

Gold phytomining using local plant enhanced by rhizobacteria and compost fertiliser

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Abstract: Spent ore is a waste material produced during mineral processing, from which precious metals such as gold can potentially be recovered through phytomining. This study aimed to analyse the geochemical characteristics of spent ore and to test the effects of rhizobacterial inoculation and compost addition on the ability of local plants to extract and accumulate gold from spent ore at the site. The research comprised the following stages: spent ore sampling, sample preparation, geochemical characterisation of the samples, an on-site phytomining experiment (including the establishment of demonstration plots, plant propagation and acclimatisation, preparation of rhizobacteria, planting and plant maintenance, harvesting and determination of Au content), and data analysis involving the calculation of the bioaccumulation factor (*BCF*) and translocation factor (*TF*), as well as ANOVA. The results showed that rhizobacterial inoculation and compost addition affected the plants' ability to absorb and accumulate Au, as reflected in their *BCF* and *TF* values. The most effective treatment comprised inoculation with *Bacillus cereus* RTKS and the addition of compost at a compost-to-spent-ore ratio of 1:1, which resulted in the highest *BCF* and *TF* values and a high Au content in the plants. This finding is significant because it indicates that rhizobacterial inoculation combined with compost in the appropriate proportion can increase plants' ability to accumulate metals from the soil, including both precious metals and pollutant metals. Gold can be recovered as a valuable product through phytomining, whereas pollutant metals can be removed from the soil through phytoremediation.

Keywords: bioaccumulation factor, gold-bearing spent ore, *Pteris vittata*, rhizobacterial inoculation, translocation factor

INTRODUCTION

Gold is a strategic commodity in Indonesia and contributes significantly to national income. Thus, gold mining plays a vital role in economic development. However, it also poses environmental challenges, particularly those associated with waste materials from ore processing, which typically contain sulphides,

especially iron-bearing sulphides such as pyrite and chalcopyrite, and contribute to the formation of acid mine drainage that may pollute the environment (Betancur-Corredor *et al.*, 2018). Acid mine drainage can be a serious environmental problem because it has a high sulphate content, a low pH and high concentrations of toxic heavy metals (Michael, Anekwe and Isa, 2023). One such material is spent ore, a waste rock generated during gold ore

processing. This material therefore requires proper management to maintain environmental quality (Yusuf, 2016; Michael, Anekwe and Makarfi, 2021; Du *et al.*, 2022). In addition, spent ore often retains low concentrations of metals remaining after the extraction process (low-grade ore) that cannot be recovered using conventional technology.

Phytomining is an alternative technology with the potential to be developed as an environmentally friendly method of recovering metals from low-grade ore. This method utilises the ability of hyperaccumulator plants to absorb and accumulate metals in their tissues, allowing the metals to be extracted from plant biomass. Careful plant selection is therefore necessary to extract gold from the soil, and the method is suitable for areas containing low-grade gold ore (Sheoran, Sheoran and Poonia, 2013; Dinh, Dobo and Kovacs, 2022). Phytomining offers a sustainable industrial-crop strategy for recovering valuable metals from sub-economic or low-grade ores where conventional mining is not economically viable because of high capital investment and complex extraction processes. This technology produces a metal-rich, low-sulphur and sulphide-free 'bio-ore' that significantly reduces downstream processing costs and energy demand compared with traditional ore refining. Furthermore, it enables critical raw materials to be recovered safely under economically viable conditions while effectively converting unproductive or contaminated land into profitable industrial assets (Minut *et al.*, 2023; He *et al.*, 2026).

Ideal plants for phytomining are local plants that are adapted to soils with a high mineral content, produce substantial biomass and grow rapidly. Phytomining efficiency increases with shoot biomass because metals translocated from the soil accumulate in shoot organs such as stems, leaves and flowers (Gagnon *et al.*, 2020).

Research into gold phytomining has been conducted since 2022, beginning with the exploration of potential hyperaccumulator plants at the Ratatotok gold mine site in Southeast Minahasa, North Sulawesi, Indonesia.

