Jurnal Presipitasi
Media Komunikasi dan Pengembangan Teknik Lingkungan
e-ISSN: 2550-0023

Vol 23, No 3, 2026,
Article available at homepage presipitasi

Original Research Article

Green Phytomining Strategies for Cu and Zn Recovery Using Terrestrial and Aquatic Hyperaccumulators

Yudha Gusti Wibowo[1*], Jarwinda[1], Hana Safitri[1], Ajeng Permata Bintang[1], Abdul Hafiz[1], Liora Simbolon[1], Jonathan Aldo Sinaga[1], Asnan Rinovan[3], Dedy Anwar[4], Aris Setiawan[5], Anis Tatik Maryani[6], Sudibyo[4], Dwi Umi Siswanti[7], Ahmad Tawfiequrahman Yuliansyah[2], Himawan Tri Bayu Murti Petrus[2]

[1]Sustainable Mining and Environmental Research Group, Department of Mining Engineering, Faculty of Technology and Industry, Insitut Teknologi Sumatera, Lampung, Indonesia
[2]Sustainable Mineral Processing Research Group, Department of Chemical Engineering, Universitas Gadjah Mada, Jalan Grafika No. 2, Bulaksumur, Depok, Sleman, Yogyakarta-55281, Indonesia
[3]Research Center for Minerals Technology, Badan Riset Inovasi Nasional, Lampung, Indonesia
[4]Department of Bioprocess Engineering, Institut Teknologi Del, Jalan Sisingamangaraja, Sitoluama, Laguboti, Toba, North Sumatera-22381, Indonesia
[5]Department of Chemical Engineering, Universitas Lampung, Jl. Prof. Dr. Ir. Sumantri Brojonegoro No.1, Gedong Meneng, Kec. Rajabasa, Kota Bandar Lampung, Lampung 35141, Indonesia
[6]Postgraduate Program of Environmental Science, Universitas Jambi, Jambi, Indonesia
[7]Department of Biology, Faculty of Biology, Universitas Gadjah Mada, Yogyakarta, Indonesia
* Corresponding Author, email: yudha.wibowo@ta.itera.ac.id

Copyright ©2026 by Authors,
Published by Environmental Engineering Department,
Faculty of Engineering, UniversitasDiponegoro
This open accessarticle is distributed under a
Creative Commons Attribution 4.0 International License

Abstract

Phytomining offers a novel and sustainable method for removing pollutants and recovering valuable metals from contaminated environments. This study investigated the potential of *Helianthus annuus* L., *Eichhornia crassipes*, and *Pistia stratiotes* in removing Cu and Zn from polluted soil and water, focusing on their metal uptake and recovery efficiency. The experimental results demonstrated that *H. annuus* removed up to 49% of Cu and 40% of Zn from soil, while *E. crassipes* and *P. stratiotes* achieved up to 99% Cu removal from water, with lower but significant Zn removal efficiencies. Bioaccumulation and translocation factors revealed that the aquatic plants had a higher capacity for metal uptake compared to terrestrial plants. The study also demonstrated that nearly 100% of the absorbed Cu could be recovered from plant biomass, providing both environmental and economic benefits. These findings highlight the potential of phytomining as a dual-purpose strategy for environmental remediation and resource recovery, offering an eco-friendly alternative to traditional mining techniques.

Keywords: Critical minerals removal; environmental remediation; phytomining; plants uptake; valuable minerals recovery

1. Introduction

Environmental degradation has become a pressing global issue due to industrial activities, affecting approximately 3.2 billion people (40% of the global population), according to the United Nations. Land degradation, driven by these activities, places up to $577 billion in annual global crop

production at risk due to pollinator loss. Moreover, 25% of global greenhouse gas emissions are attributed to land clearing, crop production, and fertilization. Among various industrial sectors, mining and metallurgical industries are among the most significant contributors to environmental pollution, particularly through the release of heavy metals such as Cu and Zn (Di Palma and Medici, 2002; Tonhá et al., 2020).

Copper and zinc, while critical and valuable minerals for industrial use, are also notorious environmental pollutants. For instance, high production rates of Cu in countries such as Chile (5.6 million tons), China (1.6 million tons), and Peru (2.4 million tons) in 2020, coupled with increasing demand, pose significant pollution risks to soil and water (Izydorczyk et al., 2021). Similarly, global Zn reserves were estimated at 230 million tons in 2018, with production and consumption rates nearly balancing at 13.42 million tons and 13.74 million tons, respectively (www.usgs.gov). Conventional mining methods, such as open-pit mining and hydro- or pyrometallurgical processes, dominate these industries and are major sources of environmental contamination (Wang et al., 2020; Zhou et al., 2021).

Despite growing awareness of these pollution problems, current research has largely focused on treatment methods for mitigating contamination rather than developing sustainable techniques for both removing and recovering valuable minerals. While many studies address pollution control, there is a significant gap in the literature regarding innovative methods that not only reduce environmental contamination but also enable the recovery of these critical minerals for reuse. No studies have explored the use of biological methods, such as phytomining, to simultaneously address environmental degradation and recover valuable metals from polluted environments.

This study seeks to fill this critical gap by being the first to investigate the potential of phytomining using *Helianthus annuus* L., *Eichhornia crassipes*, and *Pistia stratiotes* for the removal of Cu and Zn from contaminated soil and water. Additionally, this research aims to recover these metals for potential industrial use, offering a sustainable alternative to conventional mining practices that currently exacerbate environmental degradation. The novelty of this approach lies in its dual purpose environmental remediation and resource recovery, providing both ecological and economic benefits.

The objectives of this study are to (1) explore the potential of phytomining as an emerging and innovative method for the removal of Cu and Zn from contaminated environments; (2) evaluate the performance of different plants in the removal and recovery processes; (3) assess the economic and environmental benefits of phytomining; and (4) provide recommendations for further research and industrial applications.

2. Materials and Methods

2.1 Plants and Soil Sampling

Helianthus annuus L., *Eichhornia crassipes*, and *Pistia stratiotes* were collected from Lampung Province, Indonesia. These plants were used as hyperaccumulator plants (January et al., 2008; Victor et al., 2016) and are abundant in Indonesia. All plant samples were cultivated for 7 days under controlled environmental conditions to ensure acclimatization and uniformity in their physiological state.

In addition, contaminated soil and water samples were synthetically prepared to simulate pollution conditions. This involved the addition of zinc sulfate ($ZnSO_4$) and copper sulfate ($CuSO_4$) to distilled water and sterile soil, respectively, at predetermined concentrations to achieve desired levels of contamination. The concentrations used were calibrated based on preliminary toxicity assessments to ensure that they effectively mimic environmental pollution scenarios. Figure 1 shows the materials and methods used in this study. Figure 1 shows the materials and methods used in this study.

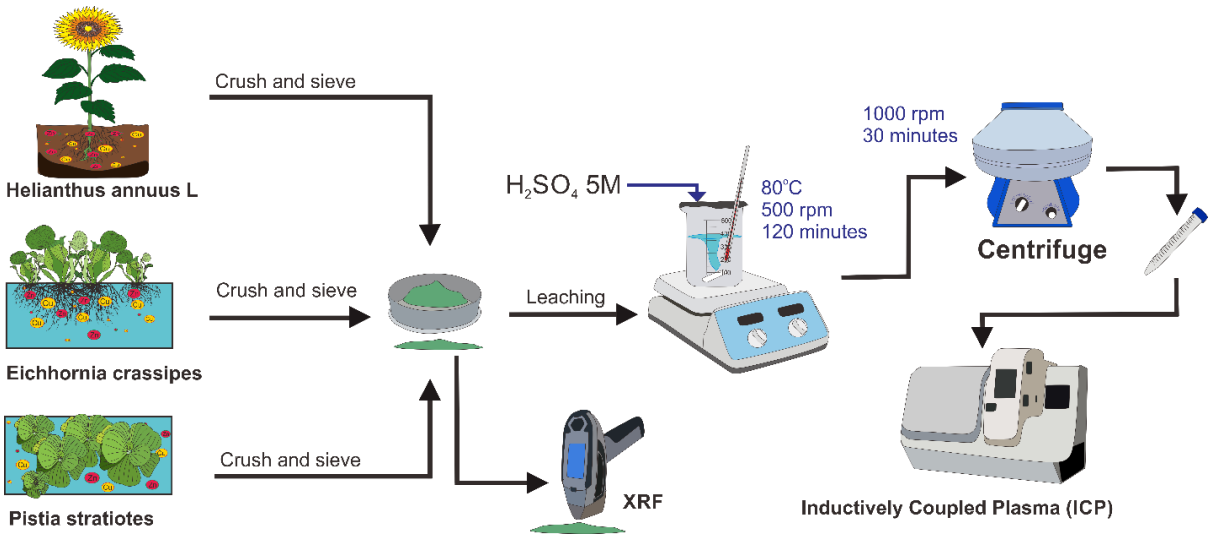

Figure 1. Materials preparation and method of the study

2.2 Experimental Design

The experimental setup involved a glass reactor measuring 31 cm x 18 cm x 23 cm filled with 10 liters of artificially polluted water. The study focused on the phytoremediation capabilities of aquatic plants *E. crassipes* and *P. stratiotes*. These plants were chosen for their known efficacy in absorbing critical minerals from contaminated environments. In addition, *H. annuus* L. was cultivated in polybags sized 40 cm × 40 cm filled with artificially contaminated soil. This setup aimed to assess the plants' ability to uptake and accumulate heavy metals from soil.

