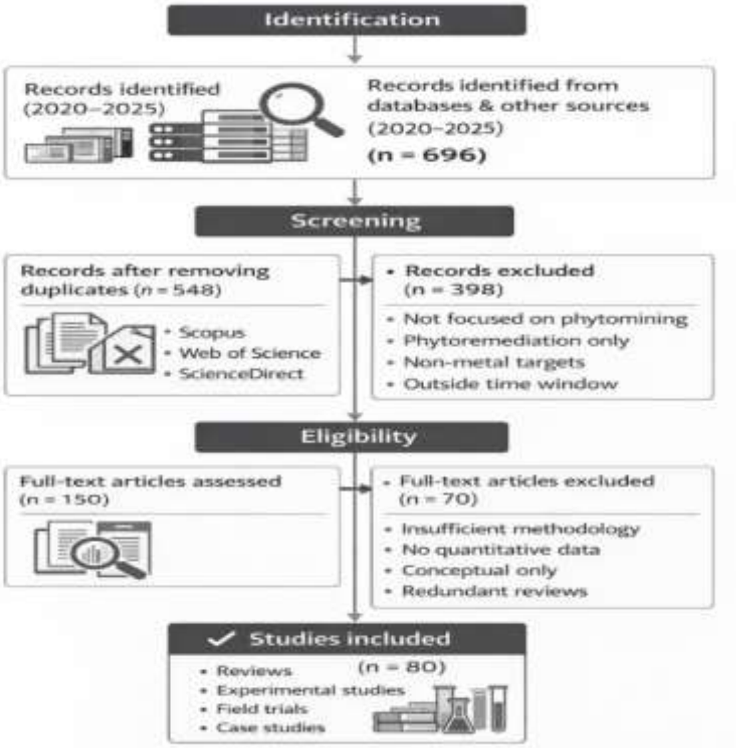

Figure 1. PRISMA 2020 flow diagram. Adapted from Page et al. (2021)

The final reference corpus comprises 80 consolidated references, ensuring comprehensive coverage while avoiding duplication among reviews, experimental studies, and case reports.

The following section (Section 3: Fundamentals of Phytomining) presents the biological, geochemical, and process principles that underpin metal uptake, accumulation, and bio-ore formation, providing the conceptual basis for the critical analysis that follows.

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3. FUNDAMENTALS OF PHYTOMINING

Phytomining is a resource-recovery strategy that couples biological uptake with metallurgical conversion. Its foundations span plant physiology, soil–solution chemistry, and downstream processing of metal-enriched biomass. Understanding these interacting mechanisms is essential for distinguishing feasible systems from purely experimental demonstrations (Chaney et al., 2020; Dinh et al., 2025).

3.1. Plant uptake and hyperaccumulation mechanisms

At the core of phytomining is the ability of certain plants—known as hyperaccumulators—to take up metals at concentrations orders of magnitude higher than in typical vegetation without showing severe toxicity symptoms. Uptake occurs primarily through root–soil solution interactions and is governed by metal speciation, bioavailability, and transport across root membranes (Fadzil et al., 2024).

Once absorbed, metals are translocated to aboveground tissues and sequestered in vacuoles or bound to organic ligands. This compartmentalization is crucial for tolerance and sustained growth. For nickel, this mechanism is well established in ultramafic soils, whereas for rare earth elements and noble metals, it is less efficient and more site-dependent (Lima et al., 2022; Dinh et al., 2022b).

A central requirement for phytomining is selecting plant species that accumulate economically meaningful concentrations of metals in their above-ground biomass. These species, commonly referred to as hyperaccumulators, vary widely in metal specificity, uptake efficiency, biomass productivity, and tolerance to contrasting substrate conditions. Representative hyperaccumulator plants, their primary target metals, typical shoot concentrations, and associated substrate types reported in the literature are summarized in Table 1, providing a comparative framework for evaluating their phytomining potential across different geological and waste-derived environments.

Table 1. Representative hyperaccumulator plants, target metals, typical shoot concentrations, and substrate types. Adapted from Chaney et al. (2020); Wang et al. (2020); Dinh et al. (2022a, 2022b); Akinbile & Makhubela (2023); Kikis et al. (2024); Rabbani et al. (2024); Alves et al. (2025); Richardson et al. (2025a, 2025b).

Plant species	Target metal(s)	Typical shoot concentration ($mg \cdot kg^{-1}$ DW)	Substrate / soil type	Notes on phytomining relevance
Odontarrhena chalcidica (syn. *Alyssum chalcidicum*)	Ni	10,000–25,000	Ultramafic soils, serpentine	Benchmark Ni hyperaccumulator used in field phytomining trials
Odontarrhena serpyllifolia	Ni	8,000–20,000	Ultramafic soils	High biomass yield; responsive to organic amendments
Alyssum murale	Ni	10,000–30,000	Ultramafic soils	Most extensively studied Ni phytomining species
Pteris vittata	Au, As	100–1,000 (Au)	Mine tailings, contaminated soils	Effective with rhizobacteria and amendments
Ipomoea batatas (sweet potato)	Au	50–500	Gold tailings, amalgamation residues	Suitable for low-grade gold phytomining
Chrysopogon zizanioides (vetiver grass)	Pd, Sc	200–2,000	Red mud, metallurgical residues	High tolerance; compatible with waste-based substrates
Portulaca grandiflora	Sc, V, Cr	300–1,500	Red mud, alkaline residues	Promising for scandium recovery
Jatropha curcas	V, Cr	200–1,000	Red mud, sludge-amended soils	Dual role: remediation and metal recovery

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Sansevieria trifasciata	V, Cr	150–900	Industrial residues	Ornamental species with metal tolerance
Alocasia macrorrhizos	Au	100–800	Gold tailings	Large biomass offsets moderate concentrations
Dracaena fragrans	Sc	300–1,200	Red mud + AMD	Effective under acidic conditioning
Duckweed (*Lemna* sp.)	Au	50–300	Mine wastewater, tailings ponds	Rapid growth; potential for nanoparticle recovery

Nickel remains the most mature phytomining target, supported by multiple field-scale demonstrations in ultramafic soils. In contrast, precious metals and critical elements, including scandium and rare earth elements, are emerging targets, often associated with mine wastes, red mud, and tailings. These systems typically require substrate conditioning and post-harvest metallurgical integration to achieve economic viability.

3.2. Soil–plant–microbe interactions

Metal uptake is not controlled solely by plants. Soil chemistry and microbial activity strongly influence metal mobility and root access. Rhizosphere processes, including pH modification, ligand exudation, and redox reactions, can either increase or decrease metal availability (Alves et al., 2021).

Recent studies highlight the roles of plant growth–promoting rhizobacteria and mycorrhizal fungi in enhancing nutrient uptake and stress tolerance. These interactions are especially relevant in marginal substrates, such as tailings and red mud, where biological assistance may compensate for poor physical or chemical conditions (Aminatun et al., 2025; Tangahu et al., 2025).

Figure 2 provides a graphical overview of key soil–plant–microbe interactions that govern metal uptake in phytomining systems. In the soil compartment, physicochemical parameters such as pH, redox potential, organic ligands, and competing ions regulate metal speciation and solubility. Root-driven processes, including rhizosphere acidification and the release of low-molecular-weight organic acids, enhance mineral dissolution and mobilize metal species. Microbial communities in the rhizosphere further promote metal availability through siderophore production, redox transformations, chelation, and enzymatic mineral weathering. These processes collectively facilitate metal transport across root membranes, xylem translocation, and accumulation in above-ground biomass, while also influencing plant stress tolerance and biomass productivity.

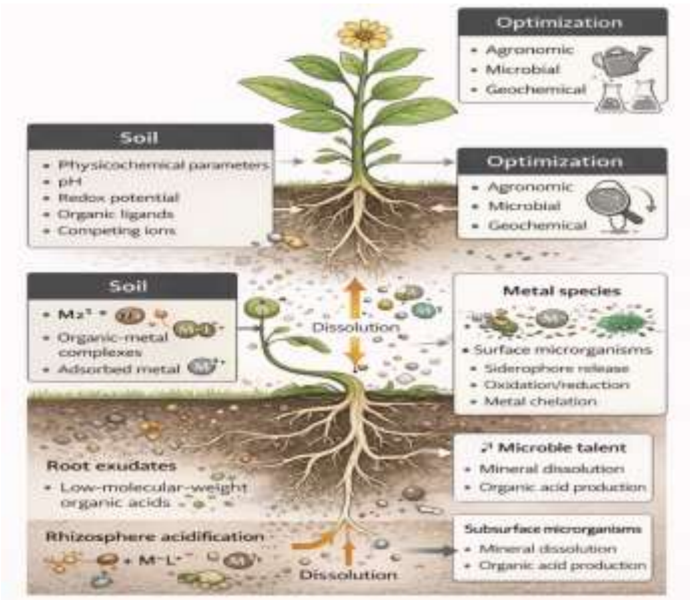

Figure 2. Conceptual diagram of soil–plant–microbe interactions controlling metal uptake in phytomining systems. Adapted from Chaney et al. (2020), Alves et al. (2021), Scotti et al. (2022), and Fadzil et al. (2024).

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This conceptual representation emphasizes that phytomining efficiency emerges from system-level interactions rather than isolated plant traits. Consequently, recent research has increasingly focused on integrated optimization strategies combining soil amendments, microbial inoculation, and agronomic management, which are examined in detail in the following section.

3.3. Biomass production and metal yield

From a resource perspective, phytomining performance is determined by the annual metal yield per unit area, which equals biomass productivity multiplied by metal concentration. High accumulation alone is insufficient if biomass yield is low. Conversely, high biomass with low metal content may not justify downstream processing (Wang et al., 2020).

This trade-off explains why nickel phytomining has advanced further than for other metals. Nickel systems benefit from both relatively high shoot concentrations and agronomically manageable biomass. For REEs, PGMs, and gold, yields remain highly variable and often marginal without site-specific optimization (Akinbile & Makhubela, 2023; Abdullahi et al., 2025).

