

# Accumulation of Potentially Toxic Trace Elements (PTEs) by Native Plant Species Growing in a Typical Gold Mining Area Located in the Northeast of Qinghai-Tibet Plateau

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## Research Article

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## Abstract

Though gold mines provide significant economic benefits to local governments, mining causes soil pollution by potentially toxic trace elements (PTEs) in mining areas, especially in the Qinghai-Tibet Plateau. Screening of native plant species from mining areas is now an effective, inexpensive, and eco-friendly method for the remediation of PTEs in situ. In the present study, we conducted experiments to assess the accumulation of As, Cd, Pb, and Zn in 12 native plant species growing on a typical gold mining area in Qinghai-Tibet Plateau. Our results showed that rhizosphere soils have high soil organic matter content, high levels of As, and moderate levels of Cd. *G. pylzowianum* accumulated relatively higher As in its shoots and exhibited TF higher than 1 for As (4.65), Cd (1.87), and Pb (1.36). *P. saundersiana* had BCF-S higher than 1 for Cd (4.52) and Pb (1.70), whereas its TF was higher than 1 for As, Cd, Pb, and Zn. These plant species also exhibit strong tolerance to these PTEs. Furthermore, *E. nutans* accumulated low levels of As, Cd, Pb, and Zn in their shoots and exhibited TF values lower than 1 for the four PTEs. Therefore, *G. pylzowianum* could be used for the in situ phytoextraction of As, and *P. saundersiana* can be used as an effective plant for Cd and Pb phytoextraction. *E. nutans* is better suited for the phytostabilisation of multiple PTEs. Our study is of significant importance for introducing native plant species to remediate PTE-contaminated soils, particularly As and Cd, and has a good potential for developing PTE phytoremediation strategies at mining sites.

## Highlights

As was the prime pollutant in soils surrounding the gold mine.

Phytoremediation of PTEs in 12 native plants was examined at a gold mining site.

*P. saundersiana* had TF higher than 1 for all PTEs.

*P. undersiana* and *G. pylzowianum* are potential phytoextractors of As from soils.

*E. nutans* has high phytostabilisation potential for all PTEs.

## 1. Introduction

Soils are essential components of terrestrial ecosystems as they play a fundamental role in food safety, ecological stability, and food security (Sun et al., 2019; Keshavarzi and Kumar, 2019). However, with the rapid development of the economy, soil contamination by potentially toxic trace elements (PTEs), which is caused by anthropogenic activities, including mining activities, industrial processes, waste disposal, and land use change (Zeng et al., 2020; Gemedo et al., 2021), has become a severe global problem. Among these activities, mining activities are currently the main source of metal contamination in soils (Zhou and Wang, 2019; Chen et al., 2021a). PTEs in soils pose significant risks to human health via bioaccumulation in plants and animals or bioconcentration in the food chain because of their toxicity, high mobility, and non-biodegradability (Jiang et al., 2018; Fang et al., 2020; Beiyuan et al., 2021).

Previous studies have found heavy arsenic (As) contamination in gold mining areas, which leads to adverse effects on plant growth and mammalian cells (Aguilar et al., 2020; Tabelin et al., 2020). Additionally, other PTEs, including cadmium (Cd), lead (Pb), chromium (Cr), zinc (Zn) and mercury (Hg), normally co-occur with As in contaminated soils of gold mining areas (Bempah and Ewusi, 2016; Gao, 2018). Therefore, remediating contaminated soils is of great significance in eliminating PTE contamination and reducing the potential ecological risks in the gold mining areas.

Phytoremediation in PTE-contaminated soils has been widely used because of its low cost and eco-friendliness compared with traditional physical or chemical approaches (Ju et al., 2020; Kanwar et al., 2020). Phytoremediation, including phytoextraction and phytostabilisation, has shown satisfactory results, and relies on the natural capacity of plants to remove or stabilise metal pollutants in contaminated sites (Cheraghi-Aliakbari et al., 2020; Egendorf et al., 2020). The uptake, translocation, and accumulation of pollutants in soil-plant systems mainly depend on the plant species (Jiang et al., 2018). Currently, only a few plant species have been identified to hyper-accumulate PTEs in their harvested parts. Therefore, more studies are needed to identify potential PTE hyper-accumulators. Native plant species preferred for phytoremediation as they have strong resistance to an excess of PTEs from the contaminated sites and pose no ecological risk to the local ecosystem (Aihemaiti et al., 2017; Hasnaoui et al., 2020). Additionally, polluted sites with unique climates may not be suitable for the growth of exotic hyper-accumulator plants. Furthermore, soil properties play a key role in controlling metal uptake by plants (Wang et al., 2020). Recently, Yu et al. (2021) indicated that the phytoremediation efficiency was correlated with soil pH and nutrients as they directly or indirectly changed the bioavailability of PTEs in soil-plant systems.