The concentration of critical minerals in the water was quantified in triplicate using an inductively coupled plasma (ICP) instrument, specifically the Thermo Scientific Vanquish iCAP RQ (model RQ 02611). In addition, a portable X-ray fluorescence (XRF) analyzer was employed to measure the concentrations of Cu and Zn in the soil samples. The phytoremediation process was conducted for 18 days. During this time, the concentrations of critical minerals in both soil and water were monitored daily. This frequent monitoring was crucial to evaluate the dynamic process of metal uptake and to adjust conditions as necessary to optimize phytoremediation efficiency.

After the completion of the phytoremediation process, the concentrations of Cu and Zn were measured in both the shoot and root tissues of the plants. This analysis aimed to determine the distribution and accumulation of metals in different plant parts, providing insights into the mechanisms of phytoremediation employed by *E. crassipes*, *P. stratiotes*, and *H. annuus* L

Subsequent to the metal concentration analysis, a leaching procedure was conducted to extract the absorbed metals from the plant tissues. This involved treating both the shoot and root parts with 5M H_2SO_4 at a temperature of 80°C. The mixture was agitated at 500 rpm for 120 minutes. This step was critical for assessing the total metal uptake by the plants and recovering the metals for further analysis.

2.3 Removal Percentage

The removal efficiency of Cu and Zn by the plants was quantified using the following formula to determine the percentage of metal removed from the environment. This formula follows the removal percentage in the adsorption process, as shown in Eq. 1 (Bhattacharya et al., 2008)

$$Removal\ percentage\ (\%) = \left(\frac{C_0 - C_e}{C_0}\right) \times 100 \qquad \text{Eq 1}$$

C_0 represents the initial concentration of metals in the soil (mg/kg) or water (mg/L) at the start of the experiment and C_e represents the final concentration of metals in the soil (mg/kg) or water (mg/L).

This formula was applied to daily collected data points from both soil and water samples, allowing for a detailed tracking of the reduction in metal concentrations over the course of the study. This approach enabled an assessment of phytoremediation progress and the effectiveness of each plant species in reducing the pollutant load.

2.4 Bioaccumulation and Translocation Factors

The bioaccumulation factor is a crucial metric used to quantify the ability of a plant to accumulate heavy metals from the soil or water into its biomass. It is calculated using the following formula (Galal and Shehata, 2015):

$$Bioaccumulation\ factor = \frac{C_{plant}}{C_{environment}} \quad \text{Eq 2}$$

Where C_{plant} is the concentration of the metal in the plant tissue (mg/kg dry weight) and $C_{environment}$ is the initial concentration of the metal in the environment (soil or water) (mg/kg or mg/L).

The translocation factor measures the efficiency of metal transport from roots to shoots, which is pivotal for understanding the distribution of metals within the plant. It is defined as follows (Galal and Shehata, 2015):

$$Translocation\ factor = \frac{C_{shoot}}{C_{root}} \quad \text{Eq 3}$$

C_{shoot} is the concentration of the metal in the shoot tissue (mg/kg dry weight) and C_{root} is the concentration of the metal in the root tissue (mg/kg dry weight).

Prior to analysis, the plant samples were prepared by drying in an oven at 150°C for two hours. This step is crucial to reduce moisture content and ensure consistent weight measurements for accurate metal concentration assessment.

2.5 Recovery of Critical Minerals

To recover critical minerals from plant biomass used in phytoremediation, root and stem powders were prepared and utilized in a leaching experiment. Specifically, 5 grams and 10 grams of the respective powders were added to a beaker containing 50 mL of 5M sulfuric acid (H_2SO_4). This acidic medium was preheated to 80°C on a hot plate to facilitate the leaching process. The mixture was continuously agitated with a magnetic stirrer bar to ensure uniform contact between the plant material and acid. The leaching was conducted for a duration of 60 minutes to maximize mineral extraction.

Following leaching, the mixture was transferred into a centrifuge tube and centrifuged at 1000 rpm for 30 minutes. This step was crucial for separating the solid biomass from the mineral-rich supernatant. The clear supernatant was then carefully collected and subjected to inductively coupled plasma (ICP) analysis to quantify the recovery of minerals. This method provides a robust measure of the efficiency of mineral extraction from treated plant biomass.

2.6 Economic Evaluation of Phytomining

The economic evaluation of the phytomining process described in this study offers essential insights into its financial feasibility. This section explores the costs involved in the establishment and operation of phytomining systems and the potential revenues derived from the recovery of critical minerals, such as Cu and Zn. Phytomining using *H. annuus*, *E. crassipes*, and *P. stratiotes* provides a sustainable approach to recovering these metals. To determine the economic performance of this system, the gross profit margin (GPM) was calculated, serving as an indicator of profitability. The formula used for the GPM is:

$$GM = \frac{Total\ revenue - Cost\ of\ Goods\ sold}{Total\ revenue} \quad \text{Eq 4}$$

The revenue generated comes primarily from the recovery of metals from plant biomass. The recovery of metals, such as Cu and Zn, from each plant species' biomass is estimated using the following equation, where R represents the total recovery, Y is the yield of biomass per hectare, and C is the concentration of metal in the biomass:

$$R = Y \times C \quad \text{Eq 5}$$

This formula provides the total amount of metal accumulated in the plant biomass, which is then scaled for a production area of 10 hectares. To estimate the annual recovery of metals, another equation is employed that considers plant growth rates and harvest frequency. The annual recovery is calculated as follows:

$$Annual\ recovery = RPc \times NHC \quad \text{Eq 6}$$

where RPc is the recovery per cycle and NHC is the number of harvest cycles per year. This allows for the estimation of the total annual recovery of Cu and Zn, considering both plant growth rates and the frequency of harvests.

The cost of production, also known as the *cost of production* (COP), represents the expenses incurred throughout the phytomining process from planting to metal recovery. It is calculated using the formula:

$$COP = \frac{Total\ production\ cost}{Total\ yield} \quad \text{Eq 7}$$

This equation ensures a clear understanding of the costs associated with each unit of biomass produced. Production costs include expenses related to land preparation, planting, harvesting, metal extraction, and processing.

By comparing the COP to the revenue generated from the sale of recovered metals, a clear assessment of the phytomining system's financial viability can be made. Additional factors, such as the market price of metals, transportation, and environmental regulations, must also be considered in the final economic analysis. Based on these calculations, phytomining using these plant species may present a sustainable and cost-effective method for metal recovery in certain regions, particularly where traditional mining methods are not feasible or environmentally damaging.

2.7 Quality Control of Samples

Rigorous quality control measures were implemented to ensure the integrity of the samples throughout the study. Prior to initiating the experimental procedures, all sampling tools were rigorously evaluated to meet the specific criteria essential for maintaining sample purity and preventing contamination. The materials used in these tools were selected for their inert properties, ensuring that they did not interact with or alter the samples. Additionally, the tools were designed to be easily washable and reusable, facilitating thorough cleaning between uses to prevent cross-contamination of the tools. The design of the sampling instruments also focused on practicality and safety; the tools were lightweight and portable, making them easy to transport and handle in various field and laboratory settings. This attention to detail in the preparation and handling of sampling equipment is crucial for achieving reliable and reproducible results in studies of phytotransformation and mineral recovery processes.

3. Result and Discussion

3.1 Soil and Water Characteristics

Figure 2 shows the concentrations of Cu and Zn in soil and water samples. Specifically, the initial soil concentrations for H. annuus were 155 mg/kg for Cu and 181 mg/kg for Zn. Additionally, the water

samples showed varied contamination levels. For *E. crassipes* and *P. stratiotes*, the concentrations of Cu and Zn exceeded the safety limits set by the World Health Organization (WHO). The WHO guideline for Cu in drinking water is 2.0 mg/L, a limit based on avoiding gastrointestinal issues associated with higher copper levels. Zinc, while typically not harmful in drinking water, can impart an astringent taste and milky appearance when concentrations exceed 3 mg/L (Fitzgerald, 1998).