Figure 3 shows the conceptual and empirical relationship between above-ground biomass yield and metal concentration for major phytomining target metals, including nickel (Ni), rare earth elements (REEs), and gold/platinum group metals (Au/PGMs). Nickel phytomining systems typically fall within an intermediate-to-favorable range, combining moderate-to-high biomass yields with shoot concentrations that commonly exceed 1 wt.% Ni in hyperaccumulators. In contrast, REE phytomining is characterized by relatively low shoot concentrations but moderate biomass productivity, whereas Au and PGM phytomining systems cluster at the low-biomass, low-concentration end of the spectrum, reflecting their limited accumulation efficiency and strong dependence on enhancement strategies.

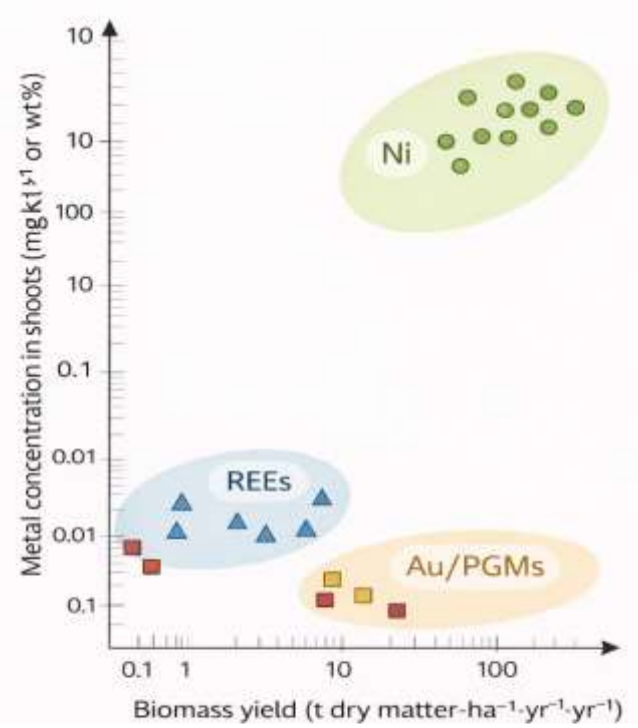

Figure 3. Comparative plot of biomass yield versus metal concentration for major phytomining target metals (Ni, REEs, Au/PGMs). Adapted from Chaney et al. (2020), Wang et al. (2020), Dinh et al. (2022a, 2022b), Rabbani et al. (2024), and Richardson et al. (2025a, 2025b).

This comparative visualization highlights why nickel remains the most technically mature phytomining target to date, while REEs and precious metals remain largely experimental. It also underscores the need for integrated strategies—such as soil amendments, microbial assistance, and optimized agronomy—to shift systems toward higher combined biomass–metal yield.

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After harvesting, biomass is converted into a bio-ore, typically through drying and thermal treatment. Ashing concentrates metals and reduces mass, but it also introduces challenges related to volatilization, loss of selectivity, and handling of residual elements (Dinh et al., 2022a).

The feasibility of phytomining ultimately depends on whether this bio-ore can be integrated into existing metallurgical routes or processed by dedicated methods. Recent work on accelerated thermal or electrothermal processing aims to shorten residence times and improve recovery in low-concentration systems, such as REEs (Deng et al., 2025; Struhs & Mirkouei, 2024).

Figure 4 schematically illustrates the integrated phytomining process chain, emphasizing the sequential and interdependent nature of biological, agronomic, and metallurgical stages. The biological phase focuses on substrate conditioning, including pH adjustment, fertilization, and microbial inoculation, followed by metal uptake by hyperaccumulator plants. Agronomic operations aim to maximize biomass production and ensure efficient harvesting. The metallurgical stage encompasses biomass processing via thermochemical or hydrometallurgical routes and subsequent metal recovery, ultimately producing a refined metal product. Recycling and biosynergy loops highlight opportunities to improve overall resource efficiency and sustainability.

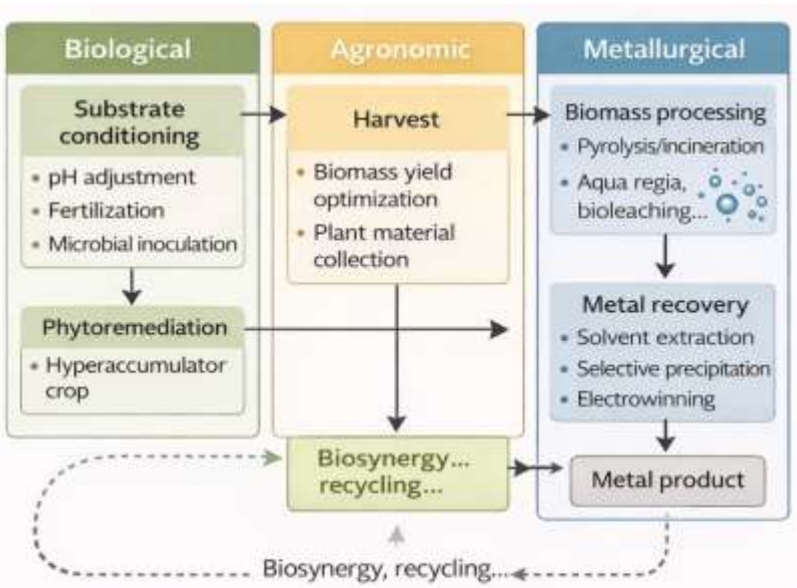

Figure 4. Generic phytomining process chain from soil to metal product, highlighting biological, agronomic, and metallurgical stages. Adapted from van der Ent et al. (2017), Chaney et al. (2020), Wang et al. (2020), Sarma et al. (2022), and Kikis et al. (2024).

This holistic representation underscores that phytomining performance cannot be evaluated solely at the plant–soil interface. Instead, overall feasibility depends on the coordinated optimization of agronomic practices and biomass-to-metal conversion pathways, reinforcing the need for interdisciplinary process design.

3.4. System boundaries and feasibility conditions

A fundamental distinction between phytomining and phytoremediation is the intentional recovery of economic value. This requires clear system boundaries, including the time horizon, land availability, regulatory constraints, and market conditions. Phytomining is therefore best viewed as a complementary or niche strategy, not a universal replacement for conventional mining (Bani et al., 2024; Dinh et al., 2025).

Figure 5 presents the integrated phytomining framework, highlighting interactions among soil geochemistry (pH, redox conditions, ligands, and competing ions), plant uptake and translocation, biomass harvesting and processing pathways (pyrolysis, leaching, refining), and the generation of economic value through metal recovery. Feedback loops emphasize the coupling between biological efficiency and downstream metallurgical performance, underscoring phytomining as a bio–geo–metallurgical system rather than a single-step extraction process.

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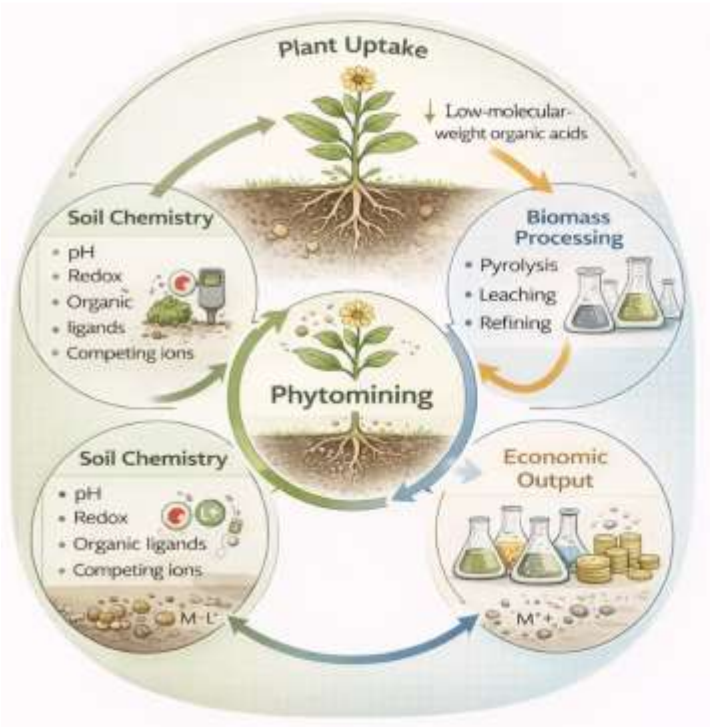

Figure 5. Integrated overview of phytomining fundamentals linking soil chemistry, plant uptake, biomass processing, and economic output. Adapted from Chaney et al. (2020), Heilmeier and Wiche (2020), Wang et al. (2020), Dinh et al. (2022a,b), Kikis et al. (2024), and Rabbani et al. (2025).

By integrating biological, agronomic, and metallurgical dimensions into a single conceptual framework, the graphical abstract visually reinforces the central premise of this review: the technical and economic viability of phytomining depends on coordinated optimization across the entire process chain, from soil conditioning to final metal recovery.

Building on the fundamental biological, geochemical, and process principles outlined in Section 3, the discussion now shifts from mechanisms to application-oriented evidence. Although phytomining follows a common conceptual framework, its technical performance and feasibility vary widely with the target metal, the host substrate, and the maturity of downstream processing routes.

Accordingly, Section 4 examines the primary target metals in phytomining research from 2020 to 2025, with an emphasis on nickel, gold, platinum-group metals, rare earth elements, copper, and selected critical metals. For each group, recent experimental results, field trials, enhancement strategies, and reported yields are critically assessed to identify realistic performance ranges, technological bottlenecks, and pathways toward industrial relevance.

4. TARGET METALS IN PHYTOMINING (2020–2025)

Between 2020 and 2025, phytomining research expanded beyond its historical focus on nickel to include precious metals, rare earth elements, and metals found in industrial residues. However, maturity, performance metrics, and feasibility conditions differ markedly across target metals. This section critically reviews the main groups investigated during this period, highlighting realistic outcomes and persistent limitations.

4.1. Nickel (Ni)

Nickel remains the most advanced and best-documented target metal in phytomining. Its predominance is linked to the presence of well-characterized hyperaccumulator species adapted to ultramafic soils, together with relatively favorable metal concentrations in aboveground biomass (Geng et al., 2020; Lima et al., 2022).

