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Incorporating hyperaccumulating plants in phytomining, remediation and resource recovery: recent trends in the African region – a review

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Phytomining, the extraction of valuable metals from soil or waste substrates using plants, has gained increasing attention as a sustainable and economically viable alternative to conventional mining practices. Central to this approach is the use of hyperaccumulating plants, which possess the remarkable ability to uptake and concentrate metals in their biomass. The recognition and use of hyperaccumulating plants have become essential components of phytomining at numerous mine sites around the globe. Metal hyperaccumulators however, suffer setbacks such as low biomass production and limited survival in harsh environments like minefields. These limitations restrict their practical application in real-world settings. This review thus explores the biological, agronomic, and environmental aspects of incorporating hyperaccumulators in phytomining. We discuss key hyperaccumulating species, factors influencing phytomining efficiency, and recent advancements in enhancing biomass yield and metal accumulation in minefields. Additionally, we evaluate the economic and ecological implications of phytomining as a green technology for resource recovery.

Sustainability spotlight

Phytomining of precious metals offers an innovative and sustainable method for resource extraction, utilising hyperaccumulating plants to harvest valuable metals from low-grade ores, such as mine tailings, and contaminated soils. This eco-friendly technology minimizes the ecological impact of traditional mining, aids in land restoration, and supports circular economy practices by recovering resources from unconventional sources. By combining principles of green chemistry with sustainable agricultural techniques, phytomining provides a promising route toward more resilient and ethical precious metal supply chains. This review highlights the significance of incorporating hyperaccumulators in the resource recovery of these high value metals and the potential of phyto-technology as a crucial advancement in sustainable resource management.

1. Introduction

The fourth industrial revolution is driving a rapidly growing demand for metals as global economies work to lessen their reliance on fossil fuels. This has in turn increased the depletion rate of the fixed ore source, potentially leading to metal resource scarcity and a looming resource crisis.[1,2] Modern industry's increasing need for precious and industrially important/high value metals such as gold (Au), platinum (Pt), palladium (Pd), nickel (Ni), cobalt (Co), silver (Ag), manganese (Mn) among others has led to an increase in mining operations, which has consequently released these metals into the environment. In addition to their vast application in jewellery and ornamental purposes, precious metals as well as high-value metals otherwise identified as critical minerals are essential components for microchips, electronics, computers, cell phones, electric vehicles, solar panels, wind turbines, defence systems and various advanced climate mitigation technologies – *clean energy*.[3,4] Mining and mineral processing produce significant amounts of wastes, as only a small portion of the ore is valuable. As a result, up to 99% of the material ends up as waste, primarily in the form of tailings.[5,6] While the exact amount of mine waste is uncertain, it is estimated that global tailings production reached approximately 223 billion metric tons between 1771 and 2019 with the amount growing at a rate of 5–14 billion tons per year *via* new production.[7–10] Recent estimates indicate that global metal mines produce 282.5 billion tons of waste annually, containing valuable metals such as copper (Cu), Au, iron (Fe), lead or zinc (Pb/Zn), Ni and others.[11] In addition, it is estimated that South Africa has 17.7 million tons of tailings from gold mining alone.[12]

A region where mining is the dominant sector, employing nearly half a million people, is Africa.[13,14] Notably, South Africa stands out in this regard. South Africa holds the world's largest reserves of platinum, gold, chromium, and vanadium, which

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are mainly extracted as primary ores from mines across several provinces, including Limpopo, Mpumalanga, and Northwest.[15,16] Gold, palladium, platinum, and base metal mining account for over 40% of the nation's economy. However, this industry has also left a legacy of mine tailings that affects various aspects of African society.[17] Recent findings indicate that around 239 million hectares of the world's unutilised lands are contaminated.[18] The Department of Agriculture and Rural Development in Gauteng, South Africa, reports that toxic mine residue covers an area of 124 square miles.[19] These mine tailing dumps are largely contaminated with a range of toxic and valuable metals such as Pb, arsenic (As), thallium (Tl), Ag, cadmium (Cd), mercury (Hg), Ni, Au, Pd, Pt and are strongly acidic, ultimately degrading soil quality.[20–23]

To address this growing issue, government officials in a number of nations have made the decision to create cutting-edge recycling technologies. One way to capture and recover these metals for economic prospects while revegetating and stabilizing waste areas is through phytomining.[24–27] Phytomining is suitable for treating large areas of soil where the metal concentration is too low to be economically viable for recovery through traditional mining methods. The phytomining technology relies on the natural strength of plants to absorb, transport and accumulate metals from low-grade ores, wastes and contaminated soil substrates into their aerial organs for economic benefits.[22,28,29] The full potential of phytomining has yet to be realised; achieving this will necessitate integrated, multidisciplinary research that combines soil biochemistry, plant science, microbiology, agricultural management, genetic engineering, environmental science and engineering (Fig. 1).

While phytomining is not a substitute for conventional mining, it could serve as a method to harness natural resources that would otherwise remain unutilised.[15] The innovative nature and claimed environmental advantages of phytomining have drawn considerable scientific attention. Nonetheless, a primary challenge of using hyperaccumulators for phytoextraction lies in the limited availability of plants with a strong capacity to accumulate the desired metal.[6] Some plants however possess remarkable ability to accumulate metals from metal-enriched soils, often ultramafic (serpentine), whether essential or non-essential at concentrations far above the usual levels compared with other plants in the same habitat.[30–33] These plants with special traits are otherwise described as hyperaccumulators and the process is termed hyperaccumulation.[34,35]

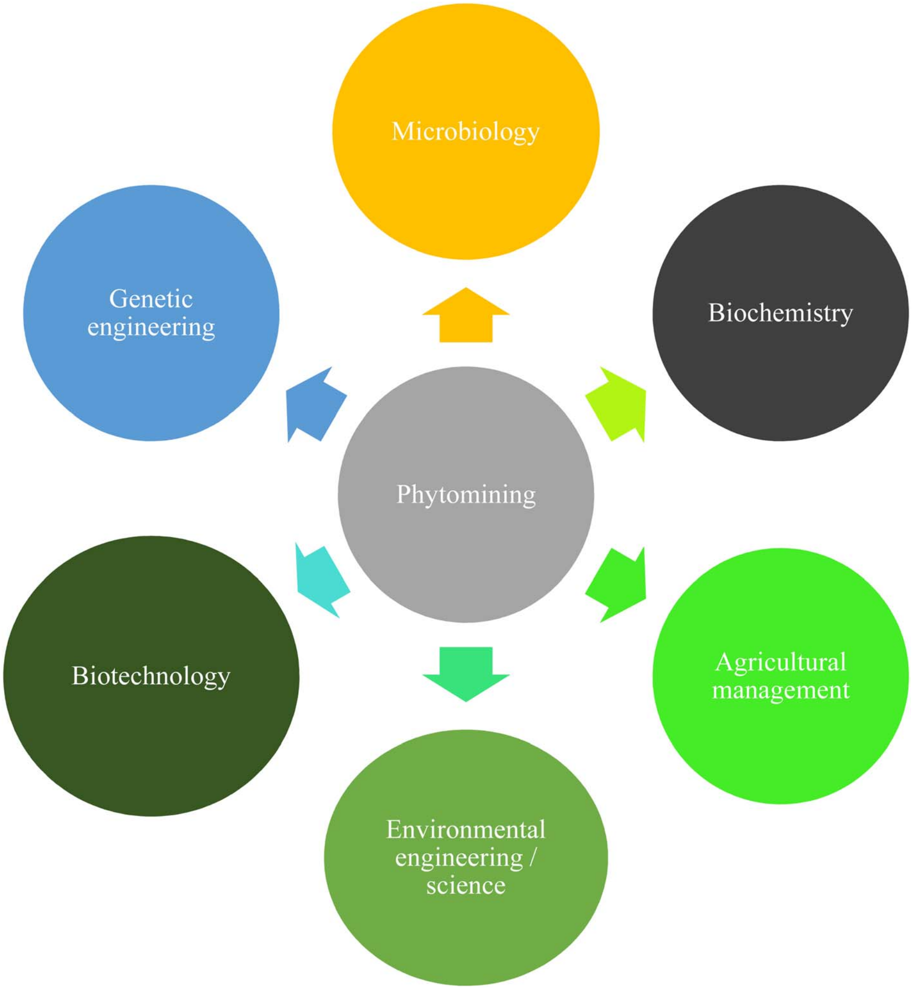

Fig. 1 Potential phytomining research areas.