In the United States, the Environmental Protection Agency (EPA) has established a maximum contaminant level goal (MCLG) for copper at 1.3 mg/L to prevent gastrointestinal distress and other health effects from prolonged exposure. The secondary maximum contaminant level (SMCL) for zinc is set at 5 mg/L, focusing on mitigating aesthetic issues, such as taste and water discoloration (https://www.epa.gov/sdwa/secondary-drinking-water-standards-guidance-nuisance-chemicals). The European Union (EU) Drinking Water Directive adheres to the WHO guideline for copper at 2.0 mg/L (Fewtrell et al., 2001). Similar to the WHO, the EU does not specify a limit for zinc, recognizing it as generally non-harmful at typical environmental levels. However, local guidelines may suggest limits to address taste and appearance concerns.

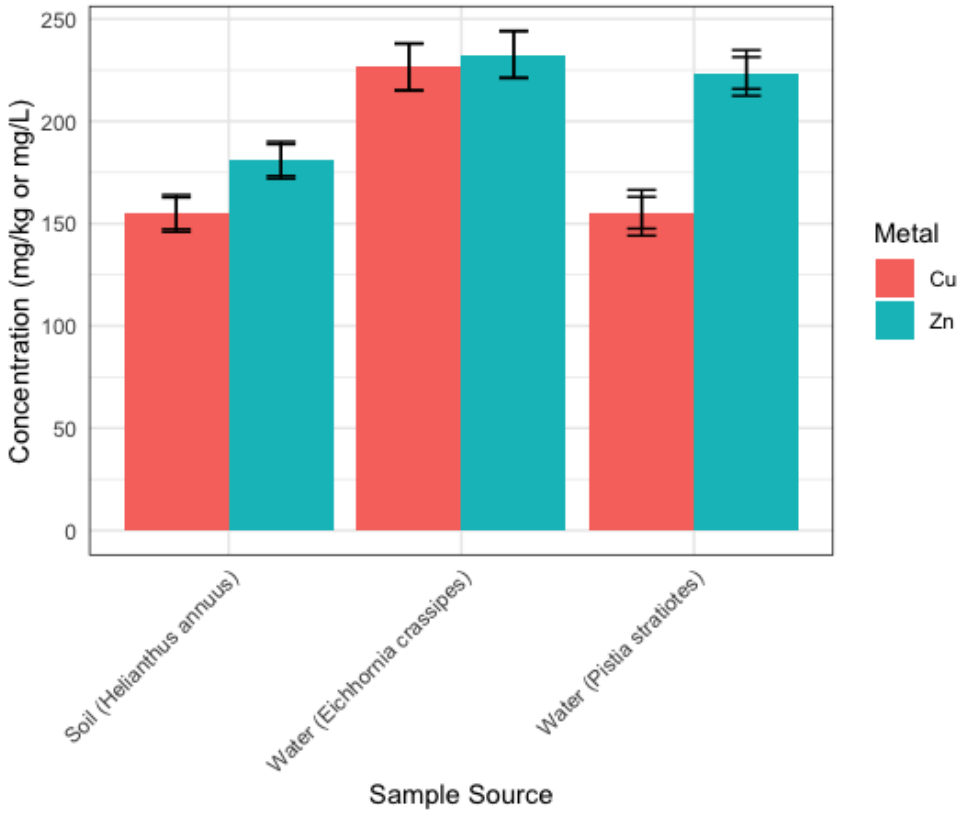

Figure 2. Soil and water characteristics

3.2 Plants Characteristics

Figure 3 illustrates the morphological characteristics of the plants studied. For this investigation, plants were selected based on uniformity in stem and root length, maintained within a 5% variation. The average stem height for *H. annuus* was approximately ±50 cm with a root length of ±7 cm. This uniformity ensures comparable physiological performance among the specimens. Similarly, for *P. stratiotes*, the shoot and root lengths were about ±8 cm and ±15 cm, respectively. *E. crassipes* exhibited a shoot height of approximately ±28 cm and a root length of ±10 cm.

Plants with proportionate stem and root dimensions typically possess robust, deep root systems, which are crucial for optimal growth and stability. Such architecture enables plants to access and

remediate pollutants over a larger soil volume, enhancing phytoremediation efficiency. Deep and sturdy roots can penetrate further into the soil to reach contaminants, whereas taller stems facilitate greater transpiration rates, aiding in the transport and volatilization of specific pollutants.

In contaminated environments, balanced stem-to-root ratios are vital for structural support, helping plants withstand abiotic stress caused by pollutants. This stability is crucial not only for preventing soil erosion but also for maintaining plant integrity during prolonged phytoremediation processes.

Healthy and expansive root systems enhance interactions within the rhizosphere, the zone where roots engage with soil microorganisms. These microorganisms often play a significant role in pollutant degradation. Well-developed root systems support a larger and more diverse microbial population, which in turn boosts pollutant breakdown. Furthermore, taller stems are essential for optimal light capture, which is critical for efficient photosynthesis. Robust photosynthesis is vital for plant growth and supports physiological processes that facilitate phytoremediation, such as the translocation of pollutants within the plant.

The balance between stem and root growth can also influence the local microclimate by regulating the temperature, humidity, and air movement around the phytoremediation site. These factors may affect pollutant volatilization, as well as the comfort and survival of microorganisms involved in phytoremediation.



Figure 3. Plants characteristics

3.3 Concentration of Critical Minerals in Soil and Water During Phytoremediation

Table 1 presents the concentrations of Cu and Zn during the 18-day phytoremediation period. *H. annuus* demonstrated significant reductions in Cu and Zn concentrations from 124 mg/kg and 163 mg/kg to 79 mg/kg and 109 mg/kg, respectively. Additionally, aquatic plants such as *E. crassipes* and *P. stratiotes* exhibited comparable results, particularly in terms of the substantial reduction in Cu. Overall, the data indicate that the removal efficiency for Cu surpassed that for Zn across all the plant species studied.

Furthermore, Table 1 illustrates that the concentration of Cu in water is more effectively reduced than in soil. This discrepancy could be attributed to the faster mobilization of Cu and Zn in aqueous environments compared to terrestrial systems. This phenomenon aligns with the findings of

electrokinetic soil remediation studies, which suggest that the introduction of a flushing fluid can accelerate pollutant mobilization (Ramadan et al., 2021; Wibowo and Ramadan, 2021).

The decline in metal concentrations is likely due to the plants' capabilities to uptake, accumulate, and potentially convert metals into less toxic forms via metabolic activities within the tissues. These results corroborate earlier research indicating that both *E. crassipes* and *P. stratiotes* are effective in mitigating pollutants in wastewater (Gusti Wibowo et al., 2023; Wibowo, Syahnur, et al., 2023).

Table 1. Critical mineral concentration in soil and water

Day	*Helianthus annuus*		*Eichhornia crassipes*		*Pistia stratiotes*	
	Cu (mg/kg)	Zn (mg/kg)	Cu (mg/L)	Zn (mg/L)	Cu (mg/L)	Zn (mg/L)
1	124	163	220.03	232.49	151.45	222
2	115	147	213.81	232.13	149.55	220.99
3	108	135.33	189.26	227.04	125	216.96
4	106	134	171.47	225.33	108.56	216.69
5	103	127.67	187.16	213.8	26.52	212.84
6	100	125.33	157.8	222.63	28.48	195.66
7	92.66	122.33	100.92	216.26	17.86	184.71
8	99	121	70.75	220.9	23.13	188.32
9	87.66	120.33	53.98	208.04	20.43	184.76
10	82.33	120	63.11	209.57	21.17	184.71
11	95	120	65	207.3	16.71	189.96
12	94.67	118	53.91	206.42	17.05	182.96
13	99	117	41.13	205.79	14.34	182.37
14	92.66	117	33.89	201.67	10.62	181.72
15	98	113	32.81	198.54	6.97	181.09
16	86	111	25.1	197.82	1.01	176.65
17	80.66	110.33	24.35	192.19	0.88	166.12
18	79.33	109	22.3	169.45	0.68	164.95

3.4 Performance of Plants in Removal Critical Minerals

Table 2 shows the removal percentage of Cu and Zn during phytoremediation. *Helianthus annuus* demonstrated a steady increase in the reduction percentages for both Cu and Zn in soil, reaching a maximum reduction of 49% for Cu and 40% for Zn by day 18. This gradual increase suggests an effective accumulation and sequestration mechanism within the terrestrial plant system, particularly for Cu.

In contrast, aquatic plants *E. crassipes* and *P. stratiotes* showed a more rapid and higher reduction efficiency for Cu in water, with both reaching near-complete removal (90% and 99%, respectively) by the end of the period. Zn removal efficiency in water is notably less effective compared to Cu, particularly in the early days of the experiment, but shows significant improvement over time, particularly in *P. stratiotes,* where it reaches 26% by day 18.

The results of this study are consistent with previous findings, suggesting that *E. crassipes* and *P. stratiotes* are potent phytoremediators in aquatic environments, capable of rapidly adapting to increased pollutant concentrations and effectively reducing them (Imron et al., 2023; Kabeer et al., 2022, 2022; Tabinda et al., 2020). The higher efficacy of Cu removal compared to Zn, particularly in water, may indicate inherent differences in the bioavailability and uptake mechanisms of these metals by the plants used. Further investigation into the metabolic pathways responsible for this discrepancy could provide insights into enhancing Zn removal rates in the future.