Hezuo City, located in the northeast of the Qinghai-Tibet Plateau, is rich in mineral resources such as copper (Cu), iron (Fe), and As, and is especially rich in gold. Zaozigou, which is located in the western zone of Hezuo City, is the largest gold mine in Gansu Province and has been explored for more than 26 years (Sui et al., 2018). Gold mines provide significant economic benefits to the local government. Nevertheless, this region is also severely affected by the presence of excessive mining activities and inadequate treatment of wastewater, leading to soil contamination by PTEs (Hu et al., 2020). In this context, the main aims of this research were to (1) assess the total concentrations of PTEs (As, Cd, Zn, and Pb) and the soil chemical properties in rhizospheric soil; (2) explore the uptake, translocation, and accumulation of PTEs in 12 native dominant plant species; and (3) screen and assess the phytoremediation potential of native plant species found in the mining area.

## 2. Materials And Methods

### 2.1 Site description

The sampling sites (Zaozigou gold mine) are located northeast of the Qinghai-Tibet Plateau, Hezuo city, Gansu Province, China ( $34^{\circ} 56' \text{N}$ – $34^{\circ} 59' \text{N}$  and  $102^{\circ} 47' \text{E}$ – $102^{\circ} 51' \text{E}$ ), which is classified as having a cold and humid alpine climate, with a mean annual rainfall of 545 mm. The altitude of the study area

ranges from 2960 to 3520 m. The mean temperature is 11.7 °C in summer and -10.7 °C in winter, and the area has an average of 270 frost days per year. Various plant species are found in the gold mining area, and the area is polluted with multiple metals and As (Hu et al., 2020).

## 2.2 Rhizosphere soil and plant sample collection and analysis

This study was conducted in September 2020 in the gold mining area. Soil samples were collected from the rhizosphere soils (0–20 cm) of plants via a soil sampler and shaking the soil, after which the plant samples were uprooted. After removing stones and other debris, the soil samples were air-dried and ground to a fine powder. Three replicates were prepared and used for the analyses, and a total of 36 soil samples were included. Soil pH and conductivity (EC) were determined using a water/soil ratio of 5:1 in an aqueous suspension. Soil organic matter (SOM) was analysed by the oxidation method with  $K_2Cr_2O_7$ - $H_2SO_4$  followed by titration with  $FeSO_4$  (Yuan et al., 2011). Soil total potassium (TN) was measured based on the method described by Estefan et al. (2013) using a Foss Kjeltec analyser. Total phosphorus (TP) was measured using the acid digestion method (Hu et al., 2018). To determine the PTE concentrations in soil, air-dried soil samples (0.5 g) were digested in  $HNO_3$ : $HClO_4$  (5:1, v/v) at 180 °C for 6 h. The PTE concentrations in the soil samples were measured using an inductively coupled plasma mass spectrometer (Agilent, Santa Clara, CA, USA).

Plant samples were collected in September 2020 from the same sites as the soil samples. Twelve plant species in this area were collected: *Poa pratensis* L., *Elymus nutans* Griseb., *Potentilla saundersiana* Royle, *Geranium pylzowianum* Maxim., *Carpesium lipskyi* Winkl., *Ligularia sagitta* (Maxim.) Mattf., *Potentilla fruticosa* L., *Artemisia frigida* Willd., *Rumex nepalensis* Spreng., *Taraxacum mongolicum* Hand.-Mazz., *Gentianopsis paludosa* (Hook. f.) Ma, and *Swertia tetraptera* Maxim (Fig. 1). These native plant species were chosen based on high abundance and vitality. At each sampling site, three to five individual plants were randomly collected. All plants had healthy root systems and no leaf chlorosis. Triplicates of each plant species were also collected. Plant species were identified on the basis of the Plant Photo Bank of China. The entire plants were carefully washed thrice with tap water, carefully rinsed with deionised water, separated into shoots and roots, air-dried and oven-dried at 72 °C for 48 h, and ground into a powder. The samples were digested with 15 ml  $HNO_3$  and 5 ml  $HClO_4$  and then filtered. After filtration, the total PTE (Cd, Pb, Zn, and As) concentrations of the digested solutions were determined using ICP-MS.

## 2.3 Statistical analysis

Bioconcentration factor (BCF) is defined as the ratio of PTE concentrations in plant tissue, and represents the absorbing ability of PTEs from the soils by plants (Chen et al., 2020) (Eq. 1). The ability of translation of PTEs in roots of plants in relation to shoots is evaluated using the Translocation factor (TF) (Chen et al., 2020) (Eq. 2)

$$BCF = C_{shoot}/C_{soil} \quad (\text{Eq. 1})$$

$$TF = C_{\text{shoot}}/C_{\text{root}} \quad (\text{Eq. 2})$$

where  $C_{\text{soil}}$ ,  $C_{\text{shoot}}$ , and  $C_{\text{root}}$  are the PTE concentrations of the soil, aerial parts of plants, and root parts of plants, respectively.

