RECENT ADVANCES IN AN EMERGING GREEN TECHNOLOGY : NICKEL PHYTOMINING

Phytomining is an emerging green technology that exploits certain plants called hyperaccumulators to extract valuable metals from soil and concentrate them into plant biomass, which is valuable for renewable energy feedstocks. This paper provides a comprehensive review of nickel (Ni) phytomining, including the biological mechanisms of Ni uptake and accumulation in hyperaccumulator plants, recent technological advances to enhance metal yield and biomass processing, as well as the key challenges and prospects of Ni phytomining. Hyperaccumulator species possess unique physiological adaptations that enable them to absorb Ni in extraordinarily high concentrations without toxic effects, involving specialized root transporters, efficient root-to-shoot translocation, and sequestration into leaf cell vacuoles.

Advances in phytomining technology, such as improved plant breeding, genetic engineering of metal transport and tolerance traits, and innovations in biomass processing (e.g., pyrolysis, bioleaching, and electrochemical recovery), are boosting the feasibility of this approach for commercial Ni production. This article discusses how these innovations address current limitations like low biomass, variable metal uptake rates, and economic viability. The environmental and economic challenges of this process are also addressed, from site selection and cultivation constraints to market fluctuations. Overall, Ni phytomining represents a sustainable alternative or supplement to conventional mining, with high potential for environmentally friendly metal extraction and land remediation. Continued research into plant genetics, soil management, and processing techniques will be crucial to unlock the full commercial potential of Ni phytomining in the coming decades.

Introduction

The global demand for battery-grade nickel is soaring and expected to triple by 2030, according to Benchmark Mineral Intelligence (2023). Meanwhile, many high-grade nickel ore reserves are gradually being depleted due to intensive extraction processes and growing consumption rates. To preserve existing nickel reserves, the process of recovering metals from alternative resources has gained significant interest. One such approach is phytomining, also known as agromining, which is an innovative and environmentally friendly process that uses plants to extract valuable metals from soil or waste materials. In phytomining, specific plants known as hyperaccumulators absorb and concentrate metals from the soil into their biomass. These plants naturally extract metal ions through their roots and transport them to shoots and leaves, where metals are stored at concentrations far higher than those found in ordinary plants. Phytomining efforts have primarily focused on metals such as nickel (Ni), cobalt (Co), zinc (Zn), gold (Au), thallium (Tl), and certain rare earth elements (REEs), because viable hyperaccumulator species are known for these elements. For example, Alyssum murale is a well-studied Ni hyperaccumulator that can tolerate and uptake large amounts of nickel; Berkheya coddii is known for accumulating cobalt (as well as nickel) in its tissues; and Arabidopsis halleri is a model Zn-hyperaccumulator often found in metal-rich soils. These hyperaccumulators and many others provide the biological foundation for phytomining, as their biomass is highly enriched in target metals ripe for harvesting and processing. In the following sections, this paper explores the physiological mechanisms that enable hyperaccumulator plants to take up and sequester nickel, highlights recent advances in phytomining technology and biomass processing that improve metal yield, discusses the challenges that currently limit large-scale nickel phytomining, and considers prospects for this novel approach to metal extraction.

Mechanisms of Nickel Uptake and Accumulation in Hyperaccumulators

Root Uptake of Nickel: Hyperaccumulator plants have evolved specialized mechanisms to efficiently absorb nickel from the soil. In Ni-rich soils like ultramafic or serpentine soils, soluble Ni is present mostly as divalent cations (Ni^{2+}). Hyperaccumulator roots absorb Ni^{2+} from the rhizosphere through membrane transport proteins with a high affinity for metal ions. Many belong to the ZIP family (Zrt- and Irt-like Proteins) of transporters, which in normal plants mediate the uptake of essential micronutrients like iron (Fe^{2+}) and zinc (Zn^{2+}). In hyperaccumulators, these transporters may be expressed at high levels constitutively or strongly induced by metal exposure, leading to enhanced Ni influx across root cell membranes (van der Pas & Ingle, 2019). Nickel exposure can trigger molecular responses similar to iron deficiency in some plants, upregulating genes like IRT1 that then shuttle Ni into root cells. The chemical form of Ni in soil also influences uptake. Hyperaccumulators tend to absorb free Ni^{2+} ions; if nickel is strongly chelated in soil solution by agents like EDTA, DTPA, or other ligands, Ni uptake can decrease despite higher Ni availability. This behavior suggests that root transporters favor ionic Ni^{2+}, and excessive chelation can render the nickel unavailable for uptake. Once Ni^{2+} crosses the root epidermis and cortex, some fraction may be immobilized or detoxified in root cells, but hyperaccumulators have adaptations to limit such sequestration in roots (e.g. by minimizing binding to root cell walls or vacuoles) so that most of the absorbed Ni can be translocated upwards (Verbruggen et al., 2009).