This study builds on the foundational work, which explored the capacities of *E. crassipes* and *P. stratiotes* in environments with lower concentrations of Cu (2, 4, 6, and 8 mg/L) (Tabinda et al., 2020). The consistent and potent performance of these aquatic plants supports their integration into existing wastewater treatment infrastructures, particularly in settings plagued by elevated Cu concentrations.

In addition to plant uptake, the reduction of critical minerals observed in this study may also be attributed to microbial activity, particularly by bacteria (Kurniawan et al., 2022). These microorganisms adapt through natural selection, modifying both their phenotype and genotype to survive in contaminated environments (Lenski, 2017). Specifically, bacteria develop resistance to toxic pollutants, such as heavy metals or other critical minerals, to preserve their populations (Kurniawan et al., 2022). These resistant strains are capable of tolerating high levels of hazardous heavy metals and can mitigate their impact through various biological mechanisms. These include biotransformation, in which the chemical structure of the metal is altered; bioreduction and bio-oxidation, which change the oxidation state of the metal; biosorption, where metals are adsorbed onto bacterial cell surfaces; and bioaccumulation, where metals are accumulated inside bacterial cells.

Moreover, the consistent performance of *E. crassipes* and *P. stratiotes* suggests that these plants can be integrated into existing wastewater treatment frameworks, particularly in settings burdened by high Cu concentrations. Future studies should explore the long-term sustainability of these plants for phytoremediation, potential toxic effects on plants at higher concentrations, and the ecological impacts of their large-scale use in natural water bodies.

Table 2. Removal percentage of critical minerals from soil and water

Day	Helianthus annuus		Eichhornia crassipes		Pistia stratiotes	
	Cu (%)	Zn (%)	Cu (%)	Zn (%)	Cu (%)	Zn (%)
1	20	10	3	0	2	1
2	26	19	6	0	4	1
3	30	25	16	2	20	3
4	32	26	24	3	30	3
5	34	29	17	8	83	5
6	35	31	30	4	82	13
7	40	32	55	7	88	17
8	36	33	69	5	85	16
9	43	34	76	11	87	17
10	47	34	72	10	86	17
11	39	34	71	11	89	15
12	39	35	76	11	89	18
13	36	35	82	12	91	18
14	40	35	85	13	93	19
15	37	38	86	15	96	19
16	45	39	89	15	99	21
17	48	39	89	17	99	26
18	49	40	90	27	99	26

3.5 Removal Mechanism

The removal of Cu and Zn from the environment via phytoremediation involves the sophisticated systems of xylem and phloem in plants (**Figure 4**), which are crucial for the absorption, transportation, and redistribution of these metals within the plant structure (Page and Feller, 2015; Song et al., 2017).

Plants absorb Cu and Zn primarily through their roots, where these metals are taken up in their ionic forms (Cu^{2+} and Zn^{2+}) from the surrounding soil solution or water. This uptake is facilitated by transport proteins located within the root cells, which allow the passage of these ions into the plant's internal systems (Grotz and Guerinot, 2006).

Once inside the root cells, Cu and Zn ions are transported across cell membranes by specialized proteins known as metal transporters. These ions can move through either the apoplast, the cell wall space, or the symplast, which is the cytoplasmic continuum interconnected by plasmodesmata, eventually reaching the vascular tissues (Eren and Argüello, 2004). After absorption, the ions are loaded into the xylem vessels, the primary conduits for upward transport to other parts of the plant, particularly the leaves. The xylem also carries water and dissolved minerals, and the movement of Cu and Zn upward is driven by transpirational pull, a process in which water evaporates from the stomata in the leaves, creating negative pressure that draws water and dissolved ions from the roots (Curie et al., 2009).

As Cu and Zn are transported via the xylem, plants initiate detoxification mechanisms to mitigate the potential toxicity of these metals. They may chelate the metals with organic acids or bind them to proteins such as metallothioneins or phytochelatins, which help prevent damage to plant tissues (Hall, 2002; Rauser, 1999). Once the metals reach the aerial parts of the plant through the xylem, they can be utilized in small amounts for essential metabolic functions or stored in vacuoles and cell walls to prevent toxicity. Excess metals are typically sequestered in older leaves or stem tissues, where they pose less risk to plant growth and development (Wei et al., 2007).

In some cases, Cu and Zn can also be redistributed throughout the plant via the phloem, a process known as remobilization, which typically occurs when the plant needs to transport these nutrients to storage tissues, such as seeds or fruits, or during the senescence of leaves and shoots (Cao et al., 2020). Although the phloem predominantly transports organic molecules, it can also carry small amounts of heavy metals along with the flow of sugars and other metabolites, although it is less commonly involved in the bulk movement of heavy metals compared to the xylem (Curie et al., 2009). This sophisticated system of uptake, transport, detoxification, and redistribution illustrates the complex interactions between plants and their environment in the context of heavy metal management.

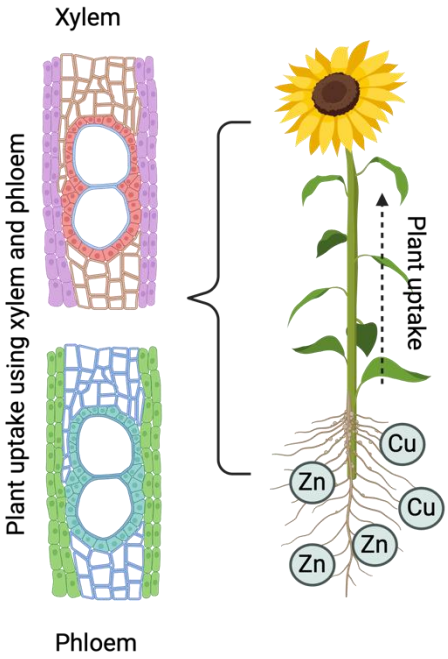

Figure 4. Removal of Cu and Zn using plant through xylem and phloem

3.6 Bioaccumulation and Translocation Factors

Table 3 presents an interesting snapshot of the concentrations of critical minerals (Cu and Zn) in the root and shoot parts of three distinct plant species: *H. annuus*, *E. crassipes*, and *P. stratiotes*. This information is vital for understanding each plant's role in the phytoremediation process, particularly in terms of their capacity to absorb and translocate these metals from their roots to their aerial parts. The BCF and TF provide useful indicators for evaluating metal accumulation and internal distribution within plant tissues; however, these parameters should be interpreted cautiously and should not be considered as standalone indicators of phytomining performance. In this study, aquatic plants, particularly *Eichhornia crassipes* and *Pistia stratiotes*, exhibited higher BCF values compared with *Helianthus annuus*, indicating their greater capacity to accumulate Cu and Zn from aqueous environments. This behavior is associated with the direct contact between the plant root systems and dissolved metal species, which generally enhances metal availability and uptake efficiency compared with soil-based systems.

The interpretation of TF provides additional insight into metal partitioning between roots and shoots. A TF value greater than one indicates preferential translocation of metals from roots to aboveground tissues, which is considered favorable for phytoextraction because the harvested biomass represents the primary metal recovery fraction. Conversely, TF values below one indicate greater metal retention in roots, suggesting phytostabilization rather than efficient aboveground extraction. Therefore, plants with high BCF but low TF may be effective for immobilizing metals, whereas plants with high BCF and TF values may offer greater potential for metal recovery through biomass harvesting.

Nevertheless, BCF and TF values are influenced by several experimental factors, including the initial metal concentration, exposure duration, biomass production, and metal partitioning among different plant tissues. A high BCF value does not necessarily translate into high phytomining efficiency because metal recovery depends on both the tissue concentration and total biomass yield. Therefore, the potential of plants for phytomining should be evaluated by integrating the accumulation capacity, biomass productivity, translocation behavior, and subsequent metal recovery efficiency, rather than relying solely on BCF and TF values.

For *H. annuus*, the data show relatively balanced concentrations of Cu and Zn between the root (157 mg/kg for Cu, 111 mg/kg for Zn) and shoot (100 mg/kg for Cu, 98 mg/kg for Zn) components. This suggests a moderate but consistent ability to translocate these metals, which could be beneficial for soil-based phytoremediation processes where both accumulation and translocation are crucial.

In contrast, *E. crassipes* displays a dramatic difference in metal concentrations between its root and shoot parts. The concentration of Cu in the roots was 348 mg/kg, which significantly increased to 1240 mg/kg in the shoots. Similarly, the Zn concentration increased from 500 mg/kg in the roots to 660 mg/kg in the shoots. These high translocation rates highlight *E. crassipes* as a particularly effective agent for the phytoremediation of water environments, capable of not only absorbing high levels of metals but also efficiently transferring them to its aerial parts, facilitating easier harvest and disposal.