Data were processed using Excel 2013, and the statistical analysis was performed with SPSS 23 for windows. Figures were drawn using the Origin 2018b software. Mean values based on triplicate measurements were calculated. The means were compared using the least significant difference (LSD) test to determine marked differences between different treatments ( $p < 0.05$ ).

## 3. Results

### 3.1. Rhizosphere soil characterization

The chemical properties of the rhizosphere soil from the study area are given in Table 1. The pH of rhizosphere soil ranged from 7.29 to 8.08, suggesting that all sampling sites were alkaline. The EC varied from 73.43 to 118.07  $\text{mS m}^{-1}$ , with the highest value observed at the rhizosphere soil of *T. mongolicum*. The SOM ranged from 37.28 to 93.56  $\text{g kg}^{-1}$ , with a marked difference ( $p > 0.05$ ) between the rhizosphere soils of *P. fruticosa* and *G. paludosa*. The rhizosphere soils of *P. pratensis* had relatively high amounts of TN and TP. Soil TN varied among different rhizosphere soils, and the rhizosphere soils of *G. pylzowianum* had the lowest value.

### 3.2. PTEs concentrations in rhizosphere soils

The contents of As, Zn, Cd, and Pb in the rhizosphere soils of the identified plant species are shown in Fig. 2. In this study, most of the As concentrations in the soil were exceeding the threshold limits of China (GB 15618–2018) ( $25 \text{ mg kg}^{-1}$ ), ranging from 22.61 to 144.22  $\text{mg kg}^{-1}$ . For the concentrations of Cd, most of the rhizosphere soils were under the threshold ( $0.5 \text{ mg kg}^{-1}$ ), but the average values in all rhizosphere soils exceeded the background values ( $0.1 \text{ mg kg}^{-1}$ ). The concentration of Zn and Pb in the rhizosphere soils ranged from 79.94 to 88.78  $\text{mg kg}^{-1}$  and 27.23 to 40.53  $\text{mg kg}^{-1}$ , respectively, and all of them were high than their background values ( $74.2 \text{ mg kg}^{-1}$  for Zn and  $26.0 \text{ mg kg}^{-1}$  for Pb).

### 3.3. PTEs concentrations in native plants

#### 3.3.1 Arsenic

PTEs can be absorbed by plants from soil. In this study, the PTE concentrations in the plant tissues of the identified plants were highly variable (Fig. 2). In this study, As concentrations in shoots ranged from 2.56 to 31.08  $\text{mg kg}^{-1}$ , and those in roots ranged from 2.17 to 56.74  $\text{mg kg}^{-1}$ . The highest As concentrations were recorded in the shoots and roots of *S. tetraptera*, which were only equal to approximately 21.55% and 39.34% of soil As concentrations, respectively. The shoots of *R. nepalensis* and *G. pylzowianum* and

the roots of *P. pratensis* and *E. nutans* also accumulated marked amounts of As. However, *L. sagitta* accumulated low levels of As in shoots ( $2.57 \text{ mg kg}^{-1}$ ) and roots ( $6.36 \text{ mg kg}^{-1}$ ).

### 3.3.2 Cadmium

In this study, the total Cd concentrations in the shoots and roots were also markedly different between the plant species (Fig. 3). The Cd concentrations ranged from 0.05 to  $2.07 \text{ mg kg}^{-1}$  for shoots and from 0.10 to  $1.37 \text{ mg kg}^{-1}$  for roots (Fig. 3). The highest Cd contents were observed in the shoots and roots of *S. tetraptera*. The Cd contents in the shoots of *P. saundersiana*, *C. lipskyi*, *L. sagitta*, *A. frigida*, and *S. tetraptera* were markedly higher than those in their rhizosphere soils.

### 3.3.3 Lead

The Pb content in the shoots of 12 investigated plants, except *P. saundersiana*, *P. fruticosa*, *A. frigida*, and *T. mongolicum*, were higher than those in their rhizosphere soils (Fig. 4). The highest shoot Pb concentrations were found in *P. saundersiana*, which was approximately 1.5 times higher than the soil Pb levels. The roots of *P. saundersiana* also showed a strong capacity to absorb Pb from the soil.

Additionally, the Pb content in the roots of *G. paludosa* was up to  $29.46 \text{ mg kg}^{-1}$ , which was markedly higher than those recorded in other plant species. The lowest concentration of Pb was found in *E. nutans* ( $3.64 \text{ mg kg}^{-1}$ ) for shoots and *L. sagitta* ( $13.14 \text{ mg kg}^{-1}$ ) for roots.