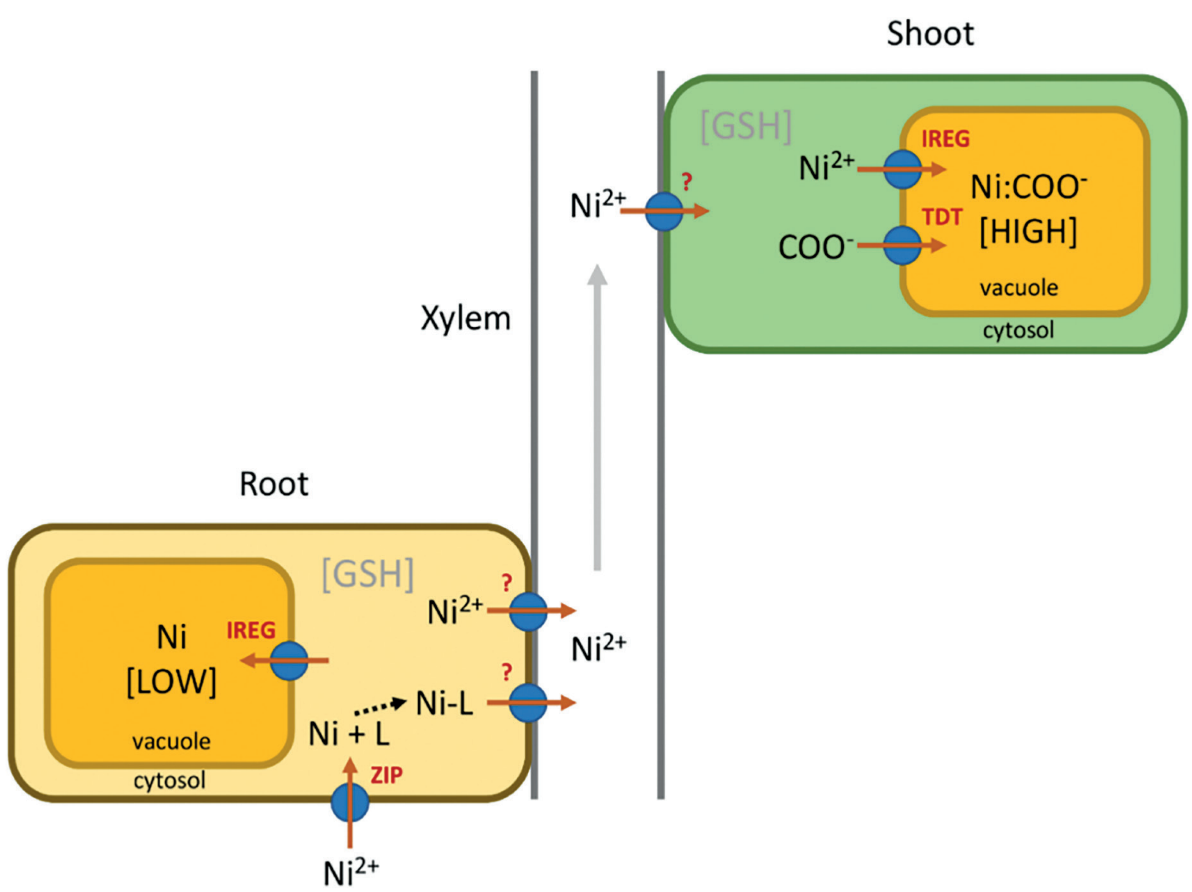

Figure 1. A schematic model of nickel hyperaccumulation in a plant. Nickel ions (Ni^{2+}) are absorbed from the soil by roots via metal transport proteins (e.g., ZIP transporters like IRT1). In root cells, Ni^2+ may bind to organic ligands such as histidine (His) or organic acids, forming Ni-ligand complexes that facilitate movement. Rather than being stored in roots, Ni is loaded into the xylem (as free Ni^2+ or Ni-ligand complex) and translocated to shoots. In leaves, Ni accumulates primarily in epidermal cells and is sequestrated in vacuoles, often as Ni-organic acid complexes (e.g., Ni-citrate), to prevent toxicity (adapted from van der Pas & Ingle, 2019).

Root-to-Shoot Translocation: After nickel enters the root symplasm, it must travel to the shoots. Efficient xylem loading and translocation are hallmark features of metal hyperaccumulators (Verbruggen et al., 2009). In hyperaccumulator species, Ni is quickly chelated by organic ligands in the root cytosol to prevent toxicity and facilitate transport. Common chelators for Ni include organic acids and amino acids like histidine and citrate, which form stable complexes with Ni in the xylem sap of Ni hyperaccumulators (Kozhevnikova et al., 2014). The formation of a Ni–ligand complex (Ni-L) in roots may also keep Ni in a form that can be loaded into the xylem rather than trapped in root vacuoles. Xylem loading of Ni likely involves specific transporter proteins, possibly cation exporters or antiporters, though the exact molecular identity of the Ni xylem loading transporters is still under investigation (van der Pas & Ingle, 2019). Evidence suggests that a majority of Ni travels in the xylem sap as free Ni^{2+}_ ions or loosely bound complexes, which differs from other metals that move primarily as chelates. The movement of Ni from roots to shoots is driven by the transpiration stream. Hyperaccumulators often exhibit high transpiration rates, which can enhance the mass flow of Ni to above-ground tissues (Bani et al., 2015). Translocation efficiency is often quantified by the translocation factor (TF), the ratio of metal concentration in shoots to that in roots. Ni hyperaccumulators typically demonstrate TF >> 1, whereas non-accumulators usually exhibit TF < 1 for Ni. This difference indicates a pronounced ability in hyperaccumulators to preferentially transport Ni to the shoot. Conversely, transporters like IREG2 (Iron Regulated transporter 2, a ferroportin family protein) can sequester metals into root cell vacuoles in non-accumulators, thereby limiting translocation; interestingly, the expression of such transporters is often reduced or their activity circumvented in Ni hyperaccumulators (Nishida et al., 2020). By minimizing Ni retention in roots, hyperaccumulators channel a large fraction of absorbed Ni into the xylem and onward to the shoots.