The results showed that the dominant plant species at the gold mine site with a relatively high capacity for gold bioaccumulation was *Pteris vittata* L., with a bioaccumulation factor (*BCF*) of 0.126 (Aminatun *et al.*, 2024b). The *BCF* is the ratio of the total gold concentration in plant tissue to the total gold concentration in the soil (Maiti *et al.*, 2021; Kurniawan *et al.*, 2022). A *BCF* value within the range $0.1 < BCF \leq 1.0$ indicates a moderate bioaccumulator (Yoon *et al.*, 2006; Herlina *et al.*, 2020; Kurniawan *et al.*, 2022). In addition to *P. vittata*, *Tridax procumbens* and *Ageratum conyzoides* were also dominant at the site, despite having relatively low *BCF* values (<0.1) (Aminatun *et al.*, 2024b). According to the literature, *A. conyzoides* is an effective hyperaccumulator of heavy metals (Hamzah and Priyadarshini, 2014; Gafur *et al.*, 2022).

The ability of plants to grow in environments with high metal concentrations is often associated with the presence of bacteria in the rhizosphere of their root systems. Rhizobacteria help to increase plant resistance to heavy-metal stress through the production of secondary metabolites such as indole-3-acetic acid (IAA) and siderophores, which chelate metals in the soil and facilitate their transfer into plant root cells (Govarthanan *et al.*, 2016).

Rhizobacterial colonies were isolated from the roots of three dominant plant species with a moderate bioaccumulation capacity (*BCF* between 0.1 and 1.0), all of which were capable of producing the hormone IAA and belonged to the plant-growth-promoting

rhizobacteria group. On the basis of resistance tests under tailings stress at an Au content of 0.25 ppm, the three most resistant isolates, which had the highest optical density values, were identified as *Bacillus cereus* RTKS, *Pseudomonas aeruginosa* RTKP1 and *Stenotrophomonas geniculata* RTKP2 (Aminatun *et al.*, 2024).

Further research showed that inoculating *P. vittata* with *P. aeruginosa* RTKP1 increased the translocation factor (*TF*) and *BCF*, particularly in the roots. Adding compost to the tailings medium at a ratio of 1:1 improved plant performance but inhibited the ability of *P. aeruginosa* RTKP1 to increase *BCF* and *TF* (Aminatun *et al.*, 2025b). These results indicate the need to optimise phytomining conditions, including by extending the incubation period and testing different combinations of other bacterial strains known to be resistant to stress caused by gold-mine tailings, namely *B. cereus* RTKS and *S. geniculata* RTKP2, as reported in previous research (Aminatun *et al.*, 2025b). The present study aimed to analyse the effects of rhizobacterial inoculation and compost addition on the effectiveness of on-site phytomining of low-grade gold ore using local plants in the Tujuh Bukit gold mine area, Banyuwangi, East Java, Indonesia. Although numerous studies of gold phytomining have been conducted, most have been limited to identifying potential hyperaccumulator plants at the laboratory or greenhouse scale and have not examined the role of rhizobacteria or compost addition as factors supporting metal accumulation (Wilson-Corral *et al.*, 2014; Krisnayanti *et al.*, 2016; El-Kassas, Abd El-Razek and Japer, 2017; Noviard *et al.*, 2021; Kurniawan *et al.*, 2022). Therefore, the objectives of the present study were to (1) analyse the geochemical characteristics of low-grade ore at the Tujuh Bukit gold mine site and (2) test the effects of rhizobacterial inoculation and compost fertiliser addition on the ability of the local plant *P. vittata* to extract and accumulate gold from low-grade ore in the heap-leach area of the mine site. The novelty of this study lies in its integration of on-site phytomining of low-grade ore at a gold mine site with rhizobacterial inoculation and compost addition to increase the effectiveness of gold phytoextraction.

STUDY MATERIALS AND METHODS

DESCRIPTION OF STUDY AREA

This research was conducted at the Tujuh Bukit gold mine site in Banyuwangi, East Java, Indonesia (Fig. 1), where demonstration plots were established at the spent-ore site. The mine is operated by PT Bumi Suksesindo. Tujuh Bukit forms part of the East Sunda magmatic arc, which contains very large Au deposits (>300 Mg Au). At Tujuh Bukit, ore mineralisation occurs in quartz veins centred in the potassic zone, and the potential for Au mineralisation remains open at depth. The Tujuh Bukit Au deposit is the largest in the Tujuh Bukit district of East Java, with an average Au content of 0.45 g.Mg^{-1} and characteristics of high-sulphidation epithermal and porphyry mineralisation (Harrison *et al.*, 2018; Maryono *et al.*, 2018; Idrus *et al.*, 2024).