### 3.3.4 Zinc

Total Zn concentrations in shoots and roots were markedly different between the plant species. The Zn concentrations in the shoots and roots ranged from  $11.40 \text{ mg kg}^{-1}$  and  $21.05 \text{ mg kg}^{-1}$  to  $44.62 \text{ mg kg}^{-1}$  and  $50.44 \text{ mg kg}^{-1}$ , respectively. In the current study, the maximum Zn accumulation in the shoots was recorded in *T. mongolicum*. Additionally, root Zn contents in *P. pratensis* and *E. nutans* were  $50.44 \text{ mg kg}^{-1}$  and  $48.71 \text{ mg kg}^{-1}$ , respectively, which were markedly higher compared to those of the other 10 plant species (Fig. 5). The lowest Zn content ( $11.40 \text{ mg kg}^{-1}$ ) in shoots was recorded in *E. nutans*, suggesting that *E. nutans* may be a potential low accumulator of Zn. Moreover, in most of native plant species, the Zn content in the shoots was markedly lower than that recorded in the roots, indicating that Zn had a low translocation rate from roots to shoots compared to As, Cd, and Pb.

## 3.4. PTEs uptake and translocation by 12 investigated plants

The efficiency of PTE uptake by native plants and its translocation can be evaluated using BCF-S and TF, respectively. A BCF-S higher than 1 indicates that the plant is efficient at absorbing and accumulating PTEs from the soils, while low BCF-S values indicate that the plant excludes. Plants with both BCF-S and TF values higher than 1 may be potential hyper-accumulators. However, plants with both BCF-S and TF values much less than 1 can stabilise PTEs in the soils. The BCF-S and TF values for the native plant species analysed in this study are shown in Fig. 6 and 7, respectively. In this study, all plant species had a BCF-S value lower than 1 for As. Among these, *G. pylzowianum* and *P. fruticosa* showed relatively high

BCF-S of 0.79 and 0.58 for As, respectively. Among 12 investigated plant species, *E. nutans* was found growing in heavy As-contaminated soils, and showed BCF-S of 0.10, 0.32, 0.13, and 0.11 for As, Cd, Zn and Pb, respectively, suggesting that *E. nutans* has great potential to stabilise As, Cd, Zn, and Pb in the contaminated soils. *P. saundersiana* showed the highest BCF-S for Cr and Cu, which were 4.52 and 1.70, respectively. In addition, no plant species showed BCF-S > 1 for Zn, suggesting that Zn is not easily absorbed by plant shoots.

Most of the native plants showed high translocation capacities for As and Cd (Fig. 7). A relatively high TF for As was found in *G. Pylzowianum* (4.65) and *P. fruticosa* (3.97). In addition, they had TF values higher than 1 for Cd and Pb. However, *P. pratensis* and *E. nutans* showed TF values lower than 1 for As, Cd, Zn, and Pb. The maximum TF (6.65) of Cd was recorded in *P. saundersiana*; which also had a TF higher than 1 for As (2.12), Pb (2.54), and Zn (1.05).

In the current study, no single plant exhibited both BCF-S and TF values higher than 1 for As concurrently, but *P. saundersiana* accumulated and translocated high levels of As, Cd, and Pb. Additionally, *P. saundersiana* was found growing in heavy As-polluted and moderately Cd-contaminated soils, demonstrating that *P. saundersiana* has the potential for phytoextraction of As and Cd from soils. For As, Cd, Zn, and Pb for all the investigated plants, BCF-S and TF values lower than 0.5 were only observed for *E. nutans*. Thus, *E. nutans* can be used to phytostabilise these PTEs in soils.

## Discussion

PTE bioavailability drives its biogeochemical behaviour in soil-plant systems, which plays an important role in PTE uptake by plants (Nejad et al., 2021). The most important factor affecting PTE bioavailability was soil chemical properties, such as soil pH, SOM, and nutrient content (Ali et al., 2020). In this study, all sampling sites had alkaline pH, which may be attributed to the impact of mining activities. These results confirm the phenomenon found by Barakan et al. (2019) related to soils of a similar gold mine, which indicated that the discharge of the alkaline mine wastewater may cause the alkalinity of the soil and the release of As and other elements into the soil environment. Electrical conductivity (EC) can enhance PTE precipitation and complexation, decrease the mobility and bioavailability of PTEs, and consequently reduce PTE accumulation in plant tissues (Aihemaiti et al., 2017). However, our study found that soil EC had no marked effect on PTE accumulation in plant shoots (Table S1), probably due to the low soil EC in the investigated soils. SOM, originating from the decomposition of plant, animal, and microbial material, has a high affinity for PTEs to increase its adsorption ability (Chen et al., 2021b). Generally, higher SOM content determines more PTE sorption sites, and thus reduces the bioavailability in soils (Hu et al., 2019). In this study, all investigated soils exhibited very high concentrations of SOM, as per the national standard, and had no significant effect on PTE accumulation in the shoots (Table S1). Furthermore, soil nutrients are crucial factors governing plant growth and influence PTE accumulation in plant tissues, such as TN and TP (Miranda et al., 2021). In this study, soil nutrients were within a high range, including high TN (more than 2 g kg<sup>-1</sup>) and extremely low TP (lower than 0.5 g kg<sup>-1</sup>) (Xu et al., 2018). Meanwhile,

total N, P and PTE contents in the soil were not markedly correlated with each other, indicating that N, P, and PTEs in these soils originated from different sources (Table S1).