Nickel Sequestration and Detoxification in Shoots: Once delivered to the shoots, nickel must be safely stored in cells to avoid phytotoxicity. Hyperaccumulators store Ni primarily in the leaves, compartmentalizing it in vacuoles or binding it to cell wall compounds to isolate it from sensitive cellular machinery in the cytoplasm. Vacuolar sequestration is a key detoxification strategy: specific tonoplast (vacuolar membrane) transporters actively import Ni from the cytosol into the vacuole. Studies using techniques like X-ray fluorescence microscopy have confirmed that in Ni-hyperaccumulator species, most of the nickel in leaf tissue is localized to vacuoles and cell walls of epidermal cells (Mustafa et al., 2023). Organic acids, particularly citrate and malate, play a major role in Ni storage by complexing with Ni inside the vacuole to reduce reactivity and limit metabolic interference. The presence of high concentrations of citrate in shoots correlates with high Ni accumulation, supporting its role in internal detoxification (Leitenmaier & Küpper, 2013). Additionally, peptides like phytochelatins or metallothioneins can bind metals, but they are not thought to be the primary Ni binding ligands in most Ni hyperaccumulators (van der Ent et al., 2013). Instead, an amino acid known as histidine has demonstrably facilitated Ni tolerance and loading into the xylem in some Ni hyperaccumulators (Kozhevnikova et al., 2014). Recent research efforts also point to a constitutively high expression of certain metal transport genes in hyperaccumulator shoots. For example, members of the Metal Tolerance Protein (MTP) family and other tonoplast transporters are upregulated in hyperaccumulator leaves, aiding in vacuolar Ni sequestration (García de la Torre et al., 2021). This coordinated network of transporters and ligands ensures that Ni arriving in the shoot is quickly chelated and locked into compartments, as shown in Figure 1.

Physiological Adaptations for Hyperaccumulation: Several unique physiological traits distinguish Ni hyperaccumulators from ordinary plants. First, hyperaccumulators often have a higher tolerance to Ni in their tissues – they can withstand leaf Ni concentrations on the order of 1–3% of dry weight (10,000–30,000 µg/g), whereas most plants would suffer severe toxicity at just a few hundred µg/g of Ni (van der Ent et al., 2013). This tolerance requires robust detoxification and repair systems, developing into an enhanced production of antioxidants and stress-related enzymes. Hyperaccumulators typically exhibit elevated activity of antioxidant enzymes like superoxide dismutase (SOD), catalase (CAT), and peroxidases, which mitigate oxidative stress caused by excess metal (Boominathan & Doran, 2002). The high Ni burden can induce reactive oxygen species (ROS) in plant cells, but hyperaccumulators counteract this reaction with a fortified antioxidant network, preventing cellular damage (Soleymanifar et al., 2023). These plants may also accumulate higher basal levels of glutathione and other antioxidants (van der Pas & Ingle, 2019), and certain secondary metabolites (e.g., flavonoids) that can chelate metals or scavenge ROS. Another adaptation is the metal's role in plant defense, as the accumulated Ni makes the foliage toxic and deters herbivores and pathogens (Boyd, 2012). This "elemental defense" hypothesis posits that hyperaccumulation could confer an ecological advantage by poisoning harmful insects or inhibiting fungal growth(Boyd, 2012). This boon may explain why natural selection favored hyperaccumulation in certain environments.