Many studies to date have concentrated on laboratory or greenhouse experiments to assess plant performance in phytomining. However, field trials, which more accurately simulate real-world conditions and provide more relevant results for evaluating effectiveness in practical applications, have been sparingly demonstrated. This may be due to the harsh conditions in the mine areas, such as high metal levels and low nutrient availability, which necessitate plants with high biomass, rapid growth, and survival abilities.

In the pursuit of field-applicable plants for phytomining valuable metals, understanding metal uptake and tolerance in plants is crucial. Utilising metal hyperaccumulators could significantly improve the metal mining cycle and make the minerals sector more sustainable. More so, hyperaccumulators have been documented and experimentally verified for elements such as nickel, zinc, cadmium, manganese, arsenic, and selenium (Se). However, the natural hyperaccumulation of gold, palladium, platinum, ruthenium, and silver remains largely unverified. This paper therefore aims to review the previous and current scenario of field and laboratory studies on phytomining. The review provides a comprehensive analysis of the emerging role of hyperaccumulating plants in phytomining, environmental remediation, and resource recovery within the African region—an area that remains underexplored despite its vast metalliferous landscapes. Unlike previous studies that focus primarily on global trends, this manuscript highlights region-specific advancements, challenges, and opportunities in utilising phytotechnologies for sustainable metal extraction and ecosystem restoration. By synthesizing recent developments, it offers new insights into species selection, the ecological implications of phytomining as a green technology, and practical applications tailored to Africa's unique environmental and socio-economic conditions, bridging the gap between research and large-scale implementation. Finally, it discusses recent innovative technologies aimed at enhancing phytomining and examines future prospects.

2. Metal hyperaccumulators

The term "hyperaccumulator" was first introduced in 1976 to describe a plant species capable of naturally accumulating exceptionally high-level concentrations of certain elements—hundreds or even thousands of times higher than those typically observed in plants growing on most common soils.[36,37]

While hyperaccumulation has been demonstrated in hydroponic systems by cultivating plants in water media with artificially high concentrations of metal salts or other media amended with large amounts of metal salts, these conditions do not fully replicate the complexity of natural soil environments. Such experiments can provide insights into certain aspects of metal uptake behaviour but do not accurately reflect the natural evolution of hyperaccumulation.[35] Thus, the criteria for classifying a species as a hyperaccumulator have been defined and refined over time. As such, the widely accepted definition of hyperaccumulators refers to plants that, when growing in their natural environment (as opposed to artificially-amended metal media), contain elemental concentrations exceeding the following thresholds in the dry weight of shoot tissue: 100 $\mu g\ g^{-1}$ for Cd, Tl, or Se; 300 $\mu g\ g^{-1}$ for Co or Cu; 1000 $\mu g\ g^{-1}$ for Ni, As, or Rare Earth Elements (REEs); 3000 $\mu g\ g^{-1}$ for zinc (Zn); 1 $\mu g\ g^{-1}$ for Au and 10 000 $\mu g\ g^{-1}$ for Mn.[31,32,35] Alternatively, certain plant species can be induced to accumulate metals through the application of chemicals to the soil (induced hyperaccumulation).[38]

Hyperaccumulators are required to demonstrate a bioconcentration factor (BF) and translocation factor (TF) greater than 1 (eqn (i) and (ii)).[39,40] The BF indicates a plant's ability to extract metals from its growing medium and store them, while the TF reflects its capacity to transport metals from the roots to the shoots.[41] While BF values are often determined based on total metal concentrations in soil, research, including the work of Broadley *et al.*,[42] has revealed that plants can only utilise the bioavailable fractions of these metals. The criteria for classifying a plant as a hyperaccumulator typically include the following: (i) a deep and widespread root system, (ii) rapid growth and large biomass production, (iii) ease of harvest, and (iv) the capacity to accumulate considerable amounts of metals in their shoots.[6,24,43]

Generally, *Brassica juncea* (Indian mustard) and *Berkheya coddii* (Asteraceae) are frequently utilised in the phytomining of precious metals (Table 2). The bioaccumulation factor and translocation factor of these plants exceed one, demonstrating their capacity to accumulate and transport precious and high value metals.[10,44]

$$\text{BF} = \text{concentration of metal in the plant/bio-available metal concentration in the substrate}^{45,46} \quad \text{(i)}$$

$$\text{TF} = \text{concentration of metal in the shoot/concentration of metal in the root}^{45} \quad \text{(ii)}$$

So far, over 800 hyperaccumulating plant species (**http://hyperaccumulators.smi.uq.edu.au/collection/**) have been identified globally across a wide range of taxonomic groups within the plant kingdom, most of which are members of the families Brassicaceae, Asteraceae, Amaranthaceae, Cyperaceae, Fabaceae, Lamiaceae, Poaceae, and Euphorbiaceae.[34,47–49] The majority of these hyperaccumulators (>70%) primarily accumulate Ni and are found in ultramafic soils that are naturally rich in Ni, Co, and sometimes Mn.[6,35,50,51] For instance, ultramafic soils in Albania have been utilised in a successful phytomining field study involving *Alyssum murale*.[52] In this study, *A. murale* was cultivated in its native soil environment, with agronomic practices optimised to enhance yield, ultimately producing a bio-ore for further processing.[53,54] Similarly, research in Indonesia has focused on reclaiming stripped land from mining operations by re-cultivating it with native Ni-hyperaccumulating species.[55]

The second largest group of hyperaccumulators, after those for Ni, is found in the Cu- and Co-rich soils of Central Africa, mainly in the Copper Hills of the Democratic Republic of Congo.[34,56] Beyond base metal phytomining, other studies have explored gold recovery from mine tailings using cyanogenic plants,[57,58] and the extraction of catalytically active nanoparticles from plants.[59,60]

Although hyperaccumulating plants hold significant potential, many are unsuitable for field phytomining demonstrations because of their low biomass production, suboptimal agronomic traits, and inability to thrive under unfavourable conditions found in mine field environments.[61] Strategies such as optimising planting density or boosting nutrient availability through fertilisation may however enhance the biomass production of hyperaccumulators.[62–64] The absorption and accumulation of metals in plants primarily depend on their bioavailability the soil substrate. Consequently, metal availability is significantly affected by factors such as pH, oxygen levels, nutrient balance, and the presence of coexisting inorganic and organic compounds.[65] However, limited studies have been conducted with natural hyperaccumulator species for Au, Pb, Pd Pt and Hg, while a myriad of hyperaccumulators have been documented for As, Cd, Co, Ni, Zn, Cu, Mn, Se and Tl.[66–68]