P. stratiotes showed an even more pronounced capability, especially for Cu, with root concentrations at 900 mg/kg and shoot concentrations matching those of *E. crassipes* at 1240 mg/kg. For Zn, the levels were nearly equal between the root (600 mg/kg) and shoot (630 mg/kg), suggesting effective uptake and balanced translocation. This species is also highly suitable for aquatic systems, where its ability to manage high metal concentrations can be leveraged for cleaning water bodies contaminated with heavy metals. These observations provide crucial insights into the potential applications of these plants in phytoremediation strategies. They suggest specific roles for each plant based on their metal handling capabilities of *H. annuus* for more balanced soil remediation, *E. crassipes*, and *P. stratiotes* for targeted, effective remediation in aquatic settings.

Table 3. Cu and Zn concentration in root and shoot

Plants	Critical minerals	Root	Shoot
Helianthus annuus	Cu	157	100
	Zn	111	98
Eichhornia crassipes	Cu	348	1240
	Zn	500	660
Pistia stratiotes	Cu	900	1240
	Zn	600	630

Table 4 concerning the Bioaccumulation Factor (BCF) and Translocation Factor (TF) for *H. annuus*, *E. crassipes*, and *P. stratiotes* reveal crucial insights into each plant's capability to accumulate and move critical minerals like Cu and Zn within their structure. The BCF indicates how effectively a plant can accumulate metals relative to their concentration in the environment, while the TF measures the plant's ability to transfer these metals from roots to aerial parts.

H. annuus demonstrates a moderate BCF for Cu (0.716) and a higher BCF for Zn (1.23), suggesting a stronger affinity for accumulating Zn from soil. Conversely, aquatic species such as *E. crassipes* and *P. stratiotes* exhibit notably higher BCFs; *E. crassipes* has BCFs of 5.47 for Cu and 2.12 for Zn, and *P. stratiotes* records 5.80 for Cu and 2.68 for Zn. These figures suggest that these aquatic plants are exceptionally adept at uptaking heavy metals from water, highlighting their substantial potential for cleaning aquatic environments.

Regarding TF, *H. annuus* more effectively translocates Cu than Zn, with TFs of 0.883 and 0.637, respectively. This indicates a greater efficiency in moving Cu to its aerial parts. *However*, E. crassipes shows a divergence in its ability to translocate Cu and Zn; it has a lower TF for Cu at 0.281, suggesting retention in the roots, whereas for Zn, the TF is 1.32, indicating efficient movement to aerial parts. *P. stratiotes* excels with TFs of 1.38 for Cu and 1.05 for Zn, pointing to its effectiveness in translocating both metals, which can be particularly advantageous for phytoextraction processes where plant biomass is harvested for metal recovery.

These findings underscore the strong phytoremediation potential of these plants, especially the aquatic types, for use in metal-polluted water environments. The variation in TF among these plants also suggests different applications based on specific site contamination profiles, paving the way for tailored phytoremediation approaches. Future studies should aim to optimize conditions that maximize the bioaccumulation and translocation abilities of these plants and explore the genetic and environmental influences that could enhance their phytoremediation efficacy.

Table 4. BCF and TF of plants

Plants	Critical minerals	BCF	TF
Helianthus annuus	Cu	0.71612903	0.88288288
	Zn	1.229732905	0.636942675
Eichhornia crassipes	Cu	5.473888668	0.280645161
	Zn	2.116402116	1.32
Pistia stratiotes	Cu	5.795235	1.377778
	Zn	2.683123	1.05

3.7 Recovery of Critical Minerals

Figure 5 shows the performance of Cu and Zn recovery from the roots and shoots of plants. This study showed that the recovery of Cu from *P. stratiotes* showed the best recovery up to 890 ppm, with a concentration of 900 ppm in the roots. This condition showed that almost 100% of Cu was successfully recovered and can be utilized in other industrial applications. Compared with previous studies, this study showed better performance in the recovery of Cu from contaminated soil compared with flushing method using 0.1 M aqueous solution of ethylenediaminetetraacetic acid, which only recovered 60% of Cu (Di Palma and Medici, 2002).

In addition, the removal of Cu from *Pistia stratiotes* also showed successful recovery with 598.81 ppm from 1240 ppm in the root. This study showed that the recovery of critical minerals from water is higher than that from soil. This finding also suggests a promising new method for the recovery of valuable minerals from industrial wastewater, such as mining and metallurgical industries. Several previous studies have reported that wastewater from mining and metallurgical industries contains high concentrations of Fe, Mn, Mg (Wibowo, Ramadan, et al., 2023), Al, Ca, (Wibowo et al., 2022), Cr, Ni, As, Cu, and Pb (Feng et al., 2004; Ramírez et al., 2018).

Figure 3(b) shows the recovery percentages of Cu and Zn in the roots and shoots of various plants. Notably, aquatic plants demonstrated higher recovery efficiency than terrestrial plants. Specifically, *E. crassipes* and *P. stratiotes* exhibited remarkably high recovery rates, approaching 100% for Cu. Contrasting behaviors were observed between *E. crassipes* and *P. stratiotes*; in *P. stratiotes*, the roots showed superior Cu recovery compared to other parts, whereas in *E. crassipes*, the shoots exhibited the highest Cu recovery rate. This differential accumulation may be attributed to the distinct physiological adaptations and metal uptake mechanisms inherent to each species, which favor metal translocation to different plant parts depending on environmental conditions and internal regulation.

H_2SO_4, a robust acid, effectively disrupts chemical bonds between metals and their associated organic or inorganic matrices, facilitating the dissolution of metals such as Cu and Zn trapped within plant tissues into solutions. The process begins with the acid penetrating plant tissues, where it degrades cell walls and liberates their contents, including the metals embedded within the cell structures. Subsequently, in this acidic milieu, Cu and Zn undergo chemical reactions to form soluble salts, such as $CuSO_4$ and $ZnSO_4$, aiding in their release from the plant matrix into the solution. Once transformed into ions, these metals can be efficiently separated from the remainder of the plant biomass through processes such as filtration or precipitation, simplifying their extraction and analysis.

During phytomining, critical minerals are typically found in the soil in solid states, often as minute mineral particles or as ions dissolved in soil pore water. Plants primarily absorb these minerals in their ionic form. In contrast, if leaching is employed, the minerals are dissolved into ions within the solution. This leaching process involves the use of water or other chemical solvents to dissolve minerals from various media, such as soil, rocks, or industrial by-products, transforming them into mobile ionic forms within the solution. Thus, these critical minerals can be utilized as valuable resources.

The solubilized minerals, once extracted, can be processed and refined for various applications, including manufacturing, technology, and environmental remediation. This dual approach of phytomining and leaching offers a comprehensive strategy for the recovery of valuable minerals, enhancing sustainability and reducing the environmental impact associated with traditional mining practices. By harnessing natural and chemical processes, these methods significantly contribute to resource conservation and the circular economy.

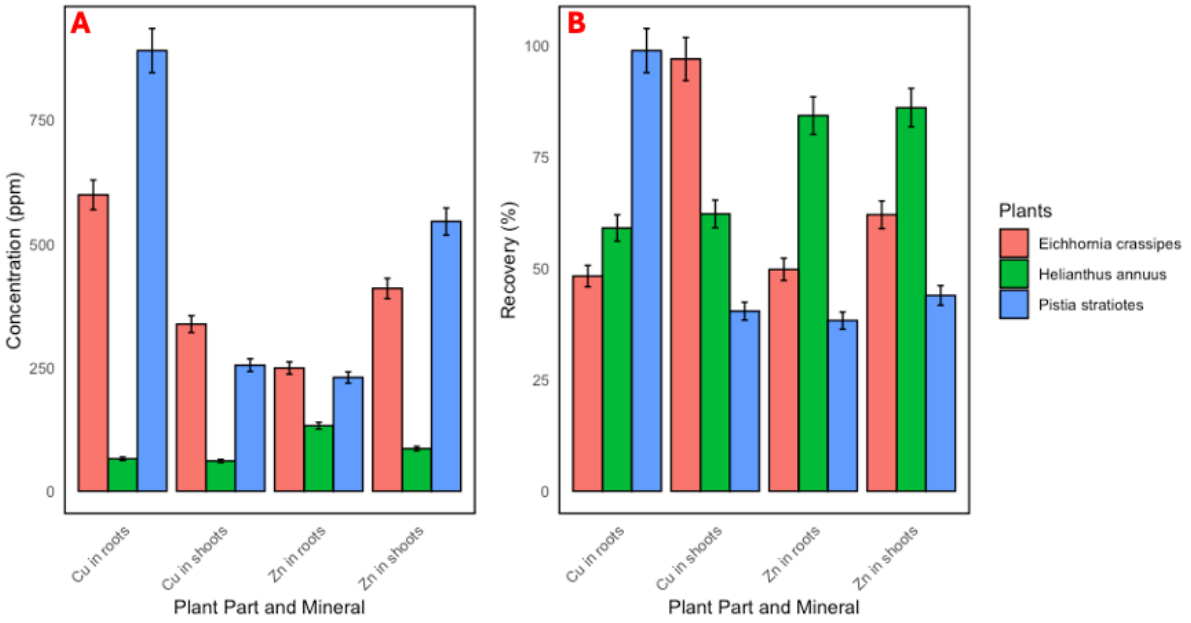

Figure 5. Recover percentage of critical minerals

3.8 Preliminary Scenario-Based Economic Assessment of Phytomining

The economic assessment presented in this study provides a preliminary scenario-based evaluation of the potential economic performance of phytomining for Cu and Zn recovery using selected metal-accumulating plants in the region. Unlike conventional mining operations, the economic performance of phytomining is strongly influenced by biological factors, including plant species, biomass productivity, metal accumulation capacity, harvesting frequency, and downstream metal recovery efficiencies. Therefore, the present calculation should be considered an indicative scenario analysis rather than a comprehensive techno-economic assessment of the process. The estimated economic outcomes depend on several assumptions, including biomass yield, metal concentration in harvested biomass, metal market prices, and operational costs, which may vary substantially depending on local environmental conditions, cultivation practices and processing technologies.