Recent studies emphasize yield optimization rather than proof of accumulation. Field and greenhouse investigations demonstrate that fertilization regimes, soil conditioning, and crop management can significantly influence annual nickel recovery (Hipfinger et al., 2021; Wang et al., 2024). Research in Sri Lanka and comparable ultramafic settings shows that site-specific soil–plant interactions govern achievable yields, reinforcing that Ni phytomining is viable only within narrow geochemical windows (Dilshara et al., 2023; Dilshara et al., 2024, 2025).

From a critical perspective, nickel phytomining is best positioned as a low-grade, long-term recovery option rather than a substitute for laterite mining. Its relevance increases on marginal lands where conventional mining is socially or environmentally constrained (Tognacchini et al., 2020; Chaney et al., 2020; Akinbile & Makhubela, 2023).

Nickel remains the most mature and extensively studied target metal in phytomining, owing to the availability of well-characterized hyperaccumulator species, particularly from ultramafic environments (Akinbile & Mbohwa, 2025a, 2025b). Studies reported between 2020 and 2025 provide quantitative data on shoot nickel concentrations, biomass productivity, and potential metal recovery rates under both experimental and field-scale conditions. These results are summarized in Table 2 to enable cross-comparison of agronomic performance and recovery potential.

Table 2. Summary of nickel shoot concentrations, dry biomass yields, and estimated annual nickel recovery rates reported for major hyperaccumulator species. Adapted from Geng et al. (2020), Wang et al. (2020), Ghafoori et al. (2022), Manteca-Bautista et al. (2022), Lima et al. (2022), Hipfinger et al. (2021), Kikis et al. (2024), and Wang et al. (2024).

Hyperaccumulator species	Substrate type	Shoot Ni concentration (mg kg^{-1} DW)	Biomass yield (t ha^{-1} yr^{-1}, DW)	Estimated Ni recovery (kg ha^{-1} yr^{-1})	Study type
Odontarrhena serpyllifolia	Ultramafic soil	10,000–18,000	6–9	60–160	Field trial
Odontarrhena chalcidica	Serpentinite soil	8,000–15,000	5–8	40–120	Field trial
Alyssum murale	Ultramafic soil	12,000–20,000	7–10	85–200	Field trial
Alyssum corsicum	Mine tailings	6,000–12,000	4–6	25–70	Pot / pilot
Odontarrhena penjwinensis	Ultramafic soil	9,000–17,000	5–7	45–120	Field trial
Alyssum serpyllifolium subsp. *malacitanum*	Ultramafic massif	7,000–14,000	4–6	30–85	Field trial
Mixed *Alyssum* spp.	Industrial Ni waste	5,000–10,000	3–5	15–50	Experimental

Despite substantial variability driven by site conditions and agronomic management, the compiled data indicate that annual nickel recovery rates exceeding 100 kg ha^{-1} are consistently achievable under optimized field conditions. These values approach thresholds considered economically relevant for niche applications, reinforcing nickel phytomining as the most technically mature phytomining pathway.ets.

4.2. Gold and precious metals (Au, PGM)

Gold and platinum-group metals have attracted attention for their high unit value, yet results remain highly heterogeneous. Laboratory and greenhouse studies confirm uptake and accumulation, but concentrations are often near detection limits and strongly dependent on substrate chemistry and amendments (Saim et al., 2020; Dinh et al., 2022a; Abdullahi et al., 2025).

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Recent reviews emphasize that the bottleneck for precious metals is not plant uptake alone but selective recovery from bio-ore. Ashing concentrates metals, yet downstream processing still entails losses, dilution by co-elements, and economic uncertainty (Masinire et al., 2022; Abdullahi et al., 2025; Yusuf et al., 2025). Consequently, most studies conclude that Au and PGM phytomining is feasible only in niche cases, such as tailings with dispersed mineralization or sites where remediation and recovery objectives overlap (Singh, 2022; Akinbile & Mbohwa, 2025b).

4.3. Rare earth elements (REEs)

REE phytomining expanded significantly after 2020, driven by strategic demand and supply-security concerns. Experimental work confirms that plants can take up REEs, but accumulation levels are generally low and element-specific (Dinh et al., 2022b; Rabbani et al., 2024, 2025).

Recent contributions have shifted from uptake studies to system-level assessment. Case studies in Idaho combined cultivation trials with preliminary techno-economic evaluations, showing that feasibility depends critically on biomass processing and concentration steps (Richardson et al., 2025a; Struhs & Mirkouei, 2024). Innovative concepts, such as rapid thermal or electrothermal treatment of biomass, aim to overcome low grades, but these approaches remain in early development (Petrov & Stefanova, 2023; Phi et al., 2023, Deng et al., 2025).

Overall, REE phytomining should be considered exploratory, with potential relevance to diffuse or secondary sources rather than primary production.

Figure 6 compares the typical shoot concentration ranges reported for light rare earth elements (LREEs, La–Nd) and heavy rare earth elements (HREEs, Sm–Lu) in phytomining systems from 2020 to 2025. LREEs generally accumulate to higher levels, often reaching 10^2–10^3 mg kg^{-1} dry biomass, whereas HREE concentrations are typically one order of magnitude lower. These differences reflect contrasting geochemical mobility, ligand affinity, and translocation efficiency within plant tissues.

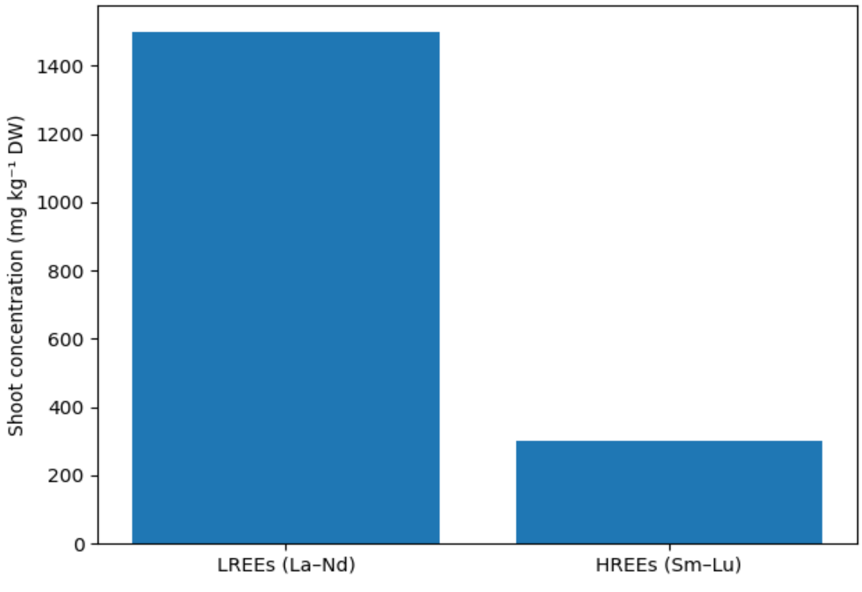

Figure 6. Comparative uptake ranges of light and heavy rare earth elements reported in phytomining studies. Adapted from Dinh et al. (2022b), Rabbani et al. (2024), Richardson et al. (2025a,b), Petrov and Stefanova (2023), and Kikis et al. (2024).

The marked disparity in LREE and HREE uptake highlights a key limitation of rare earth phytomining, underscoring the need for tailored soil amendments, chelation strategies, and plant selection to enhance HREE recovery and improve overall economic feasibility.ity.

4.4. Copper and other base metals

Copper phytomining has received less attention than nickel and REEs. Studies typically focus on contaminated soils or tailings rather than on intentional resource production. Results indicate moderate uptake but limited economic attractiveness because of relatively low concentrations and competition with established hydrometallurgical routes (Chandra et al., 2024; Ribeiro, 2022).

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Similarly, metals such as chromium and vanadium are increasingly studied in residue-based systems, particularly red mud. Although uptake can be enhanced by amendments, these systems remain immature, and long-term performance data are scarce (Fitranto et al., 2025; Praja et al., 2025).

4.5. Metals from residues and secondary sources

A notable trend since 2020 is the extension of phytomining to industrial residues, including red mud, galvanic sludge, and mine tailings. These systems blur the boundary between phytomining and phytoremediation, often prioritizing risk reduction alongside metal recovery (Tognacchini et al., 2020; Tangahu et al., 2025).

Scandium has emerged as a key target in this category. Studies report measurable uptake in red mud systems, yet scalability, consistency, and downstream processing remain unresolved challenges (Akmal et al., 2025; Arafi et al., 2025).

Figure 7 summarizes the main classes of target metals investigated in phytomining research—nickel (Ni), rare earth elements (REEs), and precious metals (Au and platinum group metals, PGMs)—and their associated substrates. Nickel phytomining is predominantly linked to primary ultramafic and lateritic soils, whereas REE phytomining spans both primary ion-adsorption clays and secondary residues. In contrast, precious metal phytomining is largely associated with secondary substrates such as mine tailings and industrial wastes.