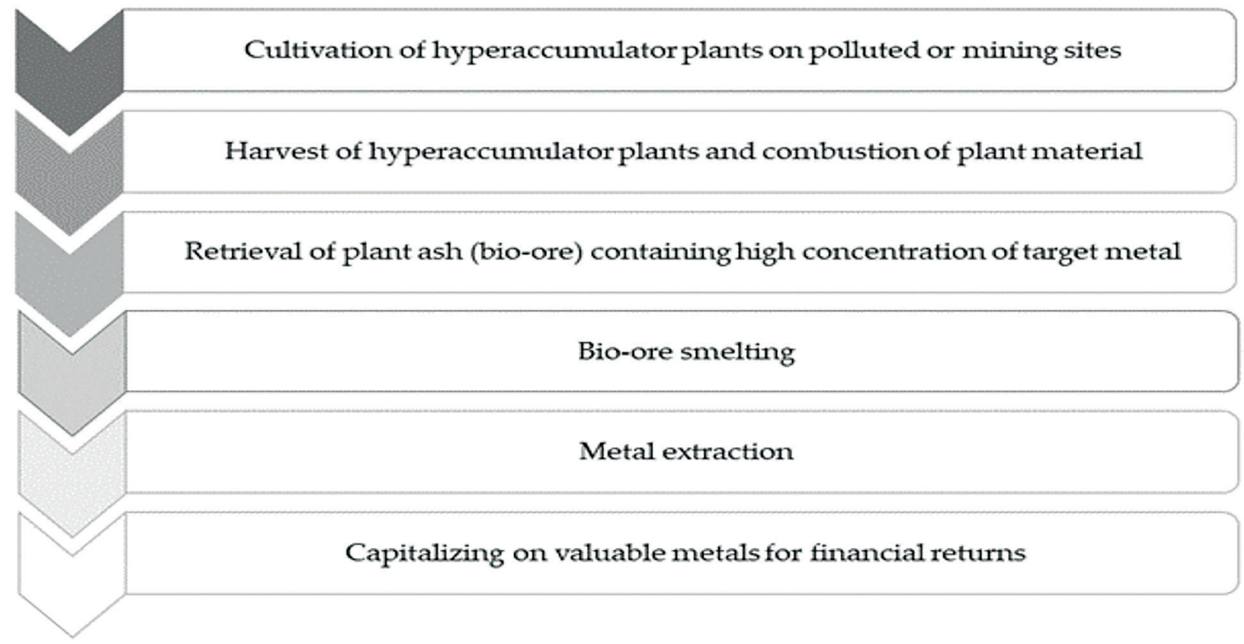

Figure 2. Strategies to enhance phytomining through biotechnology. Top: Genetic engineering involves introducing or modifying genes to create transgenic plants with enhanced metal uptake or tolerance. Bottom left: Microbe-assisted phytomining uses symbiotic microbes (AM = arbuscular mycorrhizae, PGPR = plant growth-promoting rhizobacteria) to improve metal availability and plant health. Bottom right: Chelate-assisted phytomining involves adding chelating agents (e.g., citric acid, EDTA) to mobilize metals (forming metal-chelate complexes) for easier uptake by roots. (Zhang et al., 2020, Frontiers in Plant Science).

Influence of Soil Chemistry and Microbes: The efficiency of Ni uptake is also influenced by soil properties and biota. Soil pH is a crucial factor. In acidic soils, Ni^{2+} is more soluble and available to plants, whereas in neutral to alkaline soils, Ni may precipitate or sorb onto soil particles, reducing availability (Zhong et al., 2020). Hyperaccumulators often thrive on mildly acidic soils that keep Ni mobile. Organic matter in soil can form complexes with Ni; humic substances might either facilitate Ni uptake by keeping it soluble or, conversely, strongly bind Ni and limit availability depending on the ligand chemistry (Park et al., 2011). Thus, the presence of natural chelators in the soil can modulate the amount of accessible Ni. Moreover, beneficial soil microbes significantly aid hyperaccumulators. Certain plant growth-promoting rhizobacteria (PGPR) can increase metal availability and assist plant uptake. These bacteria often produce siderophores, which are organic compounds that chelate metal ions. While they typically aid in iron acquisition, siderophores can also bind Ni and keep it in soluble forms for plant roots to absorb (Rajkumar et al., 2010). Inoculating hyperaccumulator roots with siderophore-producing bacteria has been shown to enhance Ni accumulation. For example, Pseudomonas strains isolated from serpentine soils can boost Ni uptake by increasing Ni solubility in soil and possibly affecting root physiology (Visioli et al., 2015). Likewise, arbuscular mycorrhizal fungi (AMF) form symbiotic associations with many hyperaccumulators and can improve plant growth under metal stress (Orłowska et al., 2011). Although AMF themselves do not hyperaccumulate Ni, they improve nutrient uptake and water acquisition, which can indirectly boost heavy metal capacity. In one study, Berkheya coddii (a Ni hyperaccumulator) colonized by AMF grew larger and accumulated slightly more Ni than non-mycorrhizal controls, due to better overall vigor (Orłowska et al., 2011). The combined effect of microbes can be substantial. with experiments reporting that adding a consortium of Ni-mobilizing bacteria to Ni-rich soil increased uptake in Alyssum species by 30–40 percent (Rajkumar et al., 2010; Visioli et al., 2015). These findings highlight that the plant's genetics and physiology work in tandem with soil chemistry and microbiology to achieve hyperaccumulation. Harnessing such interactions is a viable way to improve phytomining yield.

Advances in Phytomining Technologies and Biomass Processing

Hyperaccumulator Plant Selection and Breeding

Selecting the right plant species is a critical first step for successful nickel phytomining. Decades of field surveys have identified over 500 Ni-hyperaccumulator plant species worldwide (van der Ent et al., 2013). Among these species, a few standouts have been extensively studied for their exceptional Ni uptake and high biomass. Alyssum murale, also known as Odontarrhena murale, is an exceptional species native to serpentine soils in Europe, as it can accumulate >1% Ni in its shoots and has been trialed in field plantations for Ni phytomining. Agronomic research on A. murale has led to improved cultivation practices, such as optimal fertilization and planting density, that maximize Ni yield per hectare (Bani et al., 2015). Another promising species is Odontarrhena chalcidica, a Ni hyperaccumulator found in the Balkans and Turkey, known for fast growth and high Ni content. In tropical regions, the recently discovered Phyllanthus rufuschaneyi in Borneo has drawn attention for its ability to accumulate large quantities of Ni while producing ample biomass (Bouman et al., 2018). These species, under ideal conditions, can reach shoot Ni concentrations of 1–2% of dry weight and produce several tonnes of biomass per hectare, theoretically yielding upwards of 100 kg Ni per hectare annually (Chaney & Baklanov, 2017). Plant breeding and selection efforts aim to further improve these traits. Natural variability within hyperaccumulator populations is inevitable, as some ecotypes may grow larger or accumulate Ni faster. Through selective breeding or domestication programs, researchers are developing hyperaccumulator cultivars optimized for phytomining (Chaney & Baklanov, 2017). For example, field trials over multiple years with Alyssum have identified lines that consistently give higher Ni output (Bani et al., 2015). Breeding efforts focus on traits like higher biomass production, increased Ni uptake rate, and adaptation to different soil conditions. However, conventional breeding in these often slow-growing wild species is time-consuming. An alternative approach emerging in recent years is synthetic biology and genetic engineering to enhance hyperaccumulator traits.