2.1. Nickel hyperaccumulators in phytomining

According to the European Innovation Partnership (EIP), nickel is an element of significant economic value, with a relatively high market price (15.77 US $ per kilogram) compared to other metals in the same class.[69,70] Moreover, Ni was recognised as a critical metal in 2022, owing to its broad applications in the metal industry, particularly in clean energy technologies designed to support climate mitigation efforts.[71] Since the 1930s, there has been a steady rise in demand for Ni.[72,73] Currently, about two-thirds of the nickel mined globally is used in the production of stainless steel. Additionally, nickel is extensively employed in the creation of non-ferrous alloys and alloy steels for specialised industrial, military, and aerospace applications.[74] These trends are anticipated to persist or rather increase, partly because of the world's expanding infrastructure and Ni's crucial role in the manufacturing of batteries for electric vehicles.[75] Ideally, mining and recycling this metal would balance this demand. Conversely, the mining and refining of Ni generate greenhouse gas emissions (CO_2), contribute to environmental degradation (including soil contamination with potentially toxic metals and the acidification of nearby wetlands), and pose significant health risks to workers in Ni mining and refining facilities.[76–78] These adverse impacts of Ni mining (and other resource extraction) create a conflict of interest for societies that are increasingly committed to addressing climate change, protecting the environment and promoting sustainable development through global supply chains.[79]

Then as well, some countries including United States (US), Australia, New Caledonia, Canada, Italy, Russia, Brazil, Indonesia and Turkey, have extensive regions of low-grade Ni ore that are mostly abandoned.[80,81] The serpentinites (ultramafic soils) of the Barberton Greenstone Belt in South Africa covering an area of approximately 4000 km^2, and home to over 2210 plant species are no exception.[82–85] In South Africa, serpentine soils are primarily concentrated in Mpumalanga province, where the Barberton Schist Belt and the ultramafic formations of the Bushveld Igneous Complex are located.[84] Moreover, there are over 6000 "derelict and ownerless" mines on the list kept by South Africa's Department of Mineral Resources (DMR), which has become a concern for the government over time as the previous owners are nowhere to be found.[19] These contaminated areas are often suitable for Ni phytomining (an alternative method of primary Ni production that can complement traditional mining). Over the years, nickel phytomining has garnered significant attention due to high commercial demand, the vast expanse of nickel-rich natural soils, and the successful field testing of hypernickelophore plants.[86]

Until the 21st century, only high-grade nickel ores were mined, as mining low-grade ores was considered economically unfeasible. Typically, conventional mining requires an ore grade of at least 5% or more of the target metal,[87] although the cutoff grade can vary depending on factors such as metal type, market price, and mining costs. For instance, nickel ores must contain at least 3% (30 000 mg kg^{-1}) of nickel to be mined economically using traditional mining methods.[88] However, few ore bodies meet this level. Phytomining thus offers a viable method to extract from orebodies with low concentration status. This *in situ* technology entails cultivation of hyperaccumulating plant species which can extract high amounts of Ni in their above-ground tissues, followed by harvesting, incineration of the biomass and smelting to produce high-grade bio-ores from which Ni metal/pure Ni salts are recovered.[24,89,90]

Phytomining can contribute to the restoration of these ultramafic (Ni-contaminated) soils, but the success of phytoextraction by hyperaccumulating plants relies on several factors, including the plants' ability to withstand metal stress, their capacity to produce substantial biomass, and the accumulation of high metal concentrations in their aerial tissues. So far, Ni phytomining trials have been conducted in Canada, France, Albania, Italy, New Zealand, Spain, and the US, utilising ultramafic soils containing 0.05–1% total Ni.[89] As previously established, Ni hyperaccumulation occurs when there is an uptake and bio-accumulation of Ni on order of >1000 μg g^{-1} in dry leaf tissue of plant biomass.[91] The level was selected to be 100–1000 times greater than what is typically observed in plants growing on non-ultramafic soil and 10–100 times higher than what is usually found in most other plants on Ni-rich ultramafic soil.[32] The use of native plant species is however recommended due to their adaptation to the specific climatic and soil conditions of the area. Most phytomining efforts conducted so far have focused on Ni (Table 1), largely because of the abundance of hyperaccumulating plants and the widespread presence of ultramafic soils globally.[41]

The greatest number of reported Ni hyperaccumulators are domiciled in the genus Alyssum, many of which can achieve 30 g kg^{-1} Ni in dry leaf biomass.[92–94] An example of this species is *Odontarrhena chalcidica* (also known as *Alyssum murale*), a perennial crop native to ultramafic soils in the arid Mediterranean region including Albania, Turkey, and Greece; however, it can grow and hyperaccumulate Ni outside its native environment.[64,95] Early field experiments primarily focused on plants from the genus Odontarrhena particularly *Odontarrhena muralis* and *Odontarrhena corsica* (*Alyssum corsicum*).[96] For instance, Chaney *et al.* conducted a field phytomining trial to remediate Ni-contaminated soils with the recovery of high-

Table 1 An account of Ni metal hyperaccumulation with implications for phytomining attempts

Species	Region	Phytomining nature	Max conc.	Reference
Berkheya coddii	South Africa	Field and pot trials	100 kg ha^{-1}	110
Alyssum Bertolonii and *Berkheya coddii*	Italy	Field trials	13 400 and 17 000 μg g^{-1}	24
Alyssum bertolonii	Italy	*In situ* experimental plots	72 kg ha^{-1}	119
Alyssum murale	United States	Greenhouse and field trials	22 000 μg g^{-1}	97
Alyssum murale	Albania	Field experiment	11 500 μg g^{-1}	120
Alyssum murale	Albania	Field experiment	9129 μg g^{-1}	121
Alyssum murale	Albania	Field study	105 kg ha^{-1}	52
Phyllanthus rufuschaneyi	Malaysia	Field and pot experiments	>2 wt%	122
Alyssum murale and *Leptoplax emarginata*	Spain	Field experiment	4.2 and 3.0 kg Ni per ha	64
Streptanthus polygaloides	United States	Field trial	100 kg ha^{-1}	123 and 124
Berkheya coddii	Australia	Green house (glasshouse) trial	14.5 kg Ni per ha	125
Alyssum murale	Albania	Field experiment	304–853 mg m^{-2}	126
Senecio conrathii	South Africa	Field sampling trial	1695 ± 637 μg g^{-1}	127
Manihot esculenta	South Africa	Greenhouse trial	1251 μg g^{-1}	128
Odontarrhena plants (12)	Greece	Field sampling trial	18 700 μg g^{-1}	129
Odontarrhena chalcidica	Albania	Field trial	145 kg ha^{-1}	130

purity Ni metal. They utilised *Alyssum murale* and *Alyssum corsicum* to extract Ni from various Ni-rich soil types. These species are native to serpentine soils formed from ultramafic rocks in the Mediterranean region of Southern Europe.[89,97,98] A one-year field experiment was conducted in a serpentine quarry in North-West Spain, to assess the performance of four Ni hyperaccumulating plant species, *Bornmuellera emarginata* and *Odontarrhena muralis* with native populations of *Noccaea caerulescens* and *Odontarrhena serpyllifolia*. Even though plants (except for *O. muralis*) cultivated in compost-amended plots showed lower shoot Ni contents, their higher biomass production resulted in noticeably higher Ni yields (in kg ha^{-1}) for *B. emarginata* (2.9), *N. caerulescens* (1.9), and *O. muralis* (2.3). The Mediterranean species showed a greater capacity for adaptation, but all plant species were able to establish and develop in the mine soil and produce reasonable Ni yields.[99]