SAMPLING AND PREPARATION OF SPENT ORE/LOW-GRADE ORE

Before the phytomining experiment, a representative 2 kg sample of spent ore was collected from the heap-leach area at the Tujuh Bukit gold mine site, Banyuwangi Regency, East Java, Indonesia,

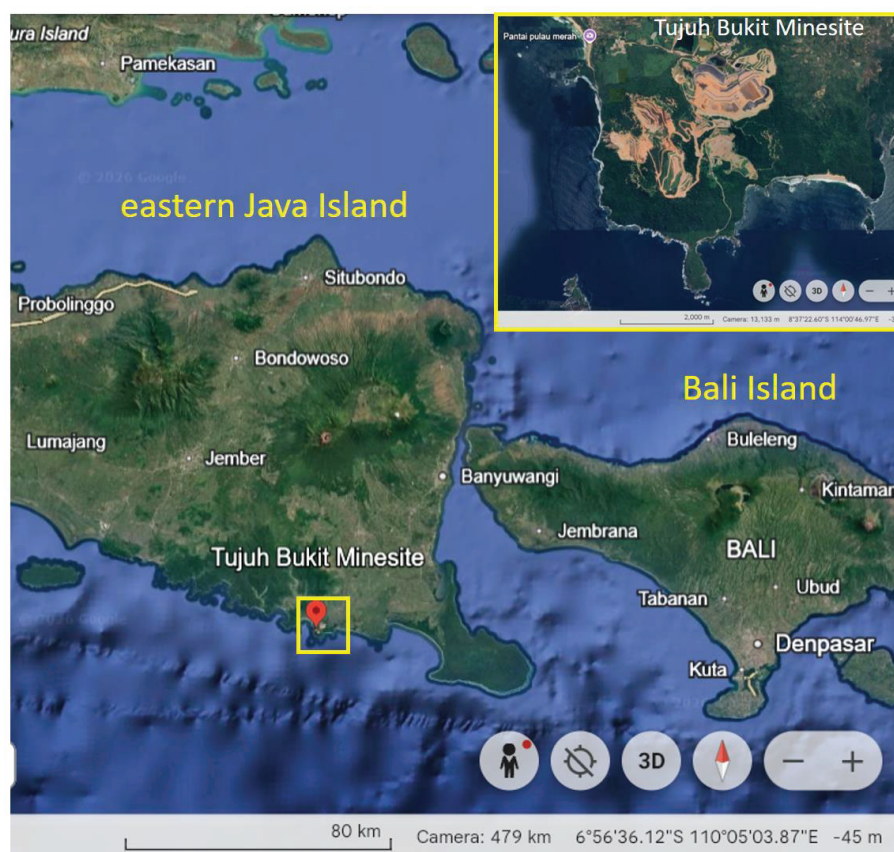


Fig. 1. Location of the study at the Tujuh Bukit mining site (Tujuh Bukit Project); source: own study base on Google Maps and Google Earth

at coordinates 175253.831 mE and 9047073.743 mN in UTM Zone 49S (WGS84), at an elevation of 138.64. The sample was then cleaned with 95% ethanol and dried in an oven at 110°C for 6–7 h. It was subsequently crushed using a primary jaw crusher and a roll crusher, homogenised using the quartering method and pulverised to a particle size of 200 mesh. The entire preparation process was carried out at the PT Bumi Suksesindo Laboratory at the Tujuh Bukit site in Banyuwangi, East Java, Indonesia.