Genetic Engineering Strategies for Enhanced Phytomining

Modern genetic tools have unlocked new possibilities to boost phytomining efficiency by modifying plant metabolism. One strategy is to transfer or upregulate genes that encode metal transporters or chelators, thereby increasing a plant's capacity to take up or tolerate metals. Researchers have already used model plants such as Arabidopsis thaliana to test genes from hyperaccumulators. For instance, overexpressing Ni transport genes from a hyperaccumulator in a non-accumulator plant can reveal their effects on Ni accumulation. Noccaea caerulescens (formerly known as Thlaspi) is a known hyperaccumulator and has genes like NcZNT1 (a zinc/nickel transporter) and NcNRAMP4 (a metal transporter) that contribute to its high Ni uptake. Fasani et al. (2021) introduced these genes into Arabidopsis thaliana and found that the transgenic plants showed significantly increased Ni accumulation and enhanced root-to-shoot translocation compared to wild-type plants. In hyperaccumulators themselves, exposure to Ni stress naturally elevates the expression of such transporter genes – e.g., NRAMP4 and ZNT1 were upregulated by ~50% under high Ni in N. caerulescens, which is believed to facilitate greater Ni absorption and movement to shoots (Fasani et al., 2021). Another genetic target is improving internal metal chelation. Upregulating enzymes like nicotianamine synthase (NAS), which produces nicotianamine – a strong metal-binding ligand in plants – has been proposed to enhance the capacity of plants to bind and safely shuttle metals in their tissues. Chaney and Baklanov (2017) reported that increasing NAS activity in plants can lead to more Ni being complexed in cytosol and thus more readily transported without harming the plant. Similarly, genes for organic acid synthesis could be boosted to ensure ample citrate or malate is available for vacuolar sequestration of Ni. For tolerance, elevating the expression of antioxidant genes or stress response regulators can help plants cope with the oxidative stress of hyperaccumulation, allowing them to accumulate even more Ni before toxicity sets in (Soleymanifar et al., 2023). Genetic engineering has also been applied to non-hyperaccumulator species to create new "crop hyperaccumulators." For example, fast-growing biomass plants like certain Brassica species or willow have been genetically modified to overexpress metal uptake genes in attempts to make them accumulate greater quantities of Ni or other metals (Ali et al., 2013). While fully converting a normal plant into a hyperaccumulator has proven challenging, some success has been observed in increasing metal uptake two- to three-fold in transgenic lines (Jan et al., 2016). An emerging genome-editing tool, CRISPR/Cas9, provides further opportunities by enabling targeted edits in hyperaccumulator genomes. CRISPR has been used to prune regulatory genes that suppress metal uptake, or to edit promoter regions to drive higher expression of key transporters (Basharat et al., 2018). Such precise breeding tools could yield hyperaccumulator variants with superior performance. Deploying genetically engineered plants in the field raises regulatory and ecological considerations; thus, careful risk assessment is needed (Jan et al., 2016). Nonetheless, as the technology matures, transgenic or gene-edited hyperaccumulators could dramatically improve phytomining yields.

Biomass Processing and Metal Recovery Techniques

After the phytomining crop is grown and harvested, the next challenge is to efficiently recover nickel from the plant biomass. The processing of "bio-ore" (dried hyperaccumulator biomass rich in Ni) can be performed via several methods, each of which holds advantages and drawbacks. The most straightforward method is thermal processing of the biomass to ash. Traditional incineration processes convert organic biomass to an ash residue that contains the metals, concentrating nickel by roughly 10–30 times compared to the raw plant material by burning off most of the carbon, hydrogen, and other volatile components (Chaney & Baklanov, 2017). The resulting ash from Ni hyperaccumulators contains 10–20% Ni by weight, creating a high-grade Ni "bio-ore" that can enter conventional metal refining streams. However, open-air incineration has flaws: it releases CO_2 and other emissions, and loses some metals as particulates or through smoke. To address these issues, pyrolysis has been explored as a cleaner alternative. Pyrolysis heats the biomass in a low-oxygen environment, causing it to decompose into biochar (charcoal), oils, and gases. The biochar retains most of the metal, with pyrolysis at moderate temperatures (450–600°C) recovering Ni nearly as effectively as full incineration while producing significantly lower combustion gas emissions since much of the carbon is fixed in the biochar. The energy content of the volatilized oils/gases can be utilized as well, improving process economics and sustainability. One study showed that pyrolyzing Alyssum biomass yielded a Ni-rich biochar with minimal loss of Ni and reduced volume, simplifying handling and smelting (Chaney & Baklanov, 2017).