In order to maximise the bioavailability of the target metal, various factors such as application of elemental sulphur and soil acidification have been proposed to be effective.[100] This could be attributed to the microbial oxidation of elemental sulphur by sulphur-oxidizing bacteria, such as *Thiobacillus* spp., which produces sulphuric acid (H_2SO_4).[101,102] This process lowers the soil pH, thereby enhancing the solubility of metals like Ni, Co, Zn, and Cd, which are more bioavailable under acidic conditions. Additionally, acidification breaks down metal complexes, transforming them into plant-accessible ionic forms, *e.g.* Zn^{2+}, Ni^{2+}, and Cu^{2+}.[103,104] In a field experiment conducted at an Austrian serpentine site, Rosenkranz and coworkers evaluated the phytomining efficacy of two plant species: *Odontarrhena chalcidica* (*Alyssum murale*) and *Noccaea goesingensis*. For *O. chalcidica*, three treatments were applied: control, sulphur application (0.46 g S per kg soil), and intercropping with the legume *Lotus corniculatus*. For N. goesingensis, the treatments included control, high-density planting (110 plants per m^2), and intercropping. Across all treatments, reports showed that *O. chalcidica* consistently produced higher shoot biomass, shoot Ni concentrations, and total harvested Ni compared to *N. goesingensis*. The highest Ni yield was achieved by *O. chalcidica* in the sulphur treatment, reaching 55 kg Ni per ha^1. In contrast, *N. goesingensis* achieved its maximum yield of 36 kg Ni per ha^1 under the high-density planting treatment.[100]

One of the primary indicators of ultramafic regions in the western North America, is the genus Streptanthus Nutt., belonging to the family of Brassicaceae Burnett (mustard family).[105] This genus has attracted extensive research interest.[106,107] Kruckeberg *et al.* previously observed that nearly all Streptanthus species are either endemic to or tolerant of ultramafic soils. However, only one species, *Streptanthus polygaloides* Gray, has been identified as a Ni hyperaccumulator. This annual plant can accumulate Ni at concentrations as high as 14 800 μg g^{-1} (1.48%) of its dry weight.[108] Sánchez-Mata *et al.* in their field experiment, reported similar values, ranging between 0.09 and 1.18% in the dry plant biomass of *Streptanthus polygaloides* grown on the ultramafic soils of the Californian Sierra Nevada foothills.[105]

The U.S. Bureau of Mines conducted pioneering Ni phytomining trials in 1995 on a natural population of *Streptanthus polygaloides* A. Gray, from the Brassicaceae family, native to serpentine soils in California.[108] The soil at the site contained a Ni concentration of 3340 μg g^{-1}, consistent with typical serpentine soils. At the optimal harvest stage, *S. polygaloides* shoots exhibited an average Ni concentration of 5300 μg g^{-1} and a biomass yield of 4.8 Mg ha^{-1} under unfertilised conditions.[109]

Berkheya coddii, an herbaceous perennial plant from the Asteraceae family, is a well-documented fast-growing, high biomass Ni hyperaccumulator plant native to South Africa's Mpumalanga Province.[110,111] Due to its rapid growth, large biomass, and capacity for hyperaccumulation, *Berkheya coddii* has gained international recognition and is regarded as a perfect candidate for phytomining metals.[110] The first recorded discovery of a nickel-hyperaccumulating plant in South Africa, *Berkheya coddii*, was published in 1989.[112] Since then, Balkwill and co-researchers have conducted extensive floristic studies on ultramafic outcrops, leading to the identification of five nickel-hyperaccumulating plant species: *Berkheya coddii*, *Berkheya zeyheri*, *Berkheya nivea Senecio coronatus* and *S. anomalochrous*.[113–115] All of these species are found on the ultramafic outcrops of the Barberton Greenstone Belt. Smith *et al.* examined 56 out of 126 Asteraceae species known for their serpentinite tolerance in the Barberton region and identified five taxa capable of hyperaccumulating Ni.[84] *Senecio coronatus* is among the most extensively studied Ni hyperaccumulator species in South Africa. This species is widely distributed across Southern African grasslands and is also found on the ultramafic outcrops of the Barberton Greenstone Belt.[116] There are two known populations of this species growing on the ultramafic outcrops: one that accumulates Ni and another that does not.[117] It has been clearly demonstrated that hyperaccumulator species can serve as "metal crops" in large-scale phytomining operations, producing metal-rich biomass (bio-ore) for commercial gain, particularly for Ni.[118] Some examples of Ni-hyperaccumulating plant species reported by researchers under both field and laboratory/greenhouse settings are hereby summarised in Table 1.

2.2. Hyperaccumulators of gold and silver in phytomining

Despite the prevalent application of phytomining in the extraction of Ni, emerging studies indicate that the phytomining of gold and silver also presents a financially feasible alternative.[131,132] Au and Ag are widely recognised as precious metals that have captivated human interest for centuries. As reported by Thakur and colleagues, the global annual consumption of Au and Ag is 320 and 7500 tons, respectively.[133] Reports of Au and Ag accumulation in plants, have been documented since the early 20th century.[57,134–136] Although Au and Ag have been identified as promising candidates for phytomining, plants generally do not accumulate them naturally.[137] Gold in its elemental form, Au(0), is generally not bioavailable; a precondition that is applicable to silver.[138] As such, induced hyperaccumulation techniques (which entail the application of chemical amendments such as chelating agents) are often employed to solubilise these metals, and enhance their availability and uptake by plants.[139] Cyanide is widely regarded as a highly effective chemical agent for solubilising Au and Ag from their ores.[137,140] Its use has been shown to significantly enhance the accumulation of Au in the aerial tissues of plants,[59,141] However, despite stringent regulations in many countries, improper handling of cyanide can lead to severe environmental consequences, particularly through accidental spills into waterways.[142–144] For instance, numerous accidental cyanide spills into rivers and streams have caused extensive harm to aquatic ecosystems.[145] These incidents are well-documented in many countries including Ghana, Kyrgyzstan, Papua New Guinea, and China. Such incidents have also been reported in Japan, Canada, and Europe.[145,146]

Conversely, certain plants primarily known as cyanogenic plants produce natural lixiviants that can mobilise metals in the soil.[57,58,68,147] For instance, cyanides are generated through the hydrolysis of cyanogenetic glycosides, which are present in numerous plant species, including cassava (*Manihot esculenta*) and acacia (*Acacia sieberiana*). Upon hydrolysis, these glycosides produce hydrogen cyanide (HCN) which naturally complexes with the target metal and promotes the uptake of non-bioavailable metal.[128] Au/Ag hyperaccumulation is characterised as accumulation beyond 1 mg kg^{-1} of dry matter.[141,148] Nonetheless, studies on the non-induced accumulation of Au in plants are limited, likely due to the lower bioconcentration factor (BF).[149] The first genuine Au phytomining experiment was not conducted until the late 1990s.[141] Building on this initial discovery, efforts have intensified to enhance the level of Au accumulation in plants. Research conducted on the laboratory scale and greenhouses has demonstrated that lixiviants such as cyanide, thiocyanate, thiosulfate, peroxide, and thiourea can be used to stimulate the absorption of Au.[141,150,151] The challenge lies in the use of chelating chemicals to enhance metal uptake, as this process can lead to soil and water contamination as mentioned previously. Moreover, mobilised metals may leach deeper into the soil and reach aquifers, while plants absorb only a small fraction of the mobilised gold.[23]