Compared to the Chinese national standards, As, Cd, Zn, and Pb levels in the soils exceeded the background values of 11.5, 0.1, 11.2, and 26.0 mg kg<sup>-1</sup>, respectively, and As and Cd concentrations surpassed their permissible limits. However, the native plants did not exhibit high levels of As in their tissues. The result for the reason could be due to the high soil SOM, which decreased As mobility and bioavailability and thus affected As uptake by plant roots (Hu et al., 2019). The differences among plant species and strong phytotoxicity of As could also have led to the low As accumulation.

In the present study, the 12 native plant species were capable of growing in soils that varied widely in this study area contaminated with As and Cd, with concentrations exceeding the Chinese national standards. This indicates that these plants have a strong tolerance for As and Cd. In recent years, few studies have explored the behavior of As uptake by native plant species. In our study, As was mainly retained in the roots of all plant species, which is similar to the findings of Wei and Chen. (2006), Sharifi et al. (2012), and Liu et al. (2014). Among these plant species, *G. pylzowianum*, *R. nepalensis*, and *S. tetraptera* had relatively higher As concentrations in their shoots, even though these plants were found in the heavy As-contaminated soil. The difference in As accumulation and distribution among the plant species are the result of complex interactions between chemical and biological factors (Aihemaiti et al., 2017). Meanwhile, As accumulation was found to be closely related to the soil As level. Although *S. tetraptera* accumulated 31.08 mg kg<sup>-1</sup> As in its shoots, the sampling sites had the highest soil As concentration (144.22 mg kg<sup>-1</sup>), and thus it may be not a suitable As phytoextractor candidate. In contrast, *G. pylzowianum* and *P. fruticosa* showed a strong capacity to absorb and translocate As, suggesting that accumulation and distribution of As is very plant-specific. The phenomenon may be attributed to the difference in aboveground biomass of these plant species, which can dilute the level of As in shoots and enhance the tolerance of plants to As toxicity.

Different results were found for Cd, Zn, and Pb concentrations in the plant tissue. Cd is not essential for plants and is considered toxic at low levels for most plant species (Wang et al., 2021). In the current study, Cd exhibited an inverse distribution pattern to that of As in the investigated plants. Six plant species showed high levels of Cd accumulation in their shoots and transferred marked levels of Cd from their roots to shoots. *S. tetraptera* accumulated the highest Cd levels in its shoots and roots, and both BCF-S and TF were higher than 1, indicating that the plant may be useful as a potential Cd hyper-accumulator to remove Cd from contaminated soils. Moreover, *S. tetraptera* grew at the most Cd-contaminated soils, thus leading to increased Cd levels in its roots and shoots. A possible reason is that Cd is distributed to non-photosynthetically active organs in plant tissues to reduce Cd toxicity by biomass diffusion (Choppala et al., 2014; Haider et al., 2021). Lotfolahi et al. (2011) also reported that shoots of *Helianthus annuus* accumulate greater Cd levels than those of roots. However, several plant species accumulate higher Cd levels in their roots than in their shoots, indicating that Cd accumulation patterns in plant species are highly variable (Shackira and Puthur, 2017).

Pb is a highly toxic element that does not play a beneficial role in the physiological and biochemical processes of plants. Among the investigated plants, *P. saundersiana* exhibited the highest Pb levels ( $67.98 \text{ mg kg}^{-1}$ ) in shoots, and *P. saundersiana* had the highest BCF and TF of 1.70 and 2.54, respectively, which indicated high accumulation and translocation efficiency. Our findings are in accordance with those of Egendorf et al. (2020), who reported that *Vetiveria zizanoides* had higher Pb levels in its shoots than its roots and exhibited a strong capacity to accumulate Pb in its shoots. Unlike the other three PTEs, Zn is an essential element for plants when present in lesser amounts, while in excessive amounts it exerts detrimental effects on plant growth and development (Rizwan et al., 2019). The highest shoot Zn levels were recorded in *P. saundersiana* and *A. frigida*, which were markedly lower than the Zn accumulation in plants in other studies, such as *Lolium perenne* L. (Zhang et al., 2019) and *Salix spp.* (Yang et al., 2020). This possible reason is the lower soil Zn levels in the study area compared with those in other Zn-contaminated soils (Zhang et al., 2019; Yang et al., 2020). In addition, Zn is difficult to accumulate in plants in the aboveground parts compared to the other three PTEs. Lam et al. (2017) also reported that Zn was actively transported to plant shoot tissues as Zn plays an important role in many plant functions, which is not consistent with our result that most plant species have higher Zn levels in their roots. A possible reason is that Zn uptake and translocation of plant species are highly variable and dependent on the soil matrix and climatic conditions (Pinto et al., 2014; Aihemaiti et al., 2017).