Biomass productivity represents one of the key parameters that control the economic potential of phytomining. A previous study reported that the maximum harvestable biomass was approximately 10–20 t ha $^{-1}$ year $^{-1}$ (Tangahu et al., 2011). In this assessment, a biomass yield of 12 tons ha^{-1} year^{-1} was considered based on reported biomass productivity values for high-biomass plant systems. However, actual biomass production may vary depending on soil quality, water availability, climate conditions, nutrient availability, and plant growth performance. Previous studies have demonstrated that metal accumulation in plant biomass varies considerably among plant species and environmental conditions, while subsequent metal recovery and partitioning are also influenced by biomass characteristics and processing strategies (Babst-Kostecka et al., 2016; Ro et al., 2018; Zhong et al., 2016). Therefore, future economic evaluations should incorporate experimentally measured biomass yield, tissue-specific metal concentrations, harvesting frequency, and recovery efficiency obtained from larger-scale phytomining trials.

For the present scenario analysis, hypothetical enriched biomass concentrations were assumed to estimate the relationship between biomass metal content and potential metal recovery. A Cu concentration of 0.375 wt% and a Zn concentration of 0.1875 wt% in harvested biomass were used as representative enrichment scenarios. These values are not intended to represent universal phytomining yields or direct experimental results, as actual metal concentrations depend strongly on plant species, contamination level, exposure duration, and environmental conditions. Based on a biomass yield of 12

tons ha^{-1} $year^{-1}$, these assumptions correspond to estimated recoveries of approximately 45 kg Cu ha^{-1} $year^{-1}$ and 22.5 kg Zn ha^{-1} $year^{-1}$, respectively. These values were subsequently used only for preliminary revenue estimation.

Metal market prices represent another important uncertainty in phytomining economics. In this assessment, Cu and Zn prices were assumed as representative market values of approximately USD 9,000 and USD 2,700 ton^{-1}, respectively. However, metal prices fluctuate continuously due to changes in supply–demand conditions, global economic trends, and geopolitical factors. Therefore, variations in commodity prices may substantially influence the estimated revenue generated from recovered metals. Similarly, operational costs associated with cultivation, harvesting, biomass processing, and metal recovery may vary depending on labor costs, technological requirements, energy consumption, and local infrastructure availability.

Under the assumed scenario, the estimated metal recovery generated potential revenues lower than the assumed annual operational cost of approximately USD 2,700 ha^{-1} $year^{-1}$, resulting in a negative gross margin. This indicates that the current phytomining configuration is not yet economically competitive under the evaluated assumptions. Nevertheless, the analysis identified several critical factors that could improve future economic performance, including enhancement of biomass productivity, improvement of metal accumulation efficiency, optimization of harvesting strategies, and reduction of downstream recovery costs. Integration with additional biomass utilization pathways, such as bioenergy production or recovery of valuable co-products, may also contribute to improving the overall economic balance of phytomining systems.

Beyond economic considerations, phytomining may provide environmental benefits by combining metal recovery with remediation of contaminated environments. The ability to generate biomass while reducing metal contamination may offer advantages over conventional remediation approaches that require extensive excavation and disposal. However, the actual environmental benefits should be quantified through a comprehensive life-cycle assessment, including cultivation inputs, biomass processing, chemical consumption, energy requirements, and waste management. Overall, the economic assessment presented here should be regarded as an initial scenario evaluation rather than as evidence of immediate economic feasibility. The results highlight that the successful implementation of phytomining requires an integrated optimization approach involving plant selection, biomass production, metal enrichment, efficient recovery processes, and environmental-economic evaluation under realistic field conditions.

3.9 Environmental Implications

Phytomining offers environmental advantages over conventional mining because it can recover metals while limiting excavation, heavy machinery use, and large-scale land disturbance. Conventional extraction commonly alters landscapes through vegetation clearance, soil removal, and waste generation, and may release heavy metals and acid mine drainage into surrounding ecosystems. Phytomining can reduce these pressures and provide a lower-impact option for metal-bearing contaminated sites by relying on plants and their root systems.

This approach can also support ecological restoration by gradually removing bioavailable metals and stabilizing contaminated substrates without extensive alteration of the original topography. Where site conditions and plant performance are suitable, this process may improve soil or water quality and facilitate the recovery of degraded land for subsequent managed uses. Figure 6 illustrates the potential role of phytomining in the restoration of an abandoned mine site.

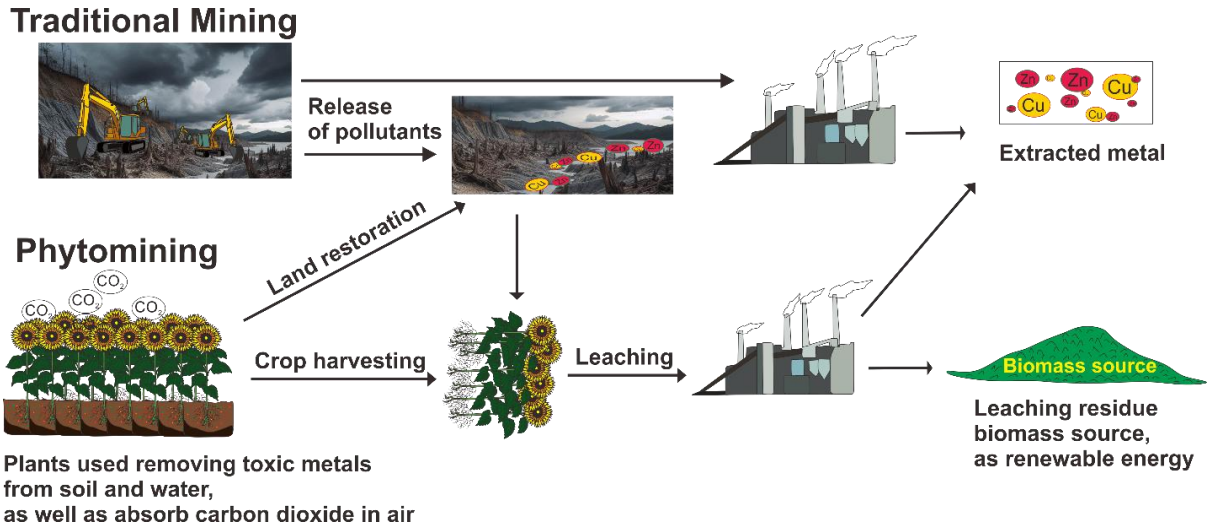

Figure 6. Phytomining in the restoration of abandoned mine sites

Additional benefits may arise from vegetation cover, including reduced erosion, improved site stability, and temporary carbon uptake during the growth of plants. Harvested biomass may also provide a secondary feedstock for energy or material recovery, provided that the accumulated metals are separated and managed safely. These co-benefits strengthen the role of phytomining as a remediation strategy, rather than merely as an alternative extraction technique.

Nevertheless, the environmental value of phytomining depends on its responsible implementation. Metal-rich biomass must be harvested, transported, processed, and stored under controlled conditions to prevent secondary contamination of the soil. Plant escape, metal transfer through food webs, chemical inputs used during recovery, and residual wastewater also require site-specific risk management. Accordingly, environmental performance should be assessed across the entire process, from cultivation and harvesting to metal recovery and final residue management.

3.10 Limitations and Recommendations for Future Research

This study has several limitations that define the scope of its conclusions. First, the experiments were conducted under controlled laboratory conditions using artificially contaminated soil and water. This design enabled a direct comparison among *Helianthus annuus*, *Eichhornia crassipes*, and *Pistia stratiotes*, but did not reproduce the heterogeneity of field sites, where pH, organic matter, competing ions, microbial communities, climate, and contaminant mixtures affect metal availability. Validation should therefore progress from controlled trials to field-contaminated soils, industrial wastewater, and mining-impacted environments across seasons and operating conditions.