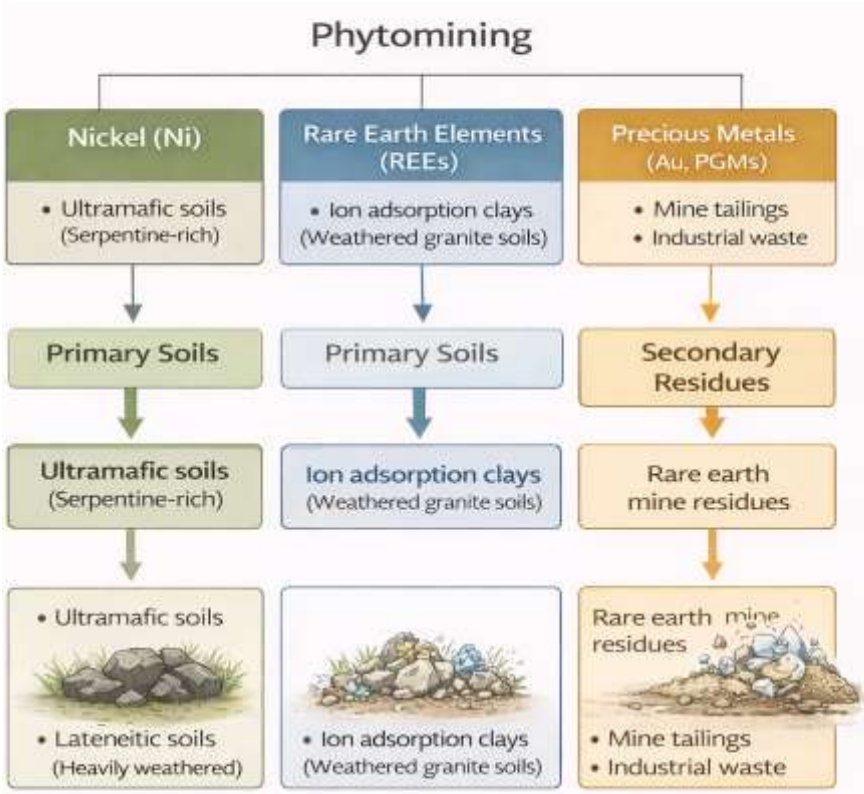

Figure 7. Classification of target metals and typical substrates in phytomining studies (primary soils vs. secondary residues).. Adapted from Chaney et al. (2020), Dinh et al. (2022a,b), Kikis et al. (2024), Akinbile and Makhubela (2023), Rabbani et al. (2024, 2025), and Richardson et al. (2025a,b).

This classification highlights a clear methodological divergence between soil-based agromining systems and residue-based phytomining approaches, with important implications for agronomic management, biomass processing strategies, and techno-economic performance.

Collectively, the literature from 2020 to 2025 shows that metal-specific behavior dominates phytomining performance. Nickel is the most mature system, whereas REEs, precious metals, and residue-derived targets remain conditional or exploratory.

These differences underscore the need to analyze not only plant uptake but also the soil environment and agronomic interventions that govern bioavailability and productivity.

Accordingly, Section 5 examines how soil properties, amendments, and agronomic strategies influence phytomining outcomes and whether reported metal uptake can be translated into reproducible and scalable systems.

5. SOIL, AMENDMENTS, AND AGRONOMIC STRATEGIES

Soil properties and agronomic management are decisive factors that control metal bioavailability, plant productivity, and ultimately phytomining yields. Evidence from 2020–2025 shows that plant genetics alone is insufficient; successful systems require engineered soil–plant–microbe interactions tailored to each target metal and substrate.

5.1. Soil type and geochemical controls

Metal availability is governed by pH, redox conditions, organic matter, and mineral hosts. Ultramafic soils naturally favor nickel phytomining because of high background Ni and low concentrations of competing cations, whereas tailings and industrial residues exhibit heterogeneous mineralogy and strong metal fixation. Studies consistently report that adjusting pH toward mildly acidic conditions enhances uptake of Ni, Cu, and REEs, while excessive acidification increases phytotoxicity and biomass loss (Wang et al., 2020; Kikis et al., 2024; Erkmen et al., 2025).

In residue-based systems such as red mud, extreme alkalinity remains the primary constraint. Partial neutralization improves plant establishment but rarely replicates the geochemical conditions of natural hyperaccumulator habitats (Schwabe, 2022; Hakim et al., 2024; Tangahu et al., 2025).

5.2. Organic and inorganic amendments

Organic amendments—cow manure, compost, sewage sludge, and digestate—are widely used to improve soil structure, nutrient availability, and microbial activity. Recent studies indicate that these materials can indirectly increase metal uptake by stimulating root growth and rhizosphere processes, particularly in red mud and tailings systems (Noviardi et al., 2024; Alves et al., 2025).

Chelating agents, such as citric acid and other low-molecular-weight organic acids, effectively mobilize metals but introduce trade-offs. While they enhance short-term uptake, they may increase leaching risks and compromise environmental safety if not carefully controlled (Hakim et al., 2024; Dhiman et al., 2024). As a result, current research favors biologically mediated mobilization over aggressive chemical chelation.

5.3. Microbial and symbiotic strategies

The integration of plant growth–promoting rhizobacteria and mycorrhizal fungi represents a significant advance in recent phytomining research. Microbial consortia enhance nutrient cycling, metal solubilization, and stress tolerance, particularly under marginal soil conditions (Alves et al., 2021; Scotti et al., 2022).

Gold and scandium phytomining studies show that inoculating with indigenous or engineered microbial communities can significantly increase uptake without proportionally increasing environmental risk (Aminatun et al., 2025; Tangahu et al., 2025). Nevertheless, the long-term stability and reproducibility of microbe-assisted systems remain underexplored.

5.4. Agronomic management and productivity constraints

Crop density, harvest frequency, fertilization regime, and climate adaptation strongly influence annual metal recovery. Field trials of nickel phytomining confirm that maximizing biomass yield is often more impactful than marginal increases in tissue metal concentration (Hipfinger et al., 2021; Wang et al., 2024).

However, most studies still rely on short-term experiments, limiting the assessment of interannual variability, soil exhaustion, and cumulative impacts. This gap hinders robust techno-economic evaluation and underscores the need for long-duration field trials.

Recent phytomining studies show that metal uptake is strongly influenced by soil characteristics and by targeted amendments and microbial strategies (Ghafoori et al., 2022; Fadzil et al., 2024; Alves et al., 2021, 2025). These interventions aim to enhance metal bioavailability, improve plant tolerance, and increase biomass productivity, particularly in marginal or contaminated substrates (Scotti et al., 2022; Hakim et al., 2024, 2025; Salsabilla et al., 2025; Tangahu et al., 2025). A comparative

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synthesis of soil types, chemical amendments, microbial approaches, and their reported effects on metal uptake in phytomining systems published between 2020 and 2025 is presented in Table 3.

Table 3. Summary of soil types, amendments, microbial strategies, and reported effects on metal uptake. Adapted from Chaney et al. (2020), Alves et al. (2021, 2025), Scotti et al. (2022), Dang and Li (2022), Fadzil et al. (2024), Hakim et al. (2024, 2025), Kikis et al. (2024), Rabbani et al. (2024), Richardson et al. (2025a,b), Salsabilla et al. (2025), Tangahu et al. (2025) and Wang et al. (2024).

Soil / Substrate Type	Target Metal(s)	Amendment Type	Microbial Strategy	Reported Effect on Metal Uptake
Ultramafic soils	Ni	Organic matter (compost, manure)	Native rhizosphere bacteria	Increased Ni bioavailability and biomass yield
Serpentine soils	Ni	NPK fertilization	None	Enhanced shoot Ni concentration; improved growth
Lateritic soils	Ni	Chelating organic acids	Arbuscular mycorrhizal fungi	Improved Ni translocation to shoots
Ion-adsorption clays	REEs	Mild acidification	Indigenous soil microbiota	Increased REE mobilization and uptake
Reclaimed tailings	REEs	Organic amendments	Plant growth–promoting rhizobacteria (PGPR)	Higher REE accumulation with limited phytotoxicity
Gold mine tailings	Au	Manure, compost	PGPR	Improved Au uptake and plant vigor
Red mud residues	Sc, V, Cr	Acid mine drainage, sludge	Bacteria-assisted systems	Enhanced metal solubilization and uptake
Industrial wastes	Ni	pH adjustment	None	Increased metal availability with limited biomass response

Overall, these findings show that successful phytomining systems require a tailored combination of soil management, chemical amendments, and microbial interactions, rather than relying solely on plant selection. Such integrated strategies are particularly critical for low-grade substrates and secondary residues, where metal bioavailability is inherently limited (Phi et al., 2023; Deng et al., 2025).

Overall, Section 5 shows that phytomining performance is constrained not only by plant uptake capacity but also by soil engineering and agronomic optimization. Even when favorable uptake is achieved, the economic and technical viability of phytomining ultimately depends on the efficiency with which metals are recovered from harvested biomass.

For this reason, Section 6 focuses on the critical bottleneck in phytomining systems: biomass processing and ash metallurgy, where low-grade bio-ores are converted into recoverable metal concentrates.F

6. BIOMASS PROCESSING AND ASH METALLURGY (CRITICAL SECTION)

Biomass processing is the primary technological bottleneck in phytomining systems and largely determines whether high plant uptake can be translated into economically viable metal recovery. While Sections 3–5 address metal acquisition in the field, Section 6 focuses on converting dilute biological material into a concentrated, metallurgically treatable intermediate.

6.1. Harvesting, drying, and volume reduction

Fresh phytomining biomass typically contains 60–85 wt.% moisture, making drying a necessary first step. Most studies from 2020 to 2025 rely on low-temperature air drying or oven drying (60–105 °C), followed by size reduction to ensure homogeneous thermal treatment (Dinh et al., 2022a; Phi et al., 2023). Although often treated as a minor operation, drying's energy demand becomes significant at scale and directly affects life-cycle performance.

Significantly, biomass-handling strategies differ between woody hyperaccumulators (e.g., Odontarrhena spp.) and herbaceous species (e.g., grasses, sweet potato, vetiver), thereby influencing logistics, grinding behavior, and ash quality (Dube et al., 2022; Chandra et al., 2024).

6.2. Thermal conversion and ash formation

Controlled combustion is the dominant method for concentrating metals from biomass. Ash yields typically range from 2 to 10 wt.% of dry biomass, resulting in enrichment factors of 1 to 2 orders of magnitude relative to plant tissue (Dinh et al., 2022b; Minuț et al., 2023). For nickel, REEs, and platinum-group elements, these metals are preferentially retained in the inorganic ash fraction rather than volatilized (Minuț et al., 2021, 2023; Erkmen et al., 2025).

However, ash composition is highly variable and reflects both plant physiology and soil inputs. Alkali metals, calcium, silica, and phosphorus often dominate the matrix, diluting target metals and complicating downstream separation (Phi et al., 2023; Rabbani et al., 2024). Uncontrolled combustion can also cause sintering or partial melting, reducing leachability.