Among the 12 native plant species, *G. pylzowianum* exhibited TF values higher than 1 for As (4.65), Cd (1.87), and Pb (1.36), while *G. pylzowianum* had the highest BCF-S values of 0.79 for As. The results clearly suggest that *G. pylzowianum* has potential use as an As hyper-accumulator, which is inexpensive, simple to operate, and more eco-friendly for cleaning As-contaminated soils in gold mining areas. *P. saundersiana* had TF values of 2.12, 6.65, 2.54, and 1.05 for As, Cd, Pb, and Zn, respectively. Additionally, it had BCF-S values of 4.52 and 1.70 for Cd and Pb, respectively. The reason for its strong accumulation and translocation capacities is ascribed to their large and deep root systems. Thus, *P. saundersiana* can be considered a potential hyper-accumulator for the remediation of soils contaminated with Cd and Pb. *E. nutans* accumulated relatively low amounts of As, Cd, Pb, and Zn in its shoots, and had a TF lower than 0.4 for all PTEs, indicating that the plant species had a strong ability to mobilise these PTEs into its roots. Thus, *E. nutans* could be considered as a potential candidate for the phytostabilisation of multiple PTEs (As, Cd, Pb, and Zn) in the gold mining area.

## Conclusion

In this study, we explored the PTE concentrations in 12 native plant species and their rhizosphere soils surrounding a typical gold mining area in the northeast of the Qinghai-Tibet Plateau. The 12 native plant species appeared to be well adapted to the gold mining area. Meanwhile, the concentrations of PTEs in plants and their rhizosphere soils varied markedly. Of the plant species evaluated, *G. pylzowianum* accumulated high levels of As in its shoots and had a TF higher than 1 for As, Cd, and Pb. Thus, it could be considered a potential hyper-accumulator for As. *P. saundersiana* was suitable for phytoextraction of

both As and Cd because of the high amounts of As and Cd in their shoots and both BCF-S and TF values higher than 1. For the first time, *E. nutans* was proposed as a candidate stabiliser for multiple PTEs. Thus, it was suitable for phytostabilisation in multiple PTE-contaminated soils. Based on the basis of these findings, our study provides insight in development of plant species that are suitable *in situ* for phytoremediation, particularly those located in the Qinghai-Tibet Plateau.

## Declarations

### Authors Contributions

Lei Wang: conceptualization, investigation, writing the original draft and analysis

Xiaorong Xie: investigation and made suggestions of the manuscript

Qifeng Li& Zhifeng Yu: investigation and formal analysis

Guangde Hu& Xixi Wang: investigation and data curation

Jinrong Liu: editing and corresponding author

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### Competing Interests

The authors declare that they have no competing interests.

### Availability of data and materials

Most data generated or analyzed during this study are included in this manuscript. Further data used during the current study are available from the corresponding author on reasonable request.

### Ethical Approval

Not applicable.

### Consent to Participate:

Not applicable.

### Consent to Publish:

Not applicable.