Second, BCF and TF were used to characterize accumulation and internal metal distribution, but neither metric alone represents phytomining performance. Their values depend on initial concentration, exposure time, biomass production, and tissue partitioning, whereas recoverable metal yield also depends on harvest frequency and downstream extraction efficiency. Future assessments should report total metal mass per plant or unit area, dry-biomass yield, harvestable shoot fraction, and recovered metal yield alongside BCF and TF.

Third, the study quantified changes in Cu and Zn concentrations but did not resolve the physiological and chemical mechanisms controlling uptake, transport, detoxification, and sequestration. Subsequent studies should combine plant-response measurements with metal speciation and tissue localization. Relevant approaches include antioxidant and chelator assays, phytochelatin and metallothionein expression analysis, X-ray absorption spectroscopy, micro-X-ray fluorescence, ion chromatography, and microscopy-based elemental mapping. These measurements would clarify why

metals are retained in roots or transferred to shoots and support mechanism-based selection of plant species and operating conditions.

Fourth, acid-assisted leaching was demonstrated only at the laboratory scale, without a complete mass balance or systematic process optimization. Future recovery trials should quantify the metal inventory in the feed biomass, leachate, solid residue, and process losses, while testing acid concentration, solid-to-liquid ratio, temperature, residence time, and energy demand. Greener alternatives, including bioleaching, selective precipitation, and electrochemical recovery, should be compared with sulfuric acid leaching in terms of recovery efficiency, reagent use, wastewater generation, and residue safety.

Fifth, the economic evaluation was a preliminary scenario analysis based partly on assumed biomass productivity, operational costs, and metal prices rather than a full techno-economic assessment. Scale-up studies should use experimentally measured yields and site-specific data for cultivation, harvesting, transport, pretreatment, extraction, labor, energy, and residue management. Sensitivity and uncertainty analyses should then identify the conditions under which repeated harvesting, higher-grade feed, coproduct utilization, or lower-cost recovery could improve feasibility. A life-cycle assessment should be conducted in parallel to ensure that economic gains are not achieved by shifting environmental burdens to chemical use, energy demand, or waste treatment.

Taken together, the next stage of research should integrate field validation, biomass productivity, mechanistic evidence, complete metal mass balances, recovery-process optimization, and environmental-economic assessment within a single framework. This progression would convert the present proof-of-concept results into evidence suitable for selecting sites, designing harvest and recovery systems, and evaluating whether phytomining can be implemented safely and at a meaningful scale.

4. Conclusion

Environmental degradation, driven by mining and industrial activities, poses a substantial threat to global ecosystems and human well-being. This study introduces a pioneering approach to addressing this issue by applying phytomining, leveraging the capabilities of *H. annuus*, *E. crassipes*, and *P. stratiotes* to remove and recover valuable minerals, such as copper (Cu), from contaminated soil and water. Notably, the phytoremediation process not only reduced pollutant concentrations by 49%, 40%, and 90% for *E. crassipes*, and 27%, 99%, and 26% for *P. stratiotes* but also facilitated nearly complete recovery of Cu, achieving concentrations as high as 890 ppm in the shoots and 900 ppm in the roots. This dual benefit underscores the potential of phytomining as a sustainable solution that couples environmental remediation with economic gain through the recovery of valuable minerals. This study also showed that the aquatic plants exhibited higher BCF and TF compared to the terrestrial plant *H. annuus*. This indicates more efficient uptake and translocation of metals, which can be crucial for optimizing phytomining processes. Furthermore, an economic analysis underscored the potential profitability of this method, highlighting its capability not only to mitigate pollution but also to contribute to economic sustainability. Given the promising results of this study, further research is recommended to optimize the efficiency and scalability of phytomining. Exploring additional plant species and varying environmental conditions can broaden the applicability and effectiveness of this method in diverse geographic and industrial contexts. Ultimately, this research paves the way for a transformative shift in how we approach the intertwined challenges of environmental pollution and resource scarcity, proposing a viable and profitable alternative to traditional mining methods that have long been detrimental to the natural world.

Data Availability and Material

All data published in this article

Ethics Statement

Not applicable

CrediT Author Statement

Yudha Gusti Wibowo: Conceptualization, Formal Analysis, Writing-Original Manuscript, Writing, Review, and Editing. Jarwinda: Conceptualization, Formal Analysis, Writing-Original Manuscript, Writing, Review, and Editing. Dwi Umi Siswanti: Conceptualization, Formal Analysis, Writing-Original Manuscript, Writing, Review, and Editing. Anis Tatik Maryani: Conceptualization, Formal Analysis, Writing-Original Manuscript, Writing, Review, and Editing. Himawan Tri Bayu Murti Petrus: Conceptualization, Formal Analysis, Writing-Original Manuscript, Writing, Review, and Editing. Hana Safitri: Methodology, Formal Analysis, Investigation. Ajeng Permata Bintang: Methodology, Formal Analysis, Investigation. Abdul Hafiz: Methodology, Formal Analysis, Investigation. Liora Simbolon: Methodology, Formal Analysis, Investigation. Jonathan Aldo Sinaga: Methodology, Formal Analysis, Investigation. Asnan Rinovan: Methodology, Formal Analysis, Investigation. Sudibyo: Methodology, Formal Analysis, Investigation. Dedy Anwar: Visualization, Writing-Review and Editing, Software. Aris Setiawan: Visualization, Writing-Review and Editing, Software. Ahmad Tawfiequrahman Yuliansyah: Visualization, Writing-Review and Editing, Software.

Declaration of Competing Interest

The authors confirm that there is no competing interest in this study.

Funding

This research was supported by the Ministry of Education, Culture, Research, and Technology through the "Penelitian Dosen Pemula Reguler" research program, under contract number 1483cq/ IT9.2.1/PT.01.03/2025

References

Álvarez-López, V., Prieto-Fernández, Á., Cabello-Conejo, M.I. and Kidd, P.S. 2016. Organic amendments for improving biomass production and metal yield of Ni-hyperaccumulating plants. Science of The Total Environment, 548–549, 370–379.

Álvarez-Mateos, P., Alés-Álvarez, F.-J. and García-Martín, J.F. 2019. Phytoremediation of highly contaminated mining soils by Jatropha curcas L. and production of catalytic carbons from the generated biomass. Journal of Environmental Management, 231, 886–895.

Babst-Kostecka, A.A., Waldmann, P., Frérot, H. and Vollenweider, P. 2016. Plant adaptation to metal polluted environments—Physiological, morphological, and evolutionary insights from Biscutella laevigata. Environmental and Experimental Botany, 127, 1–13.

Bhattacharya, A.K., Naiya, T.K., Mandal, S.N. and Das, S.K. 2008. Adsorption, kinetics and equilibrium studies on removal of Cr(VI) from aqueous solutions using different low-cost adsorbents. Chemical Engineering Journal, 137(3), 529–541.

Boulamanti, A. and Moya, J.A. 2016. Production costs of the non-ferrous metals in the EU and other countries: Copper and zinc. Resources Policy, 49, 112–118.

Cao, Y., Ma, C., Chen, H., Zhang, J., White, J.C., Chen, G. and Xing, B. 2020. Xylem-based long-distance transport and phloem remobilization of copper in Salix integra Thunb. Journal of Hazardous Materials, 392, 122428.

Curie, C., Cassin, G., Couch, D., Divol, F., Higuchi, K., Le Jean, M., et al. 2009. Metal movement within the plant: contribution of nicotianamine and yellow stripe 1-like transporters. Annals of Botany, 103(1), 1–11.

Di Palma, L. and Medici, F. 2002. Recovery of copper from contaminated soil by flushing. Waste

Management, 22(8), 883–886.

Eren, E. and Argüello, J.M. 2004. Arabidopsis HMA2, a divalent heavy metal-transporting PIB-Type ATPase, is involved in cytoplasmic Zn2+ homeostasis. Plant Physiology, 136(3), 3712–3723.

Feng, D., Van Deventer, J.S.J. and Aldrich, C. 2004. Removal of pollutants from acid mine wastewater using metallurgical by-product slags. Separation and Purification Technology, 40(1), 61–67.

Fewtrell, L., Kay, D. and MacGill, S. 2001. A review of the science behind drinking water standards for copper. International Journal of Environmental Health Research, 11(2), 161–167.

Fitzgerald, D. 1998. Safety guidelines for copper in water. The American Journal of Clinical Nutrition, 67(5), 1098S-1102S.

Galal, T.M. and Shehata, H.S. 2015. Bioaccumulation and translocation of heavy metals by Plantago major L. grown in contaminated soils under the effect of traffic pollution. Ecological Indicators, 48, 244–251.

Grotz, N. and Guerinot, M.L. 2006. Molecular aspects of Cu, Fe and Zn homeostasis in plants. Biochimica et Biophysica Acta (BBA) - Molecular Cell Research, 1763(7), 595–608.