GEOCHEMICAL ANALYSIS OF SPENT ORE

The Au content of the spent ore was analysed using fire assay atomic absorption spectrometry (FA-AAS), while the other elements were analysed using inductively coupled plasma mass spectrometry (ICP-MS) (Mashale *et al.*, 2025). These analyses were conducted at the PT Indo Mineral Research Laboratory in North Jakarta, Indonesia. The Hg content was analysed using ICP-MS at the Environmental Engineering Laboratory, Universitas Islam Indonesia, Yogyakarta, Indonesia. After the phytomining experiment, the Au content of the spent ore and plant biomass was analysed, with the plant biomass separated into roots and shoots. The Au content of the plant biomass was determined using ICP-MS.

ON-SITE PHYTOMINING EXPERIMENT

The phytomining experiment was carried out in several stages.

1) Preparation of demonstration plots and site layout. The phytomining experiment was conducted in demonstration plots, with 10 plot codes representing the treatments:

- control (spent ore only),
- PBK1 (*Bacillus cereus* RTKS + compost:spent ore of 1:1),
- PBK2 (*B. cereus* RTKS + compost:spent ore of 1:2),
- PBK3 (*B. cereus* RTKS without compost),
- PPK1 (*Pseudomonas aeruginosa* RTKP1 + compost:spent ore of 1:1),
- PPK2 (*P. aeruginosa* RTKP1 + compost:spent ore of 1:2),
- PPK3 (*P. aeruginosa* RTKP1 without compost),
- PSK1 (*Stenotrophomonas geniculata* RTKP2 + compost:spent ore of 1:1),
- PSK2 (*S. geniculata* RTKP2 + compost:spent ore of 1:2),
- PSK3 (*S. geniculata* RTKP2 without compost).

Each treatment comprised three replicates in $1 \times 1 \text{ m}^2$ demonstration plots, resulting in a total of 30 plots. The demonstration plots were arranged randomly, with 1 m between plots.

- 2) Plant propagation and acclimatisation. *Pteris vittata* plants approximately one month old were obtained from the heap-leach area. The plants were acclimatised in the nursery for seven days using soil, compost and rice husks as the growing medium. After acclimatisation, the plants were transferred to the research demonstration plots, with three plants placed in each plot.
- 3) Preparation of rhizobacterial isolates. Three strains of rhizobacteria, namely *B. cereus* RTKS, *P. aeruginosa* RTKP1 and *S. geniculata* RTKP2, were propagated on nutrient agar medium in the Microbiology Laboratory of the Faculty of Mathematics and Natural Sciences, Universitas Negeri Yogyakarta, Indonesia. Bacterial suspensions were prepared until they

reached an optical density of 1 (Aminatun *et al.*, 2025a). Optical density is used to determine microorganism concentration and thus indicates microbial density (Wacogne *et al.*, 2024; Wang *et al.*, 2024).

- 4) Planting, rhizobacterial inoculation and maintenance. Three plants were planted in each demonstration plot, with 400 cm between plants. Rhizobacterial inoculation was performed one day after planting, with each plant receiving 8 cm³ of rhizobacterial suspension. The plants were maintained until harvesting, 1.5 months after planting (Aminatun *et al.*, 2025b).
- 5) Observation of growth and environmental factors. Plant growth was assessed weekly by measuring plant height and the number of fronds and recording symptoms of chlorosis and necrosis. In particular, the curling of young fronds was monitored to evaluate the plants' adaptive capacity (Kurniawan *et al.*, 2022). In addition, climatic factors (light intensity and rainfall) and edaphic factors (soil pH, temperature and moisture) were measured weekly to ensure that the environmental conditions were suitable for plant growth.

DATA ANALYSIS

Data analysis included the calculation of bioconcentration factor (*BCF*) and translocation factor (*TF*) values, as well as tests for statistically significant differences using ANOVA. The bioconcentration factor is the ratio of the Au content of plant biomass to that of the growing medium, with the following categories: $BCF > 1$ (hyperaccumulator), $BCF = 0.1-1$ (moderate accumulator), $BCF = 0.01-0.1$ (low accumulator) and $BCF < 0.01$ (non-accumulator) (Yoon *et al.*, 2006; Herlina *et al.*, 2020; Kurniawan *et al.*, 2022). The translocation factor indicates a plant's phytoextraction ability and is calculated as the ratio of the Au content of the shoots to that of the roots (Kurniawan *et al.*, 2022). A *TF* value > 1 indicates that plants accumulate Au through a phytoextraction mechanism. Phytoextraction involves the translocation of metals from the roots to harvestable shoots (Minut *et al.*, 2023). A *TF* value < 1 indicates that plants accumulate Au through a phytostabilisation mechanism. Phytostabilisation involves immobilising metals within the root zone (Minut *et al.*, 2023).