Another innovative approach is bioleaching the metal from the biomass. In bioleaching, microbial cultures or their enzymes are used to solubilize metals. For nickel, researchers have tested acidophilic bacteria such as Acidithiobacillus ferrooxidans and Leptospirillum species, which are common in mineral ore bioleaching, to break down ash or even direct biomass and release Ni into solution. Bouman et al. (2018) reported that by inoculating Ni-rich plant ash with such bacteria in an acidic medium, they achieved up to ~85% recovery of Ni in solution within 10 days. The bacteria facilitate the oxidation of Ni compounds and maintain a low pH, thereby dissolving Ni into the leachate. The advantage of bioleaching is that it operates at ambient temperatures and can be relatively low-cost while also avoiding emissions from burning. However, the process requires careful control of environmental and sample conditions to keep the microorganisms active, and scaling up can be complex. Additionally, after leaching, the Ni must be recovered from solution (e.g., by sulfide precipitation or solvent extraction) to obtain a solid nickel product. Ongoing research focuses on optimizing bioleaching conditions for plant-based materials, as factors like silica or calcium presence in ash can affect efficiency (Meng et al., 2022).

A third method is electrochemical metal recovery. In this technique, the biomass or its ash is ashed or dissolved to obtain an ionic nickel solution. Then, using electrolysis, Ni^{2+} ions are plated onto a cathode as metallic nickel. Experimental setups with graphite or steel electrodes have shown Ni recoveries >90% from hyperaccumulator ash solutions under the right voltage and electrolyte conditions (Chaney & Baklanov, 2017). Electro-winning of nickel from bio-ore leachate could eliminate the need for high-temperature smelting, making the process more accessible in remote or low-infrastructure areas. One could envision a field-deployable unit where farmers could burn the harvested biomass in a controlled furnace, leach the ash with a weak acid, and then use electrolysis to plate out pure nickel. This decentralized approach might be attractive if economical at small scales.

In practice, a combination of methods may be used. For example, incineration or pyrolysis can first reduce the volume of the biomass drastically and concentrate the nickel. The Ni-enriched ash or char can then undergo further processing, like leaching or direct smelting. Smelting the bio-ore with conventional ores is also possible – in fact, one commercial vision of phytomining is to use hyperaccumulator-derived bio-ore as a "metal concentrate" that can be blended with traditional ore in existing nickel smelters (Chaney & Baklanov, 2017). This approach could offset some mining requirements and associated energy costs. One