Lamb and co-workers utilised an artificial Au-bearing soil substrate with a concentration of 5 mg kg^{-1} to evaluate the Au uptake capacity of *Brassica juncea*, *Berkheya coddii*, and *Cichorium intybus* in the presence of various solubilising chemicals, including ammonium thiocyanate, ammonium thiosulfate, potassium bromide, potassium cyanide (KCN), potassium iodide, and sodium thiocyanate. The study found that hyperaccumulation induced by KCN resulted in average Au concentrations of 97 mg kg^{-1} in *B. coddii* and 326 mg kg^{-1} in *B. juncea*.[152]

Relevant research indicates that mine waste dumps/tailings contain considerable amounts of Au.[1] Mohan reported that 33 million tonnes of residual waste contain 0.7–0.8 mg of Au per kilogram, potentially yielding up to 24 tonnes of Au over time.[153] As such, the reuse of this mine waste would enable beneficial secondary applications, which encompass extracting resources or transforming waste into valuable products.[59] A greenhouse study was conducted using mine tailings containing 2.35 mg kg^{-1} of Au ore sourced from an active mine in Mexico. The study aimed to assess the potential of *Sorghum halepense* for Au phytoextraction. After ten weeks of plant growth, different chemical amendments were applied including thiourea, sodium cyanide, ammonium thiosulfate, and ammonium thiocyanate to the pots two weeks before harvest. Sodium cyanide at a dose of 1 g kg^{-1} proved to be the most effective solubilising agent, leading to the accumulation of 23.9 mg kg^{-1} of Au in the aboveground dry matter of *S. halepense*.[154]

Prior investigations concerning *Medicago sativa* and *Brassica juncea* have demonstrated their exceptional capacity to accumulate metals such as Ag and Au within their tissues.[132,138,141] Bali *et al.* highlighted the ability of *Medicago sativa* and *Brassica juncea* to hyperaccumulate Au across various concentrations and exposure durations. Their findings showed that Au uptake in *Medicago sativa* increased with higher concentrations of Au substrate, while *Brassica juncea* exhibited maximum uptake after 48 hours of exposure at elevated concentrations (100–10 000 mg kg^{-1}). The roots of *Medicago sativa* accumulated a maximum of 287 mg of gold per gram of dry biomass, while *Brassica juncea* roots reached a maximum accumulation of

Table 2 An account of precious metal hyperaccumulations[a]

Element	Species	Region	Phytomining nature	Max conc.	Reference
Au	*Brassica juncea*	New Zealand	Laboratory and greenhouse trial – IH	57 mg kg^{-1}	141
Au	Five crops (carrot, red beet, onion, and 2 cultivars of radish)	New Zealand	Greenhouse trial – IH	Carrot roots −48.3 μg g^{-1} dw), and roots of two radish cultivars 113 and 102 μg g^{-1} dw	150
Au	*Brassica juncea* and *Zea mays*	Brazil	Field demonstration – IH	39mg kg^{-1}	137
Au	Australian native plant species and exotic agricultural species	Australia	Pot/laboratory trial – IH	Trifolium repens cv. Prestige – 27 g ton^{-1} dw	139
Au	*Medicago sativa* and *Brassica juncea*	Australia	Hydroponic experiment	*M. sativa*: 287 mg g^{-1}; *B. juncea*: 227 mg g^{-1}	138
Au	*Helianthus annuus* and *Kalanchoe serrata*	Mexico	Field and laboratory research – IH	– *H. annuus*: 15 mg kg^{-1} in leaves, 16 mg kg^{-1} in roots and, 21 mg kg^{-1} in plant stems; *K. serrata*: >9 mg kg^{-1} in the dry matter of aerial tissues	134
Au and Ag	Tobacco	Indonesia	Field experiment – IH	– Au: 1.2 mg kg^{-1} – Ag: 54.3 mg kg^{-1}	164
Au and Ag	*Brassica napus*	Mexico	Field trial – IH	– Au: stems – 1.5 mg kg^{-1}; roots: 10 mg kg^{-1} – Ag: ≥50 000, 30 000, and 15 000 mg kg^{-1} in roots, stems, and leaves respectively	155
Au	*Manihot esculenta* (cassava)	Australia	Pot trial and hydroponics experiment	Fibrous roots: 18.99 mg kg^{-1} Au	68
Pt, Pd, Au	*Berkheya coddii*	South Africa	Greenhouse experiment (mine tailing and artificial substrate)	– Pt: 183 μg kg^{-1} – Pd: 7677 μg kg^{-1} – Au: 1580 μg kg^{-1}	161
Pd and Pt	*Berkheya coddii*	South Africa	Field experiment	Leaf: 0.22 mg kg^{-1} Pt and 0.71 mg kg^{-1} Pd Root: 0.14 mg kg^{-1} Pt and 0.18 mg kg^{-1} Pd	44
Pd	*Chrysopogon zizanioides* (Vetiver grass)	South Africa	Hydroponic experiment	Root: 0.4 mg g^{-1} dw	165
Pd	Mustard, miscanthus, and 16 willow species and cultivars (*Arabidopsis thaliana*)	United Kingdom	Greenhouse/glasshouse trial and hydroponic experiment – (both synthetic and mine-sourced tailings) IH	Dried plant biomass contains: between 12 and 18 g kg^{-1} Pd	60

[a] IH – induced hyperaccumulation N – natural hyperaccumulation; dw – dry weight.

227 mg of gold per gram of dry biomass, both when exposed to a 10 000 ppm aqueous solution of $KAuCl_4$.[138]

Although the concentration of Ag in plants can be as high as 1 mg kg^{-1}, certain plants, such as *Lupinus angustifolius*, can accumulate up to 126 mg kg^{-1} through induced uptake.[22] Silver is naturally accumulated by plants such as *Astragalus gummifer* (legume), *Euphorbia macroclada* (spurge), and *Verbascum cheiranthifolium* (Scrophulariaceae).[118] Harris and co-researchers were the pioneers in suggesting the uptake of Ag metal nanoparticles by plants. The research revealed the accumulation of considerable amounts of Ag in *Brassica juncea* and *Medicago sativa* plants; in the hydroponic experiment, where Ag was supplied at concentrations ranging from 500 to 10 000 mg L^{-1}, the highest accumulation observed was 124 g kg^{-1} after 48 hours.[132] *Brassica napus* (rapeseed) has been found to accumulate approximately 50 000 mg kg^{-1} in its roots, 30 000 mg kg^{-1} in its stems, and 15 000 mg kg^{-1} in its leaves, while the Ag concentration in mine tailings is 22.1 mg kg^{-1}.[155] Table 2 highlights some of the most notable results achieved in hyperaccumulation of precious metals to date.