Recent studies highlight the use of temperature-controlled ashing (450–650 °C) to maintain metal accessibility while reducing losses and preventing mineral encapsulation (Heilmeier, 2021; Richardson et al., 2025b).5b).

6.3. Ash mineralogy and metallurgical implications

Ashes derived from phytomining behave as low-grade polymetallic ores rather than simple concentrates. Metals may occur as oxides, phosphates, carbonates, or amorphous phases, depending on combustion conditions and feedstock chemistry (Phi et al., 2023; Rabbani et al., 2025).

For nickel phytomining, ashes often resemble lateritic fines and can be integrated into hydrometallurgical or pyrometallurgical circuits. In contrast, REE- and PGM-bearing ashes require more selective approaches because of extremely low absolute metal concentrations and strong matrix effects (Dinh et al., 2022b; Deng et al., 2025).

Emerging strategies include:

- ash pre-concentration by physical separation,
- selective acid or alkaline leaching,
- electrothermal or plasma-assisted activation to enhance metal liberation.

Among these, electrothermal activation has attracted attention for REE recovery by rapidly modifying the ash structure while limiting reagent consumption (Deng et al., 2025).

6.4. Environmental and safety considerations

Ash handling introduces new environmental challenges. The concentration of metals also concentrates potentially toxic elements, necessitating controlled storage and treatment. Moreover, combustion emissions and fine ash particulates must be managed to prevent secondary pollution (Wang et al., 2020; Rabbani et al., 2025).

Consequently, biomass processing cannot be decoupled from environmental assessment. The transition from phytoremediation to phytomining must ensure that risk is transferred from soil to controlled industrial units rather than redistributed into new exposure pathways.

Figure 8 shows a simplified schematic of the phytomining biomass processing chain, illustrating the sequence from plant harvest to ash generation suitable for metallurgical recovery. The scheme highlights key operations, including drying, size reduction, thermal treatment (controlled combustion or pyrolysis), and ash conditioning. Each step affects metal concentration, mineralogical speciation, and the ash's suitability as a feedstock for hydrometallurgical or pyrometallurgical recovery.

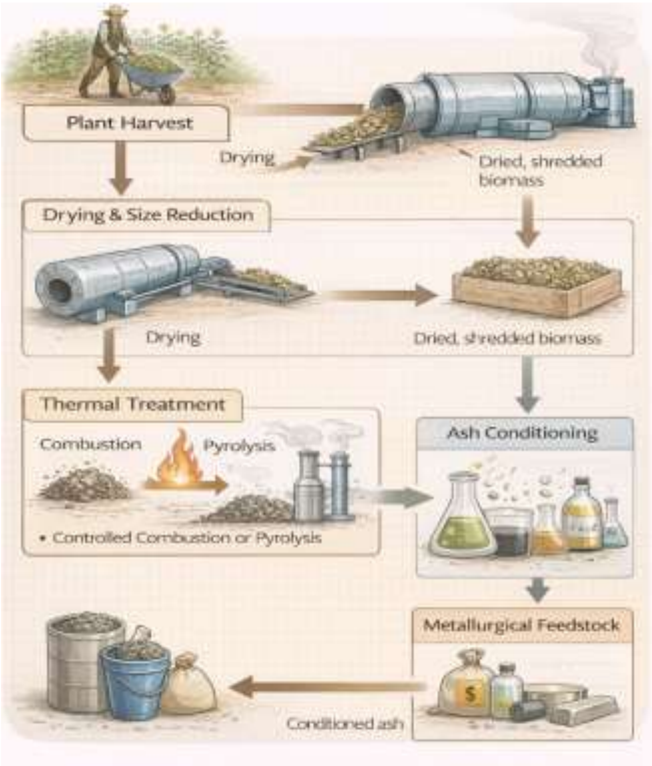

Figure 8. Simplified schematic of biomass processing in phytomining, from harvest to ash production and metallurgical feedstock. Adapted from Chaney et al. (2020), Heilmeier (2021), Dinh et al. (2022a,b), Phi et al. (2023), Rabbani et al. (2024), and Deng et al. (2025).

This processing sequence's efficiency controls the conversion of low-grade biological material into a valuable secondary resource, highlighting the importance of ash quality control in assessing the overall techno-economic viability of phytomining systems.

In summary, Section 6 shows that phytomining success is ultimately governed by ash quality and processability, not solely by plant uptake. Without efficient conversion of biomass into a metallurgically amenable material, even high-accumulation systems remain economically marginal.

Therefore, Section 7 examines the metal recovery routes applied to phytomining ash, critically comparing hydrometallurgical, pyrometallurgical, and hybrid approaches reported from 2020 to 2025.

7. METAL RECOVERY ROUTES FROM PHYTOMINING ASH

The recovery of metals from phytomining ash is the final value-creation step and determines whether phytomining serves as a remediation tool or a viable resource-recovery pathway. Because phytomining ash is low-grade, chemically complex, and highly variable, recovery routes developed between 2020 and 2025 emphasize selectivity, flexibility, and low environmental burden rather than maximum throughput (Struhs & Mirkouei, 2024).

7.1. Hydrometallurgical routes

Hydrometallurgy is the most widely studied approach for processing phytomining ash. Acid leaching with H_2SO_4, HCl, or organic acids is commonly used to recover nickel, cobalt, scandium, and rare earth elements (REEs). These systems benefit from low operating temperatures and compatibility with decentralized processing (Dinh et al., 2022b; Akmal et al., 2025).

However, ash matrices rich in Ca, Mg, P, and Si often result in high reagent consumption and poor selectivity, yielding complex liquors that require additional purification steps, such as solvent extraction, ion exchange, or selective precipitation

(Rabbani et al., 2024). For precious metals, direct leaching is often inefficient because of their ultra-low concentrations and strong matrix interference (Rabbani et al., 2025).

7.2. Pyrometallurgical and thermal approaches

Pyrometallurgical routes are less common yet strategically relevant for nickel-rich ashes and specific precious-metal systems. High-temperature treatment enables metal concentration via slag–metal partitioning or volatilization–condensation mechanisms (Tognacchini et al., 2020; Dinh et al., 2022a).

The primary limitation is the mismatch between energy demand and scale. Phytomining ash volumes are typically small and dispersed, making conventional smelting economically unfavorable unless the ashes are co-processed with industrial residues or lateritic feeds. Nevertheless, thermal routes may offer advantages when integration with existing metallurgical infrastructure is feasible (Krol-Sinclair & Hale, 2023).

7.3. Hybrid and emerging recovery strategies

Recent studies increasingly examine hybrid recovery concepts that combine moderate thermal activation with selective leaching or electrochemical steps. Electrothermal activation, for example, has shown promise in enhancing REE liberation from ash while minimizing reagent use (Deng et al., 2025).

Other emerging directions include:

- alkaline fusion followed by aqueous leaching for REEs,
- bio-hydrometallurgical concepts using microorganisms adapted to ash matrices,
- selective recovery of nanoparticles from plant-derived metal phases.

These approaches reflect a broader shift toward process intensification and circular integration rather than stand-alone extraction flowsheets.ets.

7.4. Critical assessment of recovery performance

Across the 2020–2025 literature, reported metal recoveries are often presented without complete mass balances, energy accounting, or comparisons to primary mining benchmarks. In many cases, recovery efficiencies appear technically promising but economically marginal when biomass handling, ash production, and purification steps are included (Struhs & Mirkouei, 2024; Rabbani et al., 2025).

This highlights a key insight: metal recovery cannot be evaluated in isolation from upstream agronomic performance and downstream market context. Recovery routes must be tailored to specific metals, ash chemistries, and regional infrastructure.

Table 4 shows that no single recovery route is universally optimal for phytomining ash. Hydrometallurgical processes remain the most flexible and widely used, particularly for nickel and rare earth elements, whereas pyrometallurgical routes may be justified only for ashes with sufficiently high metal grades. Hybrid and electro-assisted approaches are promising pathways to overcome selectivity and efficiency bottlenecks, but their industrial viability at scale remains to be demonstrated.

Table 4. Comparison of metal recovery routes from phytomining ash, including operating conditions, target metals, advantages, and key limitations. Adapted from: Chaney et al. (2020); Heilmeier (2021); Dinh et al. (2022a,b; 2025); Phi et al. (2023); Rabbani et al. (2024, 2025); Deng et al. (2025); Erkmen et al. (2025).

Recovery route	Typical operating conditions	Target metals	Main advantages	Key limitations
Hydrometallurgical	Acidic or alkaline leaching (H_2SO_4, HCl, HNO_3, NaOH); solid–liquid ratios 1:5–1:20; temperatures 25–90 °C; atmospheric pressure	Ni, Co, Zn, Cu, REEs, Sc	High selectivity; relatively low temperature; adaptable to low-grade ash; well-established downstream purification (SX, IX, precipitation)	High reagent consumption; co-dissolution of impurities; generation of secondary effluents; sensitivity to ash mineralogy

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Pyrometallurgical	Smelting or roasting; 800–1400 °C; controlled atmosphere (oxidizing/reducing); flux addition (CaO, SiO_2)	Ni, Co, Cu, Fe, PGMs	Rapid processing; destruction of organic residues; suitable for high-metal ash; direct production of metallic or matte phases	High energy demand; limited selectivity; volatilization losses (Zn, Pb); higher CAPEX and CO_2 footprint
Hybrid (thermo-hydrometallurgical)	Low- to mid-temperature thermal pre-treatment (300–700 °C) followed by selective leaching	Ni, Co, REEs, Sc, PGMs	Improved leachability; reduced reagent consumption; better control of speciation; balance between selectivity and throughput	Increased process complexity; additional unit operations; need for careful process integration
Electro-assisted / advanced routes	Electrothermal activation; electro-leaching; short residence times; controlled electric fields	REEs, Sc, strategic metals	High extraction efficiency; rapid kinetics; potential for process intensification	Early-stage technology; limited industrial validation; high equipment cost
Bio-hydrometallurgical (emerging)	Bioleaching using bacteria or fungi; mild pH; ambient temperature; longer residence times	Ni, Co, Cu, Zn	Low energy input; environmentally benign; compatible with circular economy concepts	Slow kinetics; process control challenges; sensitivity to ash toxicity

Although multiple recovery routes from phytomining ash have been demonstrated at laboratory and pilot scales, their practical relevance depends on economic viability and environmental performance. Accordingly, Section 8 evaluates phytomining systems through techno-economic and environmental assessments, integrating biomass production, processing, metal recovery, and sustainability metrics into a unified framework.