RESULTS AND DISCUSSION

GEOCHEMICAL CHARACTERISTICS OF SPENT ORE

Before the phytomining experiment, spent-ore samples collected from the study area were analysed for Au and Hg, as well as for multiple elements (As, Ag, Mo, Pb and Cu). Samples were collected from five points in the heap-leach area and combined to form a composite sample.

Geochemical analysis showed that the spent ore contained several heavy metals at varying concentrations: 0.33 ppm Au, 10.28 ppm Ag, 321.31 ppm Cu, 0.005 ppm Hg, 4.76 ppm Mo, 422.41 ppm Pb and 1425.99 ppm As. These elements, commonly referred to as pathfinder elements, are often geochemically associated or correlated with Au (Bayari *et al.*, 2019). They are called pathfinder elements because they serve as indicators of the presence of gold during geological exploration and commonly accumulate alongside gold in a given area. In general, elements

such as As, Ag, Cu, Pb, Hg and Mo are readily detected in rock samples surrounding gold deposits, making them a suitable combination for gold exploration (Zhen *et al.*, 2022; Abdel-Rahman *et al.*, 2023). As, Pb and Cu have been shown to be associated with Au in supergene gold-deposit environments. Gold also occurs mainly in hypogene porphyry-epithermal ores associated with iron and copper-iron sulphide minerals, primarily pyrite and chalcopyrite (Abdel-Rahman *et al.*, 2023). Furthermore, Au is positively associated with Ag, as these two elements often occur together in mineral deposits, especially in high-sulphidation epithermal mineralisation systems (Mulja, Heriawan and Supomo, 2022).

The concentrations of multiple elements (As, Ag, Mo, Pb and Cu) differed among treatments in the spent ore, shoots and plant roots (Tab. 1). Changes in the concentrations of these elements indicated that phytoremediation processes and plant-soil interactions played a role in the mobilisation and accumulation of heavy metals. In general, As, Pb and Cu concentrations in the shoots and roots tended to be lower than the initial concentrations in the spent ore. This suggests that some elements were redistributed during treatment through plant uptake, immobilisation in the medium matrix or possible geochemical transformations such as precipitation or readsorption onto soil particles (Ji *et al.*, 2021).

As shown in Table 1, following treatment with *Bacillus cereus* RTKS inoculation without compost (PBK3), the As content of the plant shoots was higher than that of the spent ore. This was probably because the plants already contained As before treatment. The plants used in the study were obtained locally from the mining area, and *Pteris vittata* has been identified as a hyperaccumulator in numerous studies (Kohda *et al.*, 2021; Gafur *et al.*, 2022; Aminatun *et al.*, 2024). Inoculation with *B. cereus* RTKS may also increase plants' ability to absorb metals without competition from naturally occurring bacteria that may be present in the compost (Aminatun *et al.*, 2024a; Aminatun *et al.*, 2025b; Aminatun *et al.*, 2026).

THE EFFECT OF RHIZOBACTERIA INDUCTION AND COMPOST FERTILISER

The effects of rhizobacterial inoculation (*B. cereus* RTKS, *Pseudomonas aeruginosa* RTKP1 and *Stenotrophomonas geniculata* RTKP2) and compost fertiliser addition (at compost-to-spent-ore ratios of 1:1 and 1:2, or without compost) on the ability of *Pteris vittata* to extract and accumulate gold from low-grade ore at the site were assessed using the *BCF* and *TF* values. Table 2 presents the Au content of the spent ore, plant shoots and roots after treatment, together with the *BCF* and *TF* calculated for each treatment.

The control treatment had the highest Au content in the spent ore among all treatments (Tab. 2). This indicates that Au mobilisation by the plants in the control treatment was relatively low, possibly because rhizobacteria and compost, which support metal bioavailability, were absent. The Au content of the plant shoots and roots was also relatively high, possibly because of the low plant biomass.