2.3. Platinum group metal hyperaccumulators in phytomining

The platinum group metals (PGMs) consisting of platinum (Pt), palladium (Pd), rhodium (Rh), ruthenium (Ru), iridium (Ir) and osmium (Os) are essential to numerous modern technologies, including catalytic converters in automobiles (auto-catalysts), chemical process catalysts critical for oil refining, jewellery, electronics, hydrogen fuel cells, and specialized medical alloys. South Africa remains the leading producer and supplier of these essential mineral resources globally (Fig. 2), sourcing them entirely from the Bushveld Complex. It is followed by Russia, with smaller yet valuable contributions from Zimbabwe, Canada, and the United States.[15,156]

PGM interactions with plants are poorly understood, and few hyperaccumulators have been identified for them to date. A few studies investigating PGM bioaccumulation were conducted in the laboratory or greenhouse and hydroponic environments. In most of these reports, the robust hyperaccumulation was stored in the roots with minimal translocation to the aerial organ of the plant. Lesniewska *et al.* reported the bioaccumulation of Pt, Pd, and Rh by *Lolium multiflorum* (ryegrass) under hydroponic conditions using nutrient solutions containing these ions at elevated (38.7 mg L^{-1} Pt, 21.7 mg L^{-1} Pd, and 7.1 mg L^{-1} Rh) and medium (3.6 mg L^{-1} Pt, 4.4 mg L^{-1} Pd, and 0.5 mg L^{-1} Rh) concentrations. The highest bioaccumulation factors were observed for Pd and Rh in the roots and for Pt in the leaves. The findings indicated that the majority of the metals studied were retained in the roots, with only a small portion being translocated to the leaves.[159]

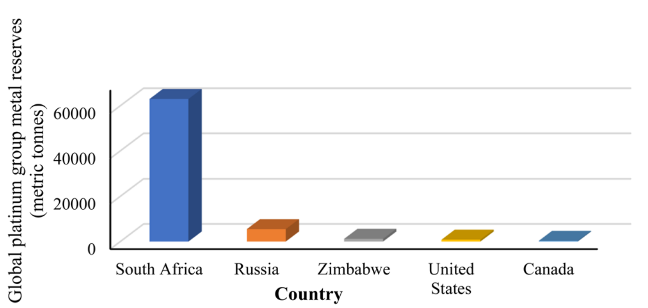

Fig. 2 World reserves of PGMs.[157,158]

Although there are no officially recognized palladium hyperaccumulators, it is expected that the threshold for PGM accumulation would be around 1 mg per kg, given their typically low concentrations in plants.[160] Potassium cyanide (KCN) has been used to enhance palladium uptake in plants. Walton applied KCN at a concentration of 10 g L^{-1} to promote palladium accumulation in *B. coddii* grown on mine tailings containing 315 µg kg^{-1} palladium. The study revealed that the plants accumulated palladium at concentrations reaching up to 7677 µg kg^{-1}.[161] Diehl and Gagnon similarly detected Pt concentrations of 14.6 mg kg^{-1} in *Daucus carota* plants collected from a location near a heavily trafficked motorway.[162]

Cassava had previously shown significant potential for minefield decontamination; despite being cultivated on an Au mine site with the aim of bioaccumulating the metal, it instead accumulated zinc and lead at levels exceeding the recommended limits for daily consumption.[163] Dwelling on this fact, our research group demonstrated the hypothesis of utilising the cassava plant (*Manihot esculenta*) to naturally accumulate Pd and Pt in an artificially contaminated potting mix. Following harvest, the cassava roots were found to contain metal concentrations of 78 ± 0.047 µg g^{-1} for Pd and 1276 ± 0.036 µg g^{-1} for Pt.[67]

3. Incorporating hyperaccumulating plants in mine fields and tailing dumps

The conventional methods for mining and recovering precious metals are expensive due to high energy consumption and the extensive use of chemicals for processes which often result in environmental pollution. To reduce costs and maintain profitability, industries typically rely on high-grade ores as raw materials.[22,166] However, mining operations face growing challenges due to the vast depletion of local high-grade ore deposits. As a result, recycling precious metals from waste streams *via* phytomining (Fig. 3) offers a viable solution to address the imbalance between supply and demand.[167]

PGM deposits are predominantly found in South Africa's Bushveld Igneous Complex, with significant concentrations in the Limpopo and Northwest provinces while gold mining activities primarily take place in the *Witwatersrand Basin*, situated in the Free State and Gauteng provinces.[44,168] Base metals, on the other hand, represent a valuable secondary product of PGM extraction. In 2013, mining companies generated 562 000 times more waste than Au, according to the South African Chamber of Mines. This figure was more than double the ratio from a decade earlier, which stood at 212 000 to 1. The increase in mine waste is attributed to the depletion of South Africa's gold reserves, with the remaining deposits located several miles underground, making extraction more challenging.[19] These

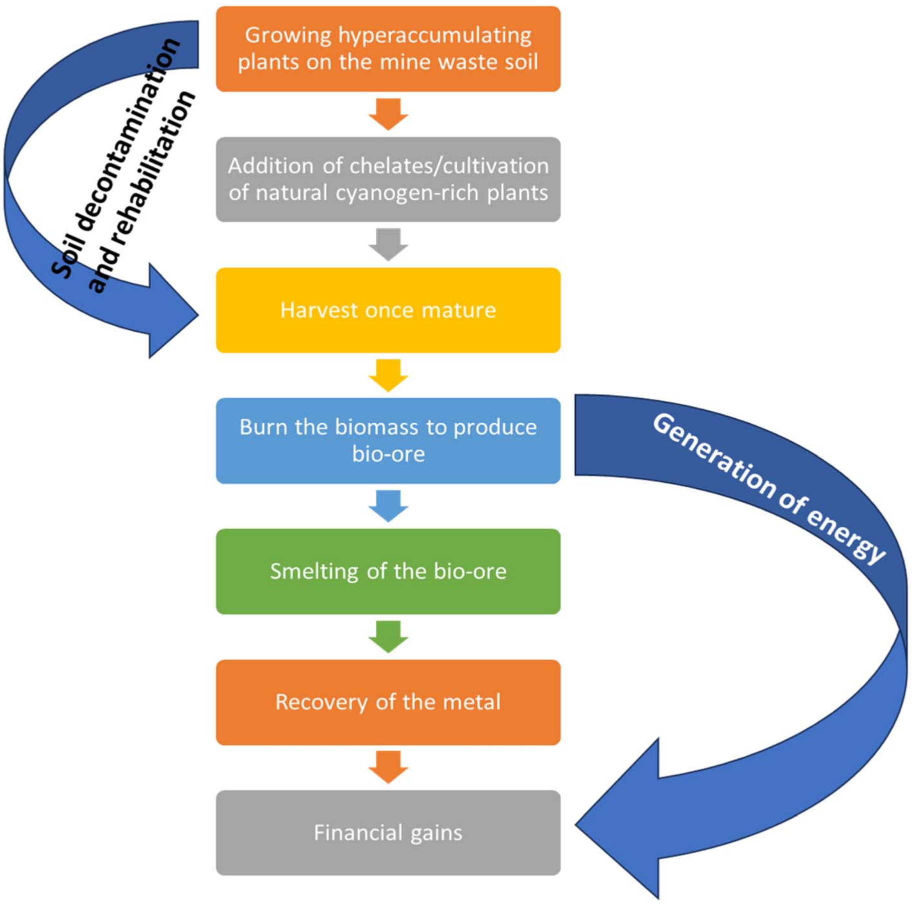

Fig. 3 Process of phytomining metals.

tailing sites and waste dumps pose a significant environmental threat to the ecosystem. Phytomining offers a cost-efficient method for extracting these high value metals from mine tailings and low-grade ores,[153] and these mine tailings provide ideal locations for implementing phytomining practices, which offer dual benefits: generating revenue and creating employment opportunities. Additionally, such practices contribute to the restoration of the area's ecosystem. Typically, there is a linear correlation between the metal content in plant tissues and the mineral concentration in the soil. Eucalyptus species serve as outstanding metal indicators and could be utilised to detect deep gold deposits (>10 m).[169] Reports have also indicated that conifers in regions with gold ores in Canada can accumulate up to 0.02 mg of gold per kilogram, which is 100 times higher than the typical background levels found in plants.[6]