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## Tables

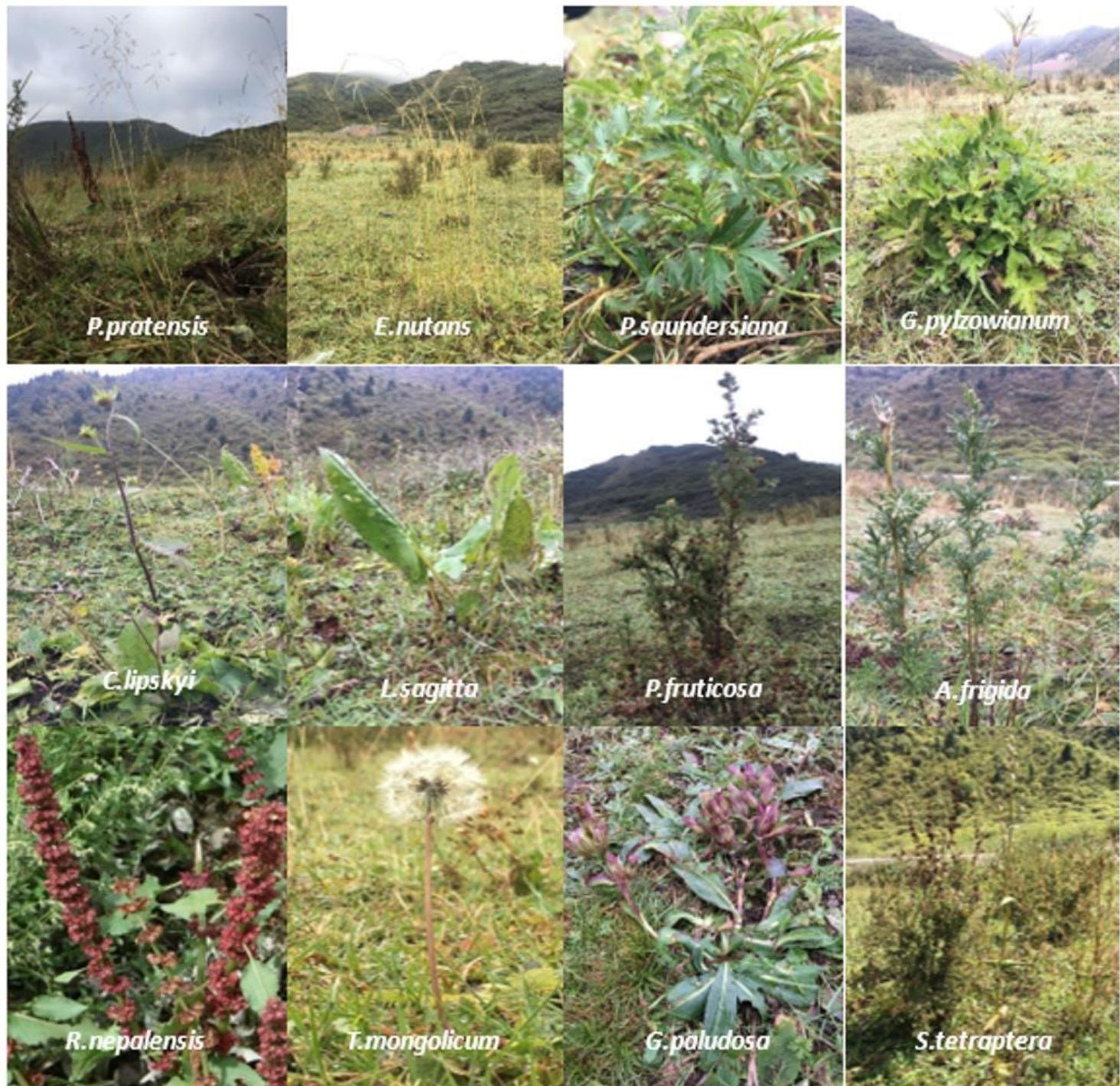
**Table 1 Basic characteristics in the rhizosphere soils**

Plant species	pH	EC	SOM	Total P	Total N
<i>P.pratensis</i>	8.08±0.10	85.47±26.22	69.65±14.57	0.47±0.11	2.60±0.11
<i>E.nutans</i>	7.67±0.12	84.07±9.11	64.38±29.82	0.39±0.06	2.20±0.61
<i>P.saundersiana</i>	7.50±0.15	83.23±8.35	54.15±15.25	0.33±0.06	2.01±0.51
<i>G.pylzowianum</i>	7.38±0.25	95.90±7.89	43.16±12.49	0.38±0.10	1.91±0.33
<i>C.lipskyi</i>	7.64±0.35	109.17±8.96	57.08±20.58	0.40±0.22	2.01±0.51
<i>L.sagitta</i>	7.63±0.10	102.43±32.76	65.57±10.62	0.47±0.09	2.38±0.60
<i>P.fruticosa</i>	7.54±0.11	89.57±15.76	37.28±5.53	0.39±0.09	2.04±0.48
<i>A.frigida</i>	7.36±0.16	81.40±3.36	72.22±36.69	0.33±0.08	2.56±0.50
<i>R.nepalensis</i>	7.29±0.10	73.43±23.02	57.99±14.10	0.48±0.08	2.49±0.32
<i>T.mongolicum</i>	7.81±0.08	118.07±18.13	43.18±12.40	0.30±0.10	2.02±0.45
<i>G.paludosa</i>	7.70±0.18	90.77±13.96	93.56±82.38	0.41±0.08	2.58±0.73
<i>S.tetraptera</i>	7.75±0.28	115.37±7.98	39.62±10.26	0.43±0.02	2.02±0.51