The PBK1 treatment produced the lowest Au content in the spent ore among all treatments (Tab. 2). This indicates that Au mobilisation by plants in the PBK1 treatment (*B. cereus* RTKS + compost-to-spent-ore ratio of 1:1) was relatively high, allowing gold to be absorbed efficiently into the plant tissues (shoots and

Table 1. Multi-element concentrations in spent ore, shoots, and roots of *Pteris vittata* after treatment as determined by ICP-MS

Element	Part	Control	PBK1	PBK2	PBK3	PPK1	PPK2	PPK3	PSK1	PSK2	PSK3
As (ppm)	spent ore	1,879.26	1,528.46	1,540.56	1,522.94	1,569.97	1,791.04	1,521.95	1,451.90	1,433.58	1,468.13
	shoot	1,094.27	1,092.64	1,179.55	1,940.32	1,214.55	1,293.19	1,047.51	1,157.85	1,244.40	1,342.71
	root	1,333.07	1,076.33	1,067.99	1,365.31	955.77	1,115.20	1,185.32	927.53	1,074.40	1,134.70
Ag (ppm)	spent ore	8.89	17.22	11.83	57.22	12.23	16.13	12.37	18.14	13.85	17.06
	shoot	166.05	97.86	5.59	2.18	4.66	16.61	26.23	6.36	4.32	3.16
	root	6.31	16.29	61.33	53.79	24.84	6.00	29.95	13.66	78.43	18.45
Mo (ppm)	spent ore	2.51	2.63	2.45	2.45	2.56	2.43	2.51	2.59	2.46	2.36
	shoot	5.94	5.90	6.08	4.50	6.56	4.93	4.87	6.07	5.28	3.51
	root	3.62	3.33	3.68	3.53	4.45	3.81	3.92	3.96	3.11	3.44
Pb (ppm)	spent ore	505.62	377.87	405.57	425.86	405.50	463.55	402.78	443.17	403.60	381.65
	shoot	124.03	139.61	147.21	73.29	162.86	153.96	112.49	186.76	127.85	79.71
	root	385.91	283.32	282.54	351.20	202.59	308.61	300.95	239.44	298.25	268.94
Cu (ppm)	spent ore	356.56	342.38	334.09	323.07	318.87	350.65	311.54	301.14	299.99	320.52
	shoot	61.73	99.23	101.00	42.57	111.72	97.35	66.86	112.52	79.27	49.43
	root	251.96	228.97	212.75	295.31	194.34	213.20	234.01	183.51	203.28	213.34

Explanations: treatments PBK1, PBK2, PBK3, PPK1, PPK2, PPK3, PSK1, PSK2 and PSK3 are defined on p. 28.

Source: own study.

Table 2. Au content of spent ore, plant shoots and roots after treatment, and calculated bioaccumulation factor (BCF) and translocation factor (TF) values for each treatment

Treat- ment code	Content of Au after treatment (ppm)												Mean of BCF values		Mean of TF values
	spent ore				shoot				root				shoot	root	
	mean	min.	max.	SD	mean	min.	max.	SD	mean	min.	max.	SD			
Control	0.640	0.50	0.76	0.10	2.535	2.15	2.97	0.33	1.820	1.70	1.95	0.10	3.96	2.84	1.39
PBK1	0.220	0.04	0.41	0.19	2.793	0.86	6.62	3.31	1.116	0.88	1.35	0.24	19.11	14.73	2.98
PBK2	0.381	0.29	0.51	0.12	0.947	0.63	1.24	0.31	0.685	0.21	1.47	0.68	2.56	1.57	2.32
PBK3	0.463	0.40	0.57	0.09	0.833	0.57	1.32	0.42	0.981	0.50	1.62	0.58	1.92	2.31	0.91
PPK1	0.396	0.30	0.51	0.11	0.683	0.66	0.71	0.03	1.088	0.80	1.29	0.26	1.82	2.77	0.66
PPK2	0.484	0.32	0.63	0.16	0.519	0.36	0.70	0.17	0.414	0.24	0.60	0.18	1.10	0.86	1.30
PPK3	0.362	0.22	0.51	0.15	0.500	0.31	0.60	0.16	0.473	0.30	0.65	0.18	1.41	1.37	1.08
PSK1	0.432	0.37	0.47	0.06	0.728	0.54	0.97	0.22	2.493	0.37	6.67	3.62	1.70	5.54	1.05
PSK2	0.524	0.36	0.75	0.20	0.704	0.52	1.06	0.31	0.534	0.39	0.65	0.13	1.33	1.12	1.34
PSK3	0.438	0.31	0.52	0.11	0.583	0.41	1.07	0.34	1.432	0.47	2.88	1.28	1.74	3.10	1.74