As previously noted, mine sites and tailings often exhibit characteristics detrimental to plant growth, such as elevated levels of toxic metals and low nutrient and organic content. Under such challenging conditions, hyperaccumulating plants may struggle to accumulate significant amounts of target metals but must still be able to survive and grow. The ideal hyperaccumulators should be fast-growing plants with high biomass production, extensive root systems, strong adaptability to high metal concentrations, capacity to thrive beyond their native collection regions and possess a significant TF. However, identifying plant species that exhibit all these characteristics is extremely challenging. For example, *Alyssum bertolonii* and *Thlaspi caerulescens* can absorb and translocate specific metals at high concentrations but have low biomass production.[28,170] This has prompted researchers to explore the use of non-hyperaccumulating plant species, such as willow and miscanthus, which are valued for their rapid growth, deep root systems, and high biomass yield.[171–174] Notably, willow, for instance, can tolerate a wide range of toxic and high value metals and flourish in adverse environments. Additionally, the substantial biomass produced by non-hyperaccumulators makes them suitable for dual purposes in phytomining, including soil remediation and bio-energy production (Fig. 3) which can be solid (charcoal), liquid (bioethanol and biodiesel), or gaseous (methane).[18,175,176]

The high costs involved in processing mine waste dumps and mine tailings using conventional methods call for a reconsideration of alternative, innovative plant-based technologies to detoxify and recapture the minerals deposited in the soil. Numerous hyperaccumulator species have been documented to extract metals in this habitat.[177] However, improving the bioavailability of these minerals requires agronomic practices, including cultivation, soil management, and breeding initiatives.[65] Phytomining, although still a ‘relatively new’ and underexplored concept, has the potential to offer economic and environmental advantages to soil end-users and managers working with metal-contaminated soils. By cultivating high-yield hyperaccumulator plants, it may transform yield shortages of certain commercial crops into opportunities, leveraging the metal-rich biomass for industrial purposes.[160]

3.1. Incorporation of food crops in phytomining

The concept of utilising food crop species for metal accumulation in phytomining requires thorough consideration. Crops like Indian mustard (*Brassica juncea*) and sunflower (*Helianthus annuus*) are frequently used in phytomining research due to their classification as "hyperaccumulators" and their rapid growth rates, which enable them to remediate larger quantities of metal efficiently. Conversely, these plant species are neither highly tolerant nor well-suited for practical field applications and are often damaged or destroyed during the phytoextraction process.[178] Additionally, many non-food biomass crops significantly surpass these species in yield, achieving comparable or higher metal concentrations in their tissues without posing a risk of contaminating the human food; however, by incorporating food crops, farmers could gain income from both the harvested metals and the sale of food products, potentially offsetting the costs of phytomining operations. Growing food crops in metal-contaminated areas could help rehabilitate degraded soils while contributing to local food security, provided that metal accumulation in edible parts remains within safe limits for consumption.

The primary concern with using food crops in phytomining is the potential for harmful levels of metals to accumulate in the edible portions, posing health risks. Careful selection of crop species and cultivars with limited translocation of metals to edible parts is essential. Certain crops, such as leafy vegetables, cereals, and root crops, may vary in their ability to tolerate and accumulate metals.[179] Breeding or genetic modification to enhance metal exclusion from grains, fruits, or leaves could also be adopted. Research is needed to identify crops that can effectively accumulate metals in non-edible tissues, such as roots or stems, while keeping edible parts safe. Optimising agronomic practices, such as soil amendments, irrigation, and fertilisation, can improve metal bioavailability and plant growth.[180] However, it is essential to prevent the accumulated metals from contaminating the food chain or causing health risks. Regulatory frameworks must ensure that food crops grown on metal-rich soils meet safety standards. Ethical concerns regarding the consumption of such crops must also be addressed through transparent communication and risk assessments. Further research is needed to develop genetically modified or selectively bred food crops that can thrive in metal-rich soils and effectively sequester metals in non-edible parts. Additionally, studies on the long-term effects of cultivating food crops in phytomining systems on soil health, crop yields, and food safety are critical.

4. Enhancing phytomining technology

Metals serve diverse roles in all living organisms, including plants, as they form the active centres of many enzymes, catalyse essential biochemical reactions, and help maintain protein structure.[181] Recent advances in genetic engineering and plant breeding offer promising avenues for improving the efficiency of phytomining.[182–184] Genetic modification of plants involves transferring a foreign gene from an organism, such as another plant species, bacteria, or animals, into the genome of a target plant. Following DNA recombination, the foreign gene is passed down, imparting specific traits to the plants.[185] Genetic modifications can target key transporters responsible for metal uptake in plants, such as ZIP (ZRT-IRT-like Proteins) family transporters, which play a crucial role in zinc, iron, and nickel uptake; Heavy Metal ATPases (HMA) which facilitate the movement of metals like cadmium, copper, and zinc across cellular membranes; and NRAMP (Natural Resistance-Associated Macrophage Protein) transporters, which enhance iron and manganese uptake and transport.[186,187] Overexpression of these transporters can significantly improve the bioaccumulation of targeted metals.

Unlike traditional breeding, genetic engineering offers the advantage of altering plants with desirable traits for phytomining in a much shorter time frame. Fast growing, high-biomass plants are frequently engineered to exhibit the primary characteristics of hyperaccumulators.[185] Transgenic approaches, such as overexpression of metal transporters and chelating proteins, have also shown potential in enhancing metal uptake and tolerance. Plants often sequester heavy metals in vacuoles to mitigate toxicity. Genetic engineering can enhance the expression of metal-binding proteins, for example, metallothioneins, small cysteine-rich proteins that bind and detoxify heavy metals; phytochelatins – peptides that chelate metals and enhance metal tolerance and ferritins – proteins that store iron and mitigate oxidative stress induced by heavy metal accumulation.[188] Genetic modifications can also focus on enhancing plant growth. Strategies like overexpression of growth-promoting genes such as those involved in hormone synthesis (*e.g.*, auxins and cytokinins) and incorporation of drought and stress-tolerant genes to improve plant resilience in metal-contaminated soils can also be adopted to improve plant biomass production.

Additionally, microbial-assisted phytomining, leveraging plant-associated microorganisms to mobilise metals, represents an emerging field of study.[85] This involves the use of bacteria and fungi that interact with plant roots to enhance metal solubility, uptake, and tolerance. These microorganisms can release enzymes and chelating agents into the rhizosphere, resulting in the formation of metal-chelate complexes, which in turn enhance metal uptake and translocation. In this way, microbial community in the rhizosphere can directly stimulate root growth, which in turn promotes plant development, enhances metal tolerance, and improves overall plant stability and suitability.[189] Certain rhizosphere bacteria can convert metals into more bioavailable forms. For example, sulphur-oxidizing bacteria (*Thiobacillus* spp.) produce sulphuric acid which enhances metal solubility and phosphate-solubilizing bacteria (*Bacillus* and *Pseudomonas* spp.) that release organic acids that increase metal availability.[102,190]

Although Fadzil *et al.* highlighted that introducing non-native, invasive species may pose a threat to biodiversity,[48] this has yet to be demonstrated in practice. Nonetheless, we believe that utilising or genetically enhancing endemic or native plants adapted to metal-enriched soils could be an effective strategy to improve phytomining efficiency and increase revenue.