8. TECHNO-ECONOMIC AND ENVIRONMENTAL ASSESSMENT

Techno-economic and environmental assessment (TEA–LCA) is essential for determining whether phytomining can move beyond proof-of-concept toward deployable resource-recovery systems. Between 2020 and 2025, assessments increasingly adopt integrated frameworks that couple agronomic performance, biomass processing, and metal recovery with economic and environmental indicators (Wang et al., 2020; Struhs & Mirkouei, 2024; Rabbani et al., 2025).

8.1. Cost structure and economic drivers

Across reported studies, biomass yield and metal concentration are the dominant drivers of operating economics. Low accumulation rates require large cultivation areas, increasing land, harvesting, and logistics costs (Chaney et al., 2020; Akinbile & Makhubela, 2023). Conversely, systems targeting nickel or scandium on ultramafic soils and red mud residues show comparatively favorable economics due to higher uptake and simpler downstream processing (Dilshara et al., 2024; Aminatun et al., 2024, 2025; Akmal et al., 2025).

Capital expenditure is typically modest because phytomining relies on agricultural infrastructure. However, processing units for drying, ashing, and metal recovery are critical cost centers. TEA studies consistently show that phytomining is most competitive when integrated with:

- existing waste-management or metallurgical facilities,
- co-processing strategies with industrial residues,
- decentralized or modular recovery units.

8.2. Environmental performance and life-cycle impacts

Life-cycle assessments highlight phytomining's strengths as a low-emission, land-restorative technology, particularly when deployed on contaminated or degraded sites (Heilmeier, 2021; Rabbani et al., 2024; Praja et al., 2025). Benefits include reduced greenhouse gas emissions compared with primary mining, avoidance of tailings generation, and concurrent soil rehabilitation.

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Nevertheless, environmental performance is sensitive to:

- energy demand for drying and ashing,
- reagent consumption during leaching and purification,
- handling and disposal of metal-enriched ash residues.

Studies emphasize that poorly optimized downstream processing can offset upstream environmental gains (Wang et al., 2020; Erkmen et al., 2025).

8.3. Integration within circular economy frameworks

Recent assessments increasingly frame phytomining within circular-economy and nature-based-solution paradigms, emphasizing co-benefits rather than metal revenue alone (Noviardi et al., 2021, 2024; Bani et al., 2024; Rabbani et al., 2025). In this context, phytomining is most viable when:

- metals recovered have strategic or critical value,
- remediation costs are internalized as avoided liabilities,
- social and ecosystem services are explicitly valued.

This reframing shifts phytomining from a substitute for conventional mining to a complementary, site-specific strategy (Balbin et al., 2024).

Table 5 shows that the literature is moving toward integrated performance reporting, yet robust benchmarking remains rare. For critical metals such as Ni and REEs, the most decisive comparators are metal yield (kg/ha·yr), end-to-end recovery (%), and the combined energy–reagent intensity per kg of recovered metal. Studies that also quantify remediation co-benefits and environmental burdens with transparent system boundaries are the most informative for deployment decisions.

Table 5. Summary of key techno-economic and environmental indicators reported for phytomining systems. Adapted from: Akinbile & Makhubela (2023); Dang & Li (2022); Kikis et al. (2024); Rabbani et al. (2025); Struhs & Mirkouei (2024); Erkmen et al. (2025); Dinh et al. (2025); Richardson et al. (2025a,b).

Indicator (reporting unit)	What it captures	Typical drivers in phytomining	Data source type most common (2020–2025)	Reporting pitfalls (critical notes)
Biomass yield (t dry matter/ha·yr)	Primary productivity that sets metal mass flow	Soil fertility, climate, amendments, cultivar choice	Field/greenhouse trials; agronomic reviews	Often reported without uncertainty; inconsistent dry-basis conversion
Shoot metal concentration (mg/kg or wt%)	Metal grade in "bio-ore."	Plant species, bioavailability, symbiosis, substrate type	Trials + reviews	Grade alone is misleading if yield is low; some studies mix root + shoot
Metal yield (kg metal/ha·yr)	Core performance metric (grade × biomass)	Above two metrics, harvest frequency	Trials; case studies	Frequently missing; prevents scale comparisons
Recovery rate to product (%)	Conversion from biomass/ash to metal or salt	Ash chemistry, route (hydro/pyro/hybrid), losses	Process-focused studies; conceptual flowsheets	Reported selectively (lab-step only), not "soil-to-product"
Reagent consumption (kg reagent/kg metal or per t biomass)	Operating intensity and cost proxy	Leaching chemistry, impurity load, solid/liquid ratio	Mostly lab studies	Often not normalized; excludes neutralization/effluent treatment
Energy demand (kWh/t biomass or kWh/kg metal)	Thermal + electrical inputs for drying/ashing/recovery	Moisture content, ashing route, pyro vs hydro	TEA/engineering papers	Boundaries differ; biomass drying frequently omitted

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CAPEX class (qualitative or USD order-of-magnitude)	Capital intensity of recovery chain	Need for furnaces, SX/IX units, gas cleaning	Mostly conceptual TEA	Many papers lack basis year, scaling rule, or equipment list
OPEX class (USD/kg metal or USD/ha·yr)	Operating cost per product or per area	Reagents, energy, logistics, labor	TEA case studies	Hidden assumptions about labor rates and local prices
Net revenue / margin (USD/ha·yr or USD/kg metal)	Economic viability signal	Metal price, yield, coproducts, remediation credits	Few TEA studies	Price volatility rarely treated; policy credits often speculative
GHG footprint (kg CO_2-eq per kg metal or per ha·yr)	Climate impact	Energy mix, thermal steps, transport distance	LCA-oriented studies	Functional unit varies; remediation co-benefits inconsistently allocated
Water footprint (m^3/ha·yr or m^3/kg metal)	Water stress relevance	Irrigation requirement, leach washing	Limited reporting	Frequently ignored or underreported in greenhouse studies
Ecotoxicity / risk reduction (qualitative or index-based)	Benefit from removing contaminants	Site contamination, uptake selectivity	Case studies; NbS framing	Often claimed without mass balance of removed vs remaining metals
Soil quality indicators (pH, OM, CEC, nutrients)	Agronomic sustainability and restoration	Amendments, microbial inoculation, crop rotation	Trials; remediation studies	Improvements may be amendment-driven rather than phytomining-driven
Social acceptance / governance (qualitative)	Deployment feasibility	Land use, community perception, regulation	Few social-science studies	Usually anecdotal; limited structured stakeholder methodology

Beyond its role as a metal recovery strategy, phytomining has attracted growing attention as a multifunctional approach that integrates resource extraction with environmental remediation and circular economy principles. By linking soil decontamination, biomass valorization, and secondary metal production, phytomining offers a pathway to simultaneously address critical raw material supply risks and legacy contamination from mining and industrial activities. Figure 9 conceptually illustrates this integrative role, positioning phytomining at the interface of circular resource flows and ecosystem restoration (Ribeiro, 2022).

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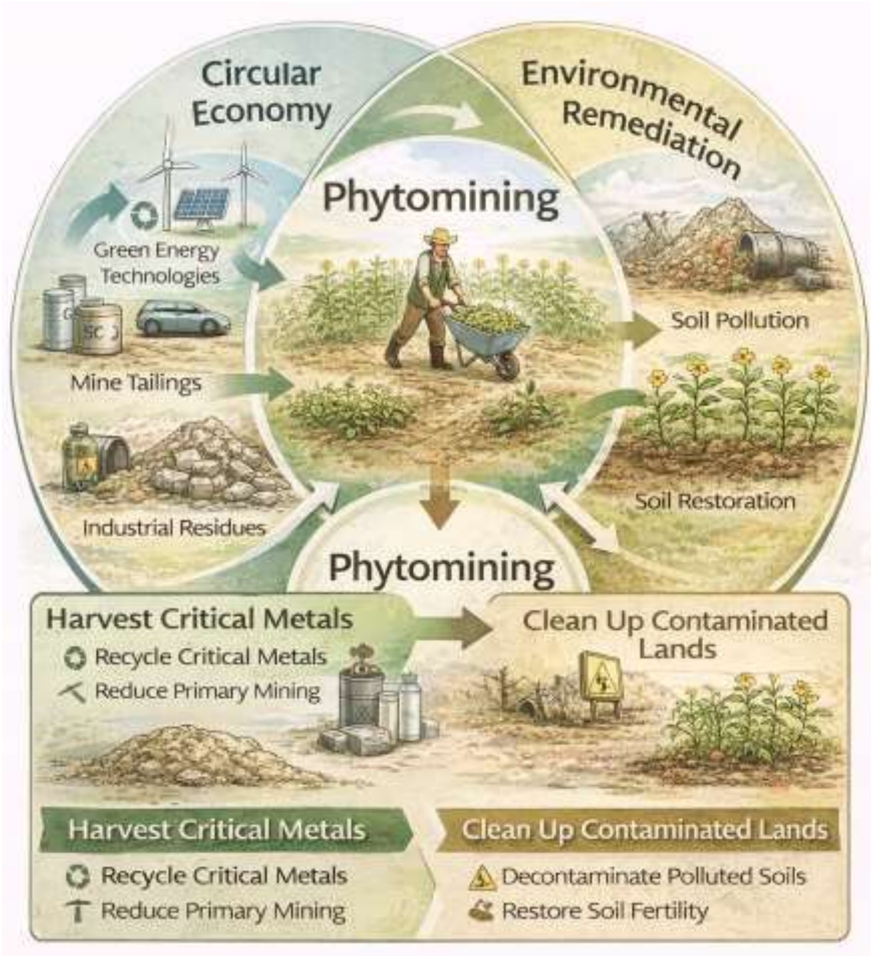

Figure 9. Conceptual integration of phytomining within circular economy and environmental remediation frameworks. Adapted from Chaney et al. (2020); Li et al. (2020); Dinh et al. (2025); Rabbani et al. (2024, 2025); Struhs and Mirkouei (2024); Richardson et al. (2025).