Explanations: SD = standard deviation; treatments PBK1, PBK2, PBK3, PPK1, PPK2, PPK3, PSK1, PSK2 and PSK3 are defined on p. 28.

Source: own study.

roots). Accordingly, the highest gold concentrations in the shoots and roots were recorded in the PBK1 treatment, at 2.793 ppm and 1.116 ppm, respectively. The highest BCF and TF values were also found in PBK1: a shoot BCF of 19.11, a root BCF of 14.73 and a TF of 2.98. These values indicate that PBK1 was the most effective treatment for increasing plants' ability to absorb gold from the medium and translocate it to their tissues. The high effectiveness of PBK1 suggests that combining rhizobacteria and compost at optimal doses can stimulate the activity of rhizosphere

microorganisms involved in Au dissolution and mobilisation. Rhizobacteria are known to produce chelating compounds, such as organic acids and siderophores, that help to dissolve gold minerals in tailings, thereby making them more readily available for uptake by plant roots (Mondal *et al.*, 2023). Furthermore, increased microbial activity can increase nutrient availability and strengthen plant root systems, making phytoextraction more efficient. Values of BCF and TF in the other treatments tended to be lower than those in PBK1, indicating that a higher dose or an

unsuitable combination of compost and rhizobacteria may reduce phytoextraction efficiency. This may be due to changes in pH (Wang *et al.*, 2006), microbial competition or an increase in organic matter that binds metals and thus reduces their availability in the medium.

The ANOVA results showed that *TF* ($p = 0.554$) and root *BCF* ($p = 0.390$) did not differ significantly among the treatment groups, whereas shoot *BCF* differed significantly ($p = 0.008$). The significant difference in shoot *BCF* among the treatment groups indicates that the treatments had a significant effect on the plants' ability to accumulate Au in their shoots. This implies that differences in the rhizobacterial strain used and the amount of compost added affected the amount of Au accumulated in the shoots but not in the roots. The PBK1 treatment, comprising inoculation with the *B. cereus* RTKS isolate and the addition of compost at a compost-to-spent-ore ratio of 1:1, produced the highest accumulation of Au in the shoots and the highest *BCF*.

Table 3 shows that, in the control treatment, plant height decreased by 5 cm and the number of fronds decreased by 0.33, indicating that plant growth was more severely inhibited in the control than in the other treatments. Furthermore, the non-uniform distribution of Au among sampling points affected measurements of its concentration at individual locations. This is consistent with previous research that found highly variable Au concentrations in 53 samples collected across 262 ha (Bazurto *et al.*, 2025).

These findings indicate that compost and rhizobacteria do not always have synergistic effects, particularly in spent-ore media under harsh environmental conditions. Consequently, both plant height and the number of fronds decreased because the tip of the longest frond curled and some fronds died.

An assessment of phytomining effectiveness showed that the highest *BCF* and *TF* values occurred in the PBK1 treatment (*B. cereus* RTKS + compost-to-spent-ore ratio of 1:1). These results indicate that improved plant growth is not always accompanied by increased metal accumulation. *B. cereus* is known to produce siderophores that bind metals (Anusaraporn *et al.*, 2023). The presence of this bacterium in the PBK1 treatment may therefore have increased Au solubility, making the metal more readily available for plant uptake. The addition of compost at a compost-to-spent-ore ratio of 1:1 in the PBK1 treatment may stimulate plant growth, increase plant biomass and enhance plant resistance to metal toxicity, thereby maximising the plant's effectiveness as a hyperaccumulator (Li *et al.*, 2021; Hosseinniaee *et al.*, 2024). Accordingly, in this study, adding compost at a compost-to-spent-ore ratio of 1:1 in the PBK1 treatment reduced the adverse effects of stress caused by Au and other heavy metals on plant growth.