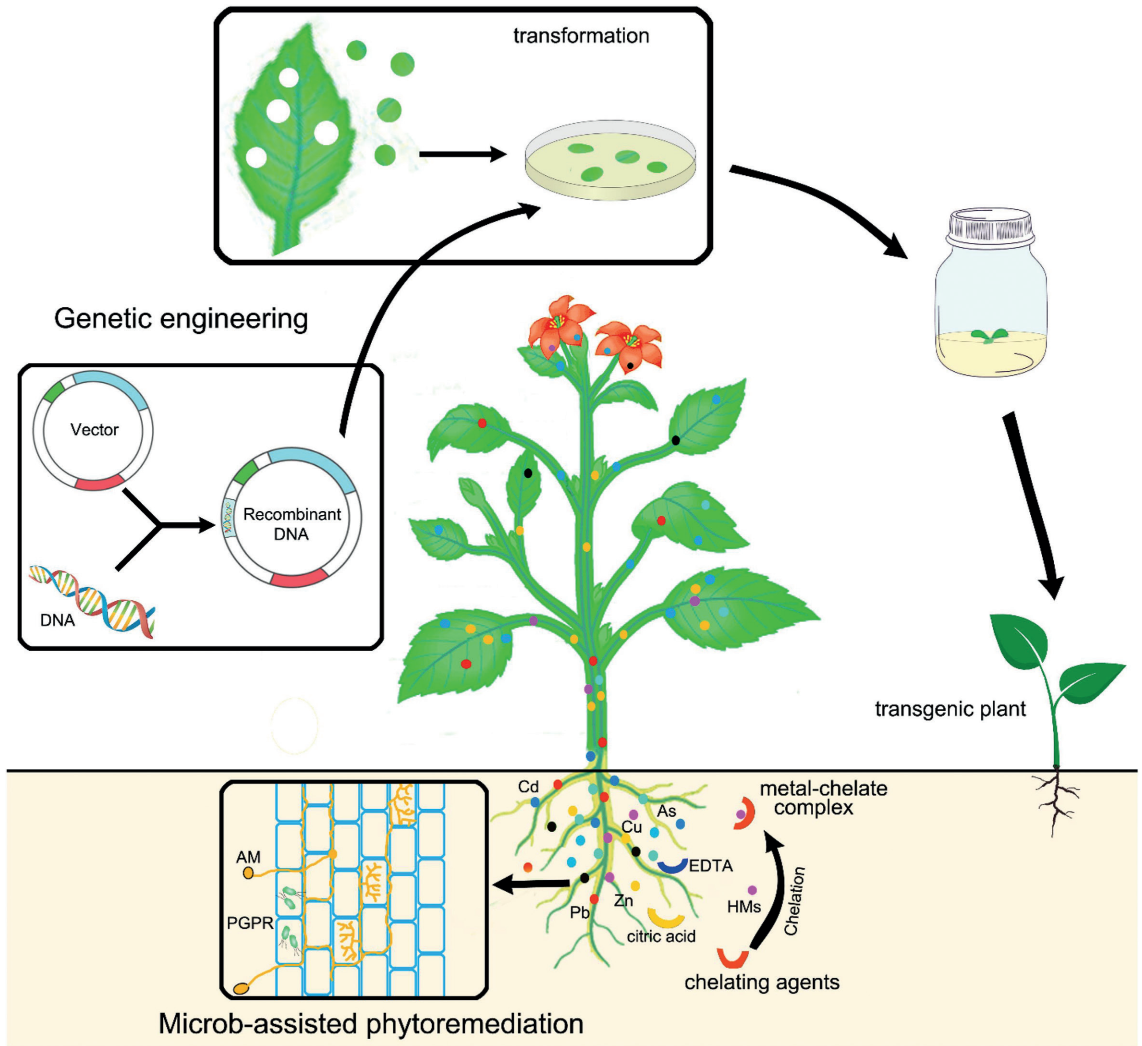

Figure 3. A simplified flowchart of a nickel phytomining process. (1) Cultivation of hyperaccumulator plants on Ni-rich (e.g., serpentine) sites. (2) Harvest of the plant biomass, which contains accumulated Ni. (3) Drying and ashing of biomass to produce Ni-rich bio-ore (plant ash). (4) Processing of bio-ore through smelting or leaching to extract nickel metal. (5) Recovery and sale of nickel product for economic return.

consideration in processing is the co-extraction of other metals: hyperaccumulators might also accumulate zinc, manganese, or cobalt as minor components, which could either add value if recovered or require separation.

Overall, advancements in biomass processing are making phytomining more efficient and eco-friendly. Techniques like pyrolysis and bioleaching reduce the carbon footprint of processing compared to open burning and offer a cleaner recovery of metals. Figure 3 illustrates the general process flow in phytomining from cultivation to metal extraction. Each step – cultivation, harvest, biomass processing, and metal recovery – has been the subject of recent innovations to improve yield and economic viability.

Challenges and Future Prospects

Current Challenges: Despite significant progress, nickel phytomining faces several challenges impeding its implementation as a commercial metal extraction strategy. One major challenge is the biomass production limitation of hyperaccumulator plants. Many Ni hyperaccumulators are slow-growing, small herbs that naturally produce limited biomass in a growing season (van der Ent et al., 2013). Even though they accumulate extraordinary concentrations of Ni, the total metal yield per hectare can be modest if the biomass is low. Researchers are addressing this limitation by experimenting with fertilization regimes, crop density, and co-cropping techniques to boost biomass (Bani et al., 2015; Lima et al., 2025). Another challenge is site selection and agronomy. Hyperaccumulators often have very specific habitat requirements (e.g., certain soil types, pH, climate). Transferring them to agricultural settings can be difficult. For instance, Alyssum murale thrives in Mediterranean climates but struggles in tropical environments without careful soil management. If phytomining is to expand, identifying or developing hyperaccumulator species suitable for different regions and climates is necessary. Along with this is the issue of land area and land use. Phytomining for Ni would likely require dedicating large areas of land to grow what is essentially a metal crop. In places where land is scarce or needed for food production, this trade-off must be considered. However, one solution is to use phytomining on lands that are metal-contaminated or marginal for agriculture, such as old mine tailings, waste dumps, or naturally metal-rich soils that are not arable. In such cases, phytomining can remediate pollution while producing metal, turning otherwise unusable land into an asset (Chaney & Baklanov, 2017).

The economic feasibility of phytomining is another critical challenge. The profitability of growing a metal crop depends on metal prices, yield, and costs of cultivation and processing. Nickel prices can be volatile; a drop in Ni price could render phytomining unprofitable, given the lower yields compared to traditional mining. A recent analysis by Chaney and Baklanov (2017) suggested that at Ni prices around $20,000 per ton, phytomining could be marginally profitable on good sites (yielding ~100 kg Ni/ha), but higher prices or increased yields improve the economics substantially. Additionally, the costs of fertilizing, weeding, harvesting, and processing must be minimized. Mechanization of planting and harvesting would be needed for large-scale operations to reduce labor costs. Another concern is the time scale, as phytomining is inherently slower than traditional mining. It may take several years to accumulate an appreciable amount of metal from a site, whereas mining can extract the same amount in days or months. Investors and stakeholders must accept longer project timelines and returns on investment. There are also environmental and regulatory hurdles. While phytomining is environmentally cleaner than mining, improper handling of metal-laden biomass or ash could cause pollution (for example, wind dispersion of ash if not properly managed). Thus, active practices for containing and transporting the bio-ore are important. Introducing non-native hyperaccumulator species to new regions could pose ecological risks (e.g., invasiveness), so risk assessments and possibly containment strategies like cultivating in controlled plantation areas are required.