While aggregated assessments provide valuable insights into feasibility and sustainability, real-world performance is highly context-dependent. Therefore, Section 9 examines case studies from 2020 to 2025, highlighting how local geology, plant selection, agronomic management, and processing routes shape phytomining outcomes in practice. (Kurniawan et al., 2021)

9. CASE STUDIES (2020–2025)

Case studies published between 2020 and 2025 provide critical insight into how phytomining performs under **realistic environmental, agronomic, and socio-economic conditions**. Unlike laboratory or greenhouse experiments, these studies expose the strong dependence of outcomes on local geology, climate, substrate chemistry, plant adaptation, and downstream processing constraints.

9.1. Ultramafic and serpentine-hosted systems (Nickel-dominated)

Nickel phytomining remains the most mature application, with multiple field studies conducted in ultramafic and serpentine soils. Case studies from Sri Lanka, Iran, the Mediterranean region, and South America consistently report high Ni accumulation in Odontarrhena and Alyssum species, confirming the robustness of these systems (Dilshara et al., 2023, 2024; Ghafoori et al., 2022). However, yield variability across sites highlights sensitivity to soil Mg/Ca ratios, organic amendments, and fertilization regimes, even within similar lithological settings.

9.2. Gold phytomining in tailings and contaminated soils

Gold-focused case studies primarily examine legacy tailings and amalgamation residues, especially in Southeast Asia and Africa. Field-scale trials with sweet potato, Pteris vittata, and Alocasia macrorrhizos show that Au recovery is technically feasible but constrained by low bioavailability and slow uptake kinetics (Noviardi et al., 2021, 2024; Saim et al., 2020). These studies consistently conclude that gold phytomining is best framed as a remediation-driven strategy, with metal recovery as a secondary benefit rather than the primary economic driver.

9.3. Rare earth elements from soils and residues

Recent case studies in the United States and Europe mark a significant advance in REE phytomining. Investigations in Idaho demonstrate measurable accumulation of light and heavy REEs in native plants grown on surface soils, supported by detailed biomass and ash characterization (Richardson et al., 2024, 2025a,b). Complementary studies of reclaimed tailings and contaminated biomass ashes indicate that REE phytomining is technically viable but critically dependent on post-harvest concentration and recovery technologies, underscoring the importance of downstream integration.

9.4. Red mud and industrial residue-based systems

Case studies of red mud amended with organic matter, sludge, or acid mine drainage demonstrate phytomining's potential for industrial residue valorization. Scandium, vanadium, and chromium uptake by grasses and tolerant plant species has been shown under semi-controlled conditions (Akmal et al., 2025; Tangahu et al., 2025; Praja et al., 2025). These systems benefit from high metal inventories but face challenges with alkalinity control, biomass productivity, and ash handling.

9.5. Socio-environmental and techno-economic perspectives

Beyond technical metrics, many case studies highlight the importance of community engagement, land-use planning, and environmental benefits, especially in urban or post-mining areas (Bani et al., 2024; al-Rawashdeh et al., n.d.). These studies stress that social acceptance, regulatory compatibility, and integration with current land management systems are crucial for sustained implementation.

Table 6 presents the diversity of phytomining case studies reported from 2020 to 2025, ranging from controlled experiments to field-scale trials. Nickel remains the most mature target metal, with multiple demonstrations under realistic agronomic conditions, whereas applications involving precious metals, rare earth elements, and scandium remain largely at the pilot or proof-of-concept stage. Collectively, these case studies highlight both the technical promise and the persistent scalability challenges of phytomining systems.

Table 6. Overview of representative phytomining case studies (2020–2025), including target metal, substrate, plant species, and key outcomes. Adapted from Chaney et al. (2020); Heilmeier (2021); Dinh et al. (2022a,b; 2025); Tognacchini et al. (2020); Wang et al. (2020); Richardson et al. (2025); Rabbani et al. (2024, 2025); Tangahu et al. (2025).

Target metal(s)	Substrate type	Plant species	Geographic context	Key outcomes
Ni	Ultramafic soil (serpentinite)	*Odontarrhena* spp.	Europe (Mediterranean, Balkans)	Shoot Ni concentrations >1–2 wt%; demonstrated agronomic feasibility and repeated harvest cycles
Ni	Serpentine mine soil	*Alyssum murale*	Albania	Field-scale validation; stable biomass yields and economic break-even under favorable Ni prices
Ni	Galvanic sludge (industrial residue)	*Odontarrhena chalcidica*	Germany	Successful growth on secondary waste; high Ni accumulation and reduced soil toxicity
Au	Gold mine tailings	*Ipomoea batatas*	Indonesia	Enhanced Au uptake with organic amendments; potential for low-cost tailings valorization

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Au	Contaminated alluvial soil	*Alocasia macrorrhizos*	Southeast Asia	Demonstrated phytoextraction of Au with cyanogenic biomass; proof-of-concept for precious metals
PGMs (Pd, Ru)	Metal-contaminated soil	*Chrysopogon zizanioides* (vetiver)	Southern Africa	Moderate PGM uptake; integration with catalytic recovery routes explored
REEs	Reclaimed tailings pond	Native grasses and herbs	Eastern Europe	Preferential accumulation of light REEs; highlighted challenges in selective recovery
REEs	Surface soil (low-grade)	Mixed hyperaccumulator assemblage	USA (Idaho)	Demonstrated feasibility of REE phytoextraction from natural soils; low but scalable yields
Sc	Red mud (bauxite residue)	*Portulaca grandiflora*	Indonesia	Sc uptake enhanced by organic amendments; promising route for critical metal recovery
V, Cr	Red mud amended with manure	*Cymbopogon citratus*	Indonesia	Simultaneous uptake of V and Cr; improved plant tolerance with sludge-based amendments
Cu	Mine tailings	Tomato (*Solanum lycopersicum*)	Europe	Limited Cu accumulation; highlighted constraints for non-hyperaccumulator crops
Multi-metals (Ni, Co, Zn)	Mixed mine wastes	Native pioneer species	Africa	Demonstrated remediation–recovery synergy; strong dependence on soil chemistry and amendments

To contextualize the diversity and geographic dispersion of recent phytomining applications, the spatial distribution of reported case studies published from 2020 to 2025 is summarized in Figure 10. This visualization highlights both the global reach of phytomining research and the regional specialization associated with specific target metals and substrates.

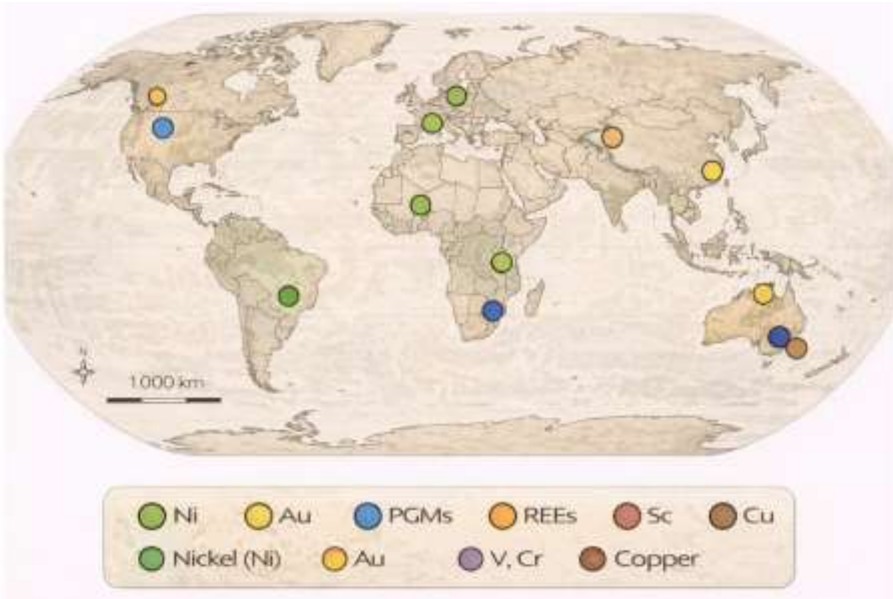

Figure 10. Geographic distribution and dominant target metals of reported phytomining case studies. Adapted from: Chaney et al. (2020); Wang et al. (2020); Dinh et al. (2022a,b); Richardson et al. (2025a,b); Akmal et al. (2025); Rabbani et al. (2024, 2025); Hakim et al. (2024, 2025).

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As shown in Figure 10, phytomining research shows clear geographic clustering driven by geological context and metal demand. Nickel remains the most extensively studied target metal, particularly in regions with ultramafic or serpentinized substrates, whereas gold and PGMs are primarily explored in legacy mine tailings and contaminated soils. In contrast, rare earth elements and scandium are emerging targets, often linked to industrial residues such as red mud, reflecting a growing alignment among phytomining, circular economy strategies, and critical raw material recovery.

Although these case studies demonstrate that phytomining can operate across diverse settings, they also reveal systematic limitations and inconsistencies that impede scalability and comparability. Consequently, Section 10 synthesizes the key knowledge gaps and research needs, focusing on standardization, process integration, and pathways to industrial relevance.

10. KEY KNOWLEDGE GAPS AND RESEARCH NEEDS

Despite the significant expansion of phytomining research between 2020 and 2025, the literature reveals persistent structural and methodological gaps that impede the translation of experimental studies into scalable technologies. These gaps persist across target metals, substrates, and geographic contexts, indicating that the main barriers are systemic rather than site-specific.