As shown in Table 1, the Pb and As contents of the spent ore were very high. These conditions can reduce plant growth and rhizobacterial activity (Wang *et al.*, 2020). Pb and As can disrupt physiological processes in plants, such as nucleic acid synthesis,

Table 3. Differences in plant height (cm) and the number of fronds between the beginning and end of the treatment period

Variable	Treatment code									
	control	PBK1	PBK2	PBK3	PPK1	PPK2	PPK3	PSK1	PSK2	PSK3
Difference in plant height (cm)	-5.00	-9.32	-8.13	-2.41	-9.87	-8.42	-4.92	-8.07	-3.32	-0.94
Difference in the number of fronds	-0.33	-2.00	-0.78	1.00	-0.67	0.22	0.56	0.89	1.00	1.22

Explanations: treatments PBK1, PBK2, PBK3, PPK1, PPK2, PPK3, PSK1, PSK2 and PSK3 are defined on p. 28.

Source: own study.

Stress caused by gold and other heavy metals in the spent ore inhibited plant growth. The results in Table 3 show that the PSK3 (*S. geniculata* RTKP2 without compost) and PBK3 (*B. cereus* RTKS without compost) treatments had the least adverse effect on plant growth, and both treatments produced more fronds than the other treatments. This indicates that rhizobacterial inoculation in the spent-ore medium reduced the adverse effects of heavy-metal stress on plant growth, even without the addition of compost. Rhizobacteria can produce growth-promoting hormones such as auxins, gibberellins and cytokinins, which support root development and nutrient uptake (Hasan *et al.*, 2024).

In treatments involving the addition of compost (at ratios of 1:1 and 1:2), plant growth tended to be lower than in treatments without compost because the tip of the longest frond curled; plant height was measured from the base of the stem to the tip of the longest frond. This condition probably resulted from competition between the inoculated rhizobacteria and microorganisms originating from the compost. Such competition can reduce the ability of rhizobacteria to colonise the rhizosphere (Aminatun *et al.*, 2025a). However, compost generally improves the structure of the growing medium and increases nutrient availability (Ullah *et al.*, 2021).

transcription and the activity of enzymes important for metabolism (Sinha *et al.*, 2023; Gupta *et al.*, 2024). High concentrations of heavy metals can also affect soil microbial diversity and reduce enzymatic activity in the rhizosphere. However, *Pteris vittata* can survive high As concentrations because of its arsenic transporter, which contributes to arsenic tolerance (Vandana *et al.*, 2020).

Overall, this study showed that treatments without compost (treatment code 3) produced the best vegetative growth, whereas the highest Au accumulation was achieved by the treatment involving *B. cereus* RTKS and compost at a compost-to-spent-ore ratio of 1:1 (PBK1). The difference between vegetative growth and metal accumulation suggests that these two parameters are governed by different mechanisms.

CONCLUSIONS

The geochemical characterisation confirmed that the spent ore contained low-grade gold (Au) together with high concentrations of heavy metals such as Pb, As and Cu. The phytomining

experiment demonstrated that treatment involving *Bacillus cereus* RTKS inoculation and a compost-to-spent-ore ratio of 1:1 (PBK1) was the most effective for phytomining because it produced the highest *BCF* and *TF* values; however, it was not the most effective treatment for plant growth. This finding shows that bacteria and compost do not always have synergistic effects, as the best vegetative growth was observed in treatments without compost. In this context, the treatments without compost (treatment code 3) represented the best compromise between maintaining plant growth and ensuring phytomining efficiency. Importantly, the findings demonstrate that rhizobacterial inoculation combined with compost in the appropriate proportion can increase plants' ability to accumulate metals from the soil, including both metals to be recovered through phytomining and pollutant metals to be removed through phytoremediation.

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CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests.

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