Gusti Wibowo, Y., Tyaz Nugraha, A. and Rohman, A. 2023. Phytoremediation of several wastewater sources using Pistia stratiotes and Eichhornia crassipes in Indonesia. Environmental Nanotechnology, Monitoring & Management, 20, 100781.

Hall, J.L. 2002. Cellular mechanisms for heavy metal detoxification and tolerance. Journal of Experimental Botany, 53(366), 1–11.

Imron, M.F., Firdaus, A.A.F., Flowerainsyah, Z.O., Rosyidah, D., Fitriani, N., Kurniawan, S.B., et al. 2023. Phytotechnology for domestic wastewater treatment: Performance of Pistia stratiotes in eradicating pollutants and future prospects. Journal of Water Process Engineering, 51, 103429.

Izydorczyk, G., Mikula, K., Skrzypczak, D., Moustakas, K., Witek-Krowiak, A. and Chojnacka, K. 2021. Potential environmental pollution from copper metallurgy and methods of management. Environmental Research, 197, 111050.

January, M.C., Cutright, T.J., Keulen, H.V. and Wei, R. 2008. Hydroponic phytoremediation of Cd, Cr, Ni, As, and Fe: Can Helianthus annuus hyperaccumulate multiple heavy metals? Chemosphere, 70(3), 531–537.

Kabeer, R., V.P., S., C.S., P.K., A.P., T., V., S., E.K., R. and K.R., B. 2022. Role of heavy metal tolerant rhizosphere bacteria in the phytoremediation of Cu and Pb using Eichhornia crassipes (Mart.) Solms. International Journal of Phytoremediation, 24(11), 1120–1132.

Khoshalan, H.A., Shakeri, J., Najmoddini, I. and Asadizadeh, M. 2021. Forecasting copper price by application of robust artificial intelligence techniques. Resources Policy, 73, 102239.

Kurniawan, S.B., Ramli, N.N., Said, N.S.M., Alias, J., Imron, M.F., Abdullah, S.R.S., et al. 2022. Practical limitations of bioaugmentation in treating heavy metal contaminated soil and role of plant growth promoting bacteria in phytoremediation as a promising alternative approach. Heliyon, 8(4), e08995.

Lenski, R.E. 2017. What is adaptation by natural selection? Perspectives of an experimental microbiologist. PLOS Genetics, 13(4), e1006668.

Nkrumah, P.N., Baker, A.J.M., Chaney, R.L., Erskine, P.D., Echevarria, G., Morel, J.L. and Van Der Ent, A. 2016. Current status and challenges in developing nickel phytomining: an agronomic perspective. Plant and Soil, 406(1–2), 55–69.

Page, V. and Feller, U. 2015. Heavy Metals in Crop Plants: Transport and Redistribution Processes on the Whole Plant Level. Agronomy, 5(3), 447–463.

Ramadan, B.S., Wulandari, M., Wibowo, Y.G., Ikhlas, N. and Nurseta, D.Y. 2021. removing ionic and nonionic pollutants from soil, sludge, and sediment using ultrasound-assisted electrokinetic treatment. In A. B. Ribeiro & M. N. Vara Prasad (Eds.), Electrokinetic Remediation for Environmental Security and Sustainability (1st ed., pp. 653–677). Wiley.

Ramírez, J.E., Rangel-Mendez, J.R., Limberger Lopes, C., Gomes, S.D., Buitrón, G. and Cervantes, F.J. 2018. Denitrification of metallurgic wastewater: mechanisms of inhibition by Fe, Cr and Ni. Journal of

Chemical Technology & Biotechnology, 93(2), 440–449.

Rauser, W.E. 1999. Structure and function of metal chelators produced by plants: The case for organic acids, amino acids, phytin, and metallothioneins. Cell Biochemistry and Biophysics, 31(1), 19–48.

Ro, H.-M., Choi, H.-J., Yun, S.-I. and Park, J.-S. 2018. Organic amendment-driven removal and speciation of metals using wormwood in two contrasting soils near an abandoned copper mine. Horticulture, Environment, and Biotechnology, 59(6), 775–786.

Rosenkranz, T., Kisser, J., Wenzel, W.W. and Puschenreiter, M. 2017. Waste or substrate for metal hyperaccumulating plants — The potential of phytomining on waste incineration bottom ash. Science of The Total Environment, 575, 910–918.

Song, Y., Jin, L. and Wang, X. 2017. Cadmium absorption and transportation pathways in plants. International Journal of Phytoremediation, 19(2), 133–141.

Tabinda, A.B., Irfan, R., Yasar, A., Iqbal, A. and Mahmood, A. 2020. Phytoremediation potential of Pistia stratiotes and Eichhornia crassipes to remove chromium and copper. Environmental Technology, 41(12), 1514–1519.

Tangahu, B.V., Sheikh Abdullah, S.R., Basri, H., Idris, M., Anuar, N. and Mukhlisin, M. 2011. A Review on Heavy Metals (As, Pb, and Hg) Uptake by Plants through Phytoremediation. International Journal of Chemical Engineering, 2011(1), 939161.

Tonhá, M.S., Garnier, J., Araújo, D.F., Cunha, B.C.A., Machado, W., Dantas, E., et al. 2020. Behavior of metallurgical zinc contamination in coastal environments: A survey of Zn from electroplating wastes and partitioning in sediments. Science of The Total Environment, 743, 140610.

Victor, K.K., Séka, Y., Norbert, K.K., Sanogo, T.A. and Celestin, A.B. 2016. Phytoremediation of wastewater toxicity using water hyacinth (Eichhornia crassipes) and water lettuce (Pistia stratiotes). International Journal of Phytoremediation, 18(10), 949–955.

Wang, R., Yan, Q., Su, P., Shu, J., Chen, M., Xiao, Z., et al. 2020. Metal mobility and toxicity of zinc hydrometallurgical residues. Process Safety and Environmental Protection, 144, 366–371.

Wei, Z.G., Wong, J.W.C., Zhao, H.Y., Zhang, H.J., Li, H.X. and Hu, F. 2007. Separation and determination of heavy metals associated with low molecular weight chelators in xylem saps of indian mustard (Brassica juncea) by size exclusion chromatography and atomic absorption spectrometry. Biological Trace Element Research, 118(2), 146–158.

Wibowo, Y.G. and Ramadan, B.S. 2021. Enhanced remediation and recovery of metal-contaminated soil using electrokinetic Soil Flushing. In A. B. Ribeiro & M. N. Vara Prasad (Eds.), Electrokinetic Remediation for Environmental Security and Sustainability (1st ed., pp. 603–627). Wiley.

Wibowo, Y.G., Ramadan, B.S., Sudibyo, S., Safitri, H., Rohman, A. and Syarifuddin, H. 2023. Efficient remediation of acid mine drainage through sustainable and economical biochar-CaO composite derived from solid waste. Environment, Development and Sustainability, 26(7), 16803–16826.

Wibowo, Y.G., Safitri, H., Malik, I.B.I., Sudibyo and Priyanto, S. 2022. Alternative Low-cost treatment for real acid mine drainage: performance, bioaccumulation, translocation, economic, post-harvest, and bibliometric analyses. Sustainability, 14(22), 15404.

Wibowo, Y.G., Syahnur, M.T., Al-Azizah, P.S., Arantha Gintha, D., Lululangi, B.R.G. and Sudibyo. 2023. Phytoremediation of high concentration of ionic dyes using aquatic plant (Lemna minor): A potential eco-friendly solution for wastewater treatment. Environmental Nanotechnology, Monitoring & Management, 20, 100849.

Zhang, Jianwei, Wang, Y., Wang, X., Wu, W., Cui, X., Cheng, Z., et al. 2022. Hydrothermal conversion of Cd/Zn hyperaccumulator (Sedum alfredii) for heavy metal separation and hydrochar production. Journal of Hazardous Materials, 423, 127122.

Zhang, Jin, Wu, S., Xu, J., Liang, P., Wang, M., Naidu, R., et al. 2021. Comparison of ashing and pyrolysis treatment on cadmium/zinc hyperaccumulator plant: Effects on bioavailability and metal speciation in solid residues and risk assessment. Environmental Pollution, 272, 116039.

Zhong, D., Zhong, Z., Wu, L., Ding, K., Luo, Y. and Christie, P. 2016. Pyrolysis of Sedum plumbizincicola,

a zinc and cadmium hyperaccumulator: pyrolysis kinetics, heavy metal behaviour and bio-oil production. Clean Technologies and Environmental Policy, 18(7), 2315–2323.

Zhou, H., Liu, G., Zhang, L., Zhou, C., Mian, M.M. and Cheema, A.I. 2021. Strategies for arsenic pollution control from copper pyrometallurgy based on the study of arsenic sources, emission pathways and speciation characterization in copper flash smelting systems. Environmental Pollution, 270, 116203.