10.1. Lack of standardized performance metrics

One of the most critical gaps is the lack of standardized metrics for reporting phytomining performance. Studies often report metal concentrations in plant tissues (mg kg^{-1}) without consistently reporting biomass productivity, metal yield per unit area, or cycle-based recovery efficiency. This prevents meaningful comparisons between systems and obscures the true techno-economic relevance of reported results (Akinbile & Makhubela, 2023; Dang & Li, 2022). Future work should adopt harmonized indicators such as kg metal ha^{-1} yr^{-1}, ash-grade-normalized recovery, and recovery per agronomic cycle (Bani et al., 2024).

10.2. Limited integration between agronomy and metallurgy

Most studies treat plant cultivation and metal recovery as separate domains, with limited feedback between agronomic optimization and downstream processing requirements. However, ash composition, mineral speciation, and impurity loads directly govern metallurgical recoverability, particularly for REEs and PGMs (Dinh et al., 2022a, 2022b). Research must shift toward co-designing agronomic and metallurgical stages rather than optimizing them independently.

10.3. Insufficient field-scale and long-term data

Although field trials have increased, long-term, multi-cycle datasets remain scarce. Seasonal variability, soil depletion, and cumulative changes in substrate chemistry are rarely quantified beyond one or two growing seasons (Wang et al., 2020). This limits confidence in yield stability, land-use planning, and life-cycle assessments. Longitudinal studies spanning multiple years are essential to validate phytomining as a persistent land-use strategy.

10.4. Unresolved challenges in biomass processing

Biomass handling, drying, combustion, and ash management remain underexplored relative to plant uptake studies. Energy demand, volatilization losses, and trace-element redistribution during thermal treatment are often assumed rather than measured (Phi et al., 2023). This gap is particularly critical for volatile or redox-sensitive metals, underscoring the need for integrated mass and energy balances.

10.5. Socio-economic and regulatory uncertainties

Although phytomining is often framed as a nature-based or circular-economy solution, few studies rigorously examine regulatory pathways, land tenure, or community acceptance. Case studies show that social factors can be decisive, particularly in post-mining or urban settings (Bani et al., 2024; al-Rawashdeh et al., n.d.). Interdisciplinary research that integrates policy and governance dimensions remains limited.

Addressing these gaps requires moving beyond proof-of-concept demonstrations toward integrated, system-level innovation. Therefore, Section 11 discusses future perspectives, highlighting technological advances, hybrid process concepts, and strategic research directions that can advance phytomining from an experimental remediation tool to a complementary resource-recovery pathway.

11. FUTURE PERSPECTIVES

Looking beyond the current state of the art, the future of phytomining depends on its ability to evolve from a niche, site-specific technique into a robust, integrated resource-recovery strategy. Between 2020 and 2025, research has laid a solid conceptual foundation, but the next phase must focus on system optimization, technological integration, and strategic positioning within broader mineral supply chains.

11.1. Integration with hybrid extraction pathways

Future phytomining systems are likely to operate as hybrid platforms, combining biological accumulation with advanced thermal, hydrometallurgical, or electrochemical recovery methods. Recent work on rapid thermal activation of phytomining biomass and selective leaching of ashes shows that process intensification can significantly improve metal recovery efficiency, particularly for REEs and PGMs. Coupling phytomining with bioleaching, mechanochemical activation, or electrothermal treatments is a promising approach to overcoming current metallurgical bottlenecks.

11.2. Expansion toward critical and strategic metals

While nickel and gold remain the most mature targets, future research is expected to expand to critical and strategic metals, including REEs, scandium, vanadium, and selected platinum-group elements. These metals often occur at low concentrations in soils, tailings, and industrial residues yet have high economic leverage. Advances in plant selection, rhizosphere engineering, and biomass processing may enable phytomining to contribute meaningfully to diversified supply portfolios, particularly for low-grade or dispersed resources.

11.3. Digital tools and data-driven optimization

The application of **data-driven approaches** represents an emerging frontier. Machine learning, geospatial analysis, and digital soil–plant modeling can support site screening, crop selection, and yield prediction at early project stages. Integrating these tools with life-cycle assessment and techno-economic modeling will allow rapid scenario evaluation and risk reduction before field deployment.

11.4. Alignment with circular economy and land restoration strategies

Phytomining is increasingly positioned at the intersection of resource recovery, land remediation, and ecosystem restoration. Future implementations are likely to prioritize multi-functionality, combining metal recovery with soil stabilization, biodiversity enhancement, and post-mining land reuse. This alignment strengthens the social license for phytomining projects and improves their compatibility with environmental policy frameworks.

11.5. From experimental pilots to decision-support systems

Rather than competing directly with conventional mining, the future of phytomining lies in its role as a complementary, low-impact option. The transition from experimental pilots to deployable solutions will require decision-support frameworks that integrate agronomic performance, metallurgical recovery, environmental impacts, and socioeconomic constraints into unified design criteria.

Considering these future directions, Section 12 consolidates the key findings of this critical review, highlighting the current technological status, limitations, and realistic potential of phytomining as an emerging sustainable metal recovery pathway.

12. FUTURE PERSPECTIVES

The future development of phytomining will depend on its ability to transition from isolated experimental studies to integrated, system-oriented resource recovery strategies. Research published between 2020 and 2025 indicates that phytomining is unlikely to replace conventional mining but may play a complementary role in specific niches defined by low-grade resources, environmental constraints, and land restoration needs (Chaney et al., 2020; Akinbile & Makhubela, 2023).

12.1. Integration with hybrid extraction pathways

A key future direction is integrating phytomining with hybrid extraction routes that combine biological uptake with intensified downstream processing. Recent studies show that thermal activation, selective leaching, and electrothermal treatments of phytomining biomass or ash can significantly enhance metal recovery, particularly for rare earth elements and platinum-group metals (Dinh et al., 2022a, 2022b; Deng et al., 2025). Such hybridization mitigates the limitations of low metal grades in biomass and improves overall process efficiency.

12.2. Expansion toward critical and strategic metals

While nickel and gold remain the most mature targets, future research is clearly shifting toward critical and strategic metals, including rare earth elements, scandium, vanadium, and selected PGMs. These elements are increasingly linked to energy transition technologies and pose significant supply risks, thereby enhancing the strategic relevance of phytomining despite its modest yields (Rabbani et al., 2024; Dilhara et al., 2024). Progress in plant selection, rhizosphere engineering, and amendment strategies is expected to broaden the feasible metal portfolio.

12.3. Digital tools and data-driven optimization

The application of data-driven and digital tools presents an emerging opportunity for phytomining development. Geospatial analysis, machine learning, and predictive soil–plant models can support early-stage site screening, crop selection, and yield forecasting, thereby reducing experimental uncertainty and development costs (Li et al., 2020; Wang et al., 2020). Integrating these tools with techno-economic and life-cycle assessment frameworks remains an important research frontier.

12.4. Alignment with circular economy and land restoration strategies

Phytomining is increasingly framed within circular-economy and nature-based-solution paradigms, particularly in post-mining areas, contaminated soils, and industrial residues. Studies show that integrating metal recovery with soil remediation, biomass valorization, and ecological restoration improves both environmental performance and social acceptance (Bani et al., 2024; Rabbani et al., 2025). This multifunctional positioning may become a defining feature of future phytomining projects.

12.5. From experimental pilots to decision-support frameworks

Rather than scaling through replication of pilot trials alone, future progress will require decision-support systems that integrate agronomic performance, biomass processing, metallurgical recovery, environmental impacts, and socioeconomic constraints. Several authors highlight the need for unified design criteria and standardized evaluation frameworks to guide investment and policy decisions (Dang & Li, 2022; Akinbile & Mbohwa, 2025).

Based on these forward-looking insights, Section 13 consolidates the main conclusions of this critical review, synthesizing the technological maturity, limitations, and the realistic role of phytomining in sustainable metal supply chains.

13. CONCLUSIONS

This critical review assessed phytomining developments published between 2020 and 2025, covering the entire value chain from plant uptake through biomass processing, metal recovery, and system-level evaluation. The analysis confirms that phytomining is technically feasible yet strongly context-dependent, best positioned as a complementary option rather than a replacement for conventional mining.

Among target metals, nickel and gold have the most mature applications, supported by field trials and agronomic optimization. In contrast, rare earth elements, scandium, and platinum-group metals remain at an early stage of development and are more sensitive to inefficiencies in biomass processing and ash metallurgy. These differences highlight that phytomining performance is governed not only by biological accumulation but also by biomass yield, ash chemistry, and downstream process selectivity.

A central conclusion of this review is that the primary bottleneck in phytomining lies beyond phytoextraction, in biomass handling, thermal treatment, and metal recovery from ash. Energy demand, volatilization losses, impurity enrichment, and variable ash mineralogy often dominate overall feasibility. Studies that explicitly integrate agronomic and metallurgical considerations consistently report more realistic recovery projections and greater system coherence.

From an environmental perspective, phytomining aligns with circular-economy and nature-based-solution frameworks, particularly for post-mining landscapes, contaminated soils, and industrial residues. Its multifunctional character—combining metal recovery, soil remediation, and land rehabilitation—represents a key advantage over single-purpose technologies. However, the lack of standardized performance metrics, long-term field data, and harmonized techno-economic assessments continues to constrain scalability and comparability.

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Overall, phytomining should be viewed as a strategic niche technology rather than a universal solution. Its future relevance will depend on integrated system design, realistic benchmarking, and coupling with efficient recovery routes. When evaluated holistically and deployed under appropriate boundary conditions, phytomining can contribute meaningfully to diversified, resilient, and lower-impact metal supply chains.

Author Contributions

The author conceptualized the study, designed the methodology, performed the literature search and screening, curated the data, wrote and revised the manuscript, and prepared the figures.

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Data Availability Statement

No new data were created or analyzed in this study. All data supporting the findings of this review are available within the article and its referenced literature.

Conflict of Interest

The author declares that there are no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Novelty Statement

This review offers a critical, up-to-date assessment of phytomining research published from 2020 to 2025, integrating plant uptake mechanisms, biomass processing routes, and downstream metallurgical constraints into a unified analytical framework. Unlike previous reviews, this study explicitly evaluates scalability limitations and techno-industrial bottlenecks that impede commercial implementation. The work advances the field by positioning phytomining as a complementary metal recovery strategy rather than a standalone industrial solution.

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