Future Prospects: Looking ahead, research and development efforts are likely to alleviate many of the current challenges of nickel phytomining, potentially making it a viable supplement or alternative to conventional mining for certain contexts. One avenue of progress is the discovery of new hyperaccumulator species and the improvement of known ones. Botanists continue to explore ultramafic ecosystems around the world, and new Ni-hyperaccumulators are still being identified (Gei et al., 2020). These discoveries might yield species that are better suited to cultivation or have higher productivity. Concurrently, breeding programs including the use of genomic selection or mutation breeding) could produce "domesticated" hyperaccumulators that retain high Ni uptake but grow faster and larger, similar to how wild plants were domesticated into crops. In parallel, the biotechnological enhancements discussed earlier will likely become more refined. One could envision a future hyperaccumulator crop that is inoculated with a consortium of microbes to maximize growth and Ni availability, and perhaps engineered to express certain genes for superior performance. Field trials that combine these approaches are already underway on test plots in various countries (e.g., Albania, Malaysia, USA) to evaluate real-world performance (van der Ent et al., 2021).

Another worthwhile prospect is integrating phytomining into a broader phytomanagement or land management scheme. For instance, Ni hyperaccumulators can be grown in rotation with other crops on mildly contaminated soils. During their growth, they clean the soil by removing nickel deposits, allowing a conventional crop to thrive once Ni levels drop to safer thresholds. This strategy could be particularly useful for rehabilitating polluted farmlands. In mining areas, phytomining could be used to extract residual metals from mining waste, like tailings or overburden, which would be left unused otherwise. By doing so, mining companies can improve overall resource recovery and reduce the toxic metal content of wastes. This concept of "from waste to value" is gaining traction (Chowdhury & Talan, 2025). If regulations incentivize or require greener practices, companies might adopt phytomining as part of mine closure plans or environmental mitigation, turning a cost center into a profit center if metals are recovered.

Economically, phytomining's viability can be bolstered through credits or ecosystem service payments. Hyperaccumulator crops not only extract metals but also sequester carbon in their biomass during growth. If part of that biomass carbon is stored as biochar in pyrolysis and returned to the soil, phytomining could be carbon-negative, potentially earning carbon credits. Furthermore, the restoration of vegetative cover on degraded lands has ecosystem benefits (e.g., soil stabilization, biodiversity habitat) that could be monetized or subsidized by governments. These additional value streams could make phytomining projects more financially attractive.

For metals market prospects, as the demand for battery metals like Ni increases with the electric vehicle revolution, there is a strong push to develop new sources of these metals. Phytomining could become part of the supply chain, particularly for regions that lack high-grade mines but have suitable soils (e.g., some Pacific islands, parts of Southeast Asia, or Africa with ultramafic geology). Phytomining might not replace traditional mining, but even if phytomining contributes a few percent of global nickel production, that amount would be significant and could be locally important for communities practicing it. Notably, phytomining is a low-capital endeavor compared to opening a mine; it leverages agriculture, which many communities are familiar with, thus lowering the barrier to entry. This democratization of metal production is an intriguing prospect: small farmers could become suppliers of nickel by growing "metal crops," diversifying rural economies.

Ultimately, Ni phytomining stands at an interdisciplinary frontier of plant science, soil science, and metallurgy. Continued research is steadily addressing its current limitations. If breakthroughs in plant yield or processing efficiency continue, phytomining could transition from experimental trials to commercial operations in the coming decades. Beyond nickel, success in Ni phytomining will also pave the way for phytomining of other valuable metals (such as cobalt or rare earths) using similar principles. The future of nickel phytomining will depend on collaborative efforts among botanists, agronomists, engineers, and economists to optimize each link of the chain from seed to metal. With sustainable technologies becoming ever more important, phytomining offers a compelling vision of farming metals in harmony with the environment.

Conclusion

Nickel phytomining represents a novel convergence of agriculture and metallurgy to sustainably harvest metals from the earth. Hyperaccumulator plants have evolved the remarkable ability to extract and endure extraordinarily high levels of nickel, and humans are now learning to harness these biological capabilities for practical metal production. Recent innovations that improve phytomining yields, like genetic enhancement, soil amendments, and enhanced plant processing schemes, are steadily pushing nickel phytomining closer to feasibility. However, wide implementation is stifled by economic hurdles, market volatility, and various other agronomical issues.

Yet, the future outlook for nickel phytomining is optimistic. This technique offers an environmentally friendly alternative for metal extraction that can remediate contaminated lands and reduce the ecological footprint of mining. As society increasingly values sustainability, phytomining could gain traction, especially in regions with suitable soils where traditional mining is not viable or has ceased. In moving forward, a multidisciplinary approach is essential. Advances in plant biotechnology, for example, can be paired with metallurgical engineering innovations to create integrated phytomining systems with high efficiency.

In summary, nickel phytomining is a promising green technology at the intersection of botany and mining. It transforms an ecological curiosity – hyperaccumulator plants – into a practical tool for sustainable resource recovery. While not yet a replacement for conventional mining, it has the potential to complement and partially supplant some mining activities, particularly for low-grade resources and in environmental clean-up scenarios. With ongoing scientific and engineering advances, phytomining could play a meaningful role in the circular economy of metals, turning sunlight, soil, and seeds into a source of one of the world's most important industrial metals. The fields of application for phytomining are growing, and nickel, quite literally, is just the green beginning.

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