Furthermore, the effectiveness of metal extraction relies on the metal concentration in the soil and the substrate's pH level. Soil pH can be lowered using various substances, such as ammonia-based fertilizers, acids, and zero-valent sulphur as amendments. However, the extent to which pH can be reduced is limited, as most plant species can only grow within a specific pH range. Typically, the lowest pH tolerable for many plants is around 4.5.[65]

5. Economic and environmental implications

Phytomining offers dual benefits of resource recovery and land rehabilitation, particularly in areas with low-grade ores or metal-contaminated soils. By rehabilitating degraded lands, phytomining can restore habitats and promote biodiversity. However, careful management is needed to avoid introducing invasive plant species that may threaten local ecosystems. The economic feasibility depends on factors such as the market value of the target metal, operational costs, and biomass processing methods. While phytomining is less invasive than conventional mining, it may still pose environmental risks, such as unintended metal leaching. A careful assessment of these risks is crucial to ensure sustainable implementation.[48]

For phytomining to be economically viable, extensive mineralised areas are necessary to produce a high biomass of the desired plant species, enabling the recovery of significant amounts of the target metal. This large biomass would require a centralised incineration facility, generating revenue from both metal sales and energy production. Successful implementation of this technology requires experienced project designers who can carefully select the appropriate plant species and cultivars for specific metals (or metal combinations) and regions, while effectively managing the system to optimise metal recovery.[22] Additionally, soil amendments can increase the overall cost of phytomining operations. The global phytoextraction market, valued at 34–54 billion USD, is growing in developed countries, presenting a promising opportunity for this green technology.

To estimate the potential revenue from metals extracted by hyperaccumulating plants per hectare (Table 3), we analysed current metal prices alongside data on metal concentrations and biomass yields. For instance, in the case of nickel, hyperaccumulating plants can typically store up to 4% Ni in their leaves. Field trials indicate that species such as *Alyssum murale* can yield between 5 and 10 metric tonnes of dry biomass per hectare each year. With a 4% nickel concentration, this corresponds to roughly 200 to 400 kilograms of Ni per hectare (ha) annually. Given the current Ni price of $7.1373 per pound, or approximately $15.73 per kilogram, this implies that cultivating nickel hyperaccumulators could generate annual revenues ranging from $3146 to $6292 per hectare, depending on plant species, growth conditions, and market fluctuations.[92,191] Nevertheless, to assess the feasibility of the phytomining process, it is crucial to carefully evaluate practical challenges such as plant selection, cultivation methods, metal extraction efficiency, and economic considerations.

6. Recent developments and prospects

In recent years, Africa has made notable progress in using hyperaccumulating plants for phytomining valuable metals, environmental cleanup, and resource recovery. These advancements are especially relevant due to the continent's large-scale mining operations and related environmental concerns. Efforts to catalogue native African plant species with hyperaccumulation capabilities have increased significantly. In South Africa, for example, *Berkheya zeyheri*, a species native to serpentine soils, has shown an exceptional ability to absorb high levels of nickel, making it a promising option for phytoremediation and phytomining projects.[198]

Various initiatives have been introduced to utilise the phytoremediation/phytomining capabilities of native plants. In the Zambian Copperbelt, projects are exploring the combination of phytomining with ethanol production.[199] This strategy aims to cleanse heavy metal-contaminated soils while producing biofuels, offering economic benefits alongside environmental restoration.[200,201] Across Africa, governments and research institutions are increasingly acknowledging the

Table 3 Current metal prices based on reported metal concentrations and biomass yields of hyperaccumulators

	Metal	Metal concentration	Biomass yield (ha per year)	Metal yield (kg per ha per year)	Current metal price (USD per kg)	Estimated revenue (USD per ha per year)	References
1	Ni	40 g kg^{-1}	*Alyssum murale*: 5–10 metric tonnes	200–400	7.1373–15.73	3146–6292	191
2	Co	600 μg g^{-1}	*Berkheya coddii*: 16.5 kg	16.5	21.55	355.58	192 and 193
3	Pt	8.7 g kg^{-1}	*Sinapis alba*: 5 metric tonnes	8.7	31 816.36	276 809.33	194
4	Pd	0.4 mg g^{-1}	*Chrysopogon zizanioides*: 20 metric tonnes	1.6	31 252.13	50 003.41	165 and 195
5	Au	1 mg kg^{-1}	10 metric tonnes	0.01	92 025	920.25	196
6	Tl	5.88 kg	*Silene latifolia*	5.88	7400	43 512	197

importance of phytomining. In South Africa, for instance, environmental policies have been introduced to encourage research and the application of phytoextraction technologies. This support has facilitated the discovery of numerous plant species suitable for ecological restoration, such as *Eichhornia crassipes* (water hyacinth), which is used for nutrient removal from water systems.[202]

Despite these advancements, several challenges persist that undermine this progress. The lack of prioritisation for phytoextraction funding by many African governments has led to dependence on individuals with limited expertise, often resulting in ineffective project execution. Conversely, selecting appropriate hyperaccumulator plants demands specialised expertise. However, the limited number of professionals in this field often results in inadequate plant selection for Africa's diverse soil conditions.[203] The absence of research centres and adequate laboratory equipments limits academics' ability to effectively communicate phytomining concepts to the public, resulting in low confidence in the technology.

Looking ahead, incorporating hyperaccumulating plants into phytomining and remediation in Africa presents significant potential. The concept offers a dual benefit of environmental cleanup and economic gain. For example, studies have explored the feasibility of using hyperaccumulating plants to recover precious metals from mine tailings, presenting a sustainable approach to resource recovery. In addition, equipping local communities with knowledge about the advantages and techniques of this phytotechnology can increase involvement in environmental restoration projects. Educational programs can encourage community-driven efforts to rehabilitate polluted lands through the use of native hyperaccumulating plants. With continued research, policy support, and community engagement, these green technologies have the potential to address environmental pollution and contribute to sustainable development across the continent.

7. Conclusion

The incorporation of hyperaccumulating plants in phytomining represents a promising strategy for sustainable metal recovery and environmental management. Despite its potential, phytomining faces challenges such as low biomass yields, limited metal recovery rates, and long cultivation cycles. Future research should prioritise the development of high-yielding, fast-growing hyperaccumulator species; integration of phytomining with other remediation and agricultural practices; exploration of underutilised hyperaccumulating species and novel ecosystems; genetic modification of genes associated with metal uptake, translocation, sequestration, and tolerance to enhance metal accumulation or tolerance in plants. Additionally, natural cyanogenic plants that release lixiviants and chelating agents, along with beneficial microorganisms, can be utilised to increase metal bioavailability, thereby facilitating metal accumulation in plants. These approaches can also improve soil health, further promoting plant growth and fitness. Economic modelling to optimise profitability and scalability should also be explored. Likewise, the discovery of new hyperaccumulator plants has the potential to significantly advance phytomining as a green technology. Targeted research in underexplored regions and soils, combined with advances in plant screening and genetic engineering, could uncover species with enhanced metal uptake capabilities. For instance, the Barberton Greenstone Belt, in South Africa is known for its ultramafic soils; this region has already yielded hypernickelophore plants. Additional undiscovered species may also be present. While significant progress has been made in understanding and optimising this technology, continued interdisciplinary research is needed to overcome existing limitations and fully realise its potential. By bridging gaps between plant science, agricultural management, biotechnology, and environmental engineering, phytomining can contribute to a greener and more resource-efficient future.

Data availability

There are no supporting data for this work elsewhere.

Author contributions

Babatunde Joseph Akinbile: writing the original draft, review, editing, and validation. Charles Mbohwa: supervision and validation.

Conflicts of interest

The authors declare no conflict of interest.

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