**Table 2 PETs concentrations (mean ± SD) of the rhizosphere soils (mg kg<sup>-1</sup>)**

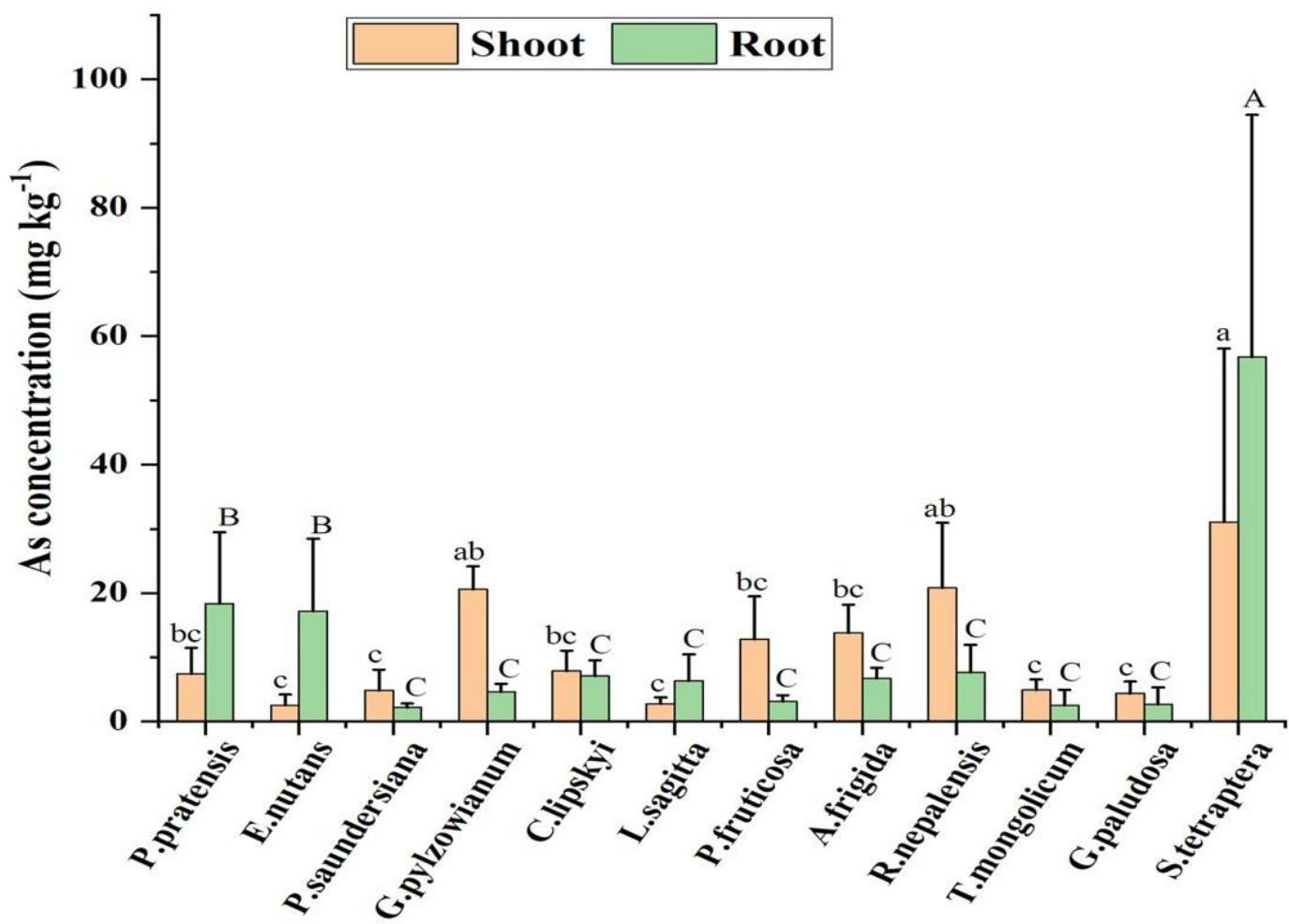
Plant species	As	Cd	Zn	Pb
<i>P.pratensis</i>	36.53 ± 18.79c	0.16 ± 0.01d	82.66 ± 7.49	32.90 ± 5.68
<i>E.nutans</i>	22.61 ± 6.27c	0.16 ± 0.035d	84.74 ± 2.37	35.58 ± 7.47
<i>P.saundersiana</i>	27.67 ± 10.23c	0.15 ± 0.021d	82.88 ± 0.38	40.53 ± 2.76
<i>G.pylzowianum</i>	28.00 ± 7.19c	0.34 ± 0.086c	84.53 ± 6.64	32.95 ± 6.51
<i>C.lipskyi</i>	27.31 ± 6.32c	0.17 ± 0.012d	82.33 ± 5.02	27.23 ± 2.54
<i>L.sagitta</i>	27.92 ± 1.35c	0.15 ± 0.021d	79.94 ± 3.05	37.51 ± 6.09
<i>P.fruticosa</i>	22.43 ± 1.21c	0.42 ± 0.105c	86.51 ± 4.51	28.22 ± 1.81
<i>A.frigida</i>	26.42 ± 3.78c	0.16 ± 0.015d	83.89 ± 2.84	37.32 ± 4.69
<i>R.nepalensis</i>	106.74 ± 44.75b	0.16 ± 0.02d	88.15 ± 2.61	31.10 ± 5.39
<i>T.mongolicum</i>	26.55 ± 2.22c	0.16 ± 0.027d	88.78 ± 2.30	32.04 ± 3.24
<i>G.paludosa</i>	23.27 ± 4.19c	1.01 ± 0.197a	83.50 ± 3.63	40.01 ± 4.06
<i>S.tetraptera</i>	144.22 ± 36.91a	0.71 ± 0.099b	85.85 ± 8.63	35.26 ± 4.64
Background level	11.2	0.1	74.2	26.0
Limit	25.0	0.5	250.0	80.0

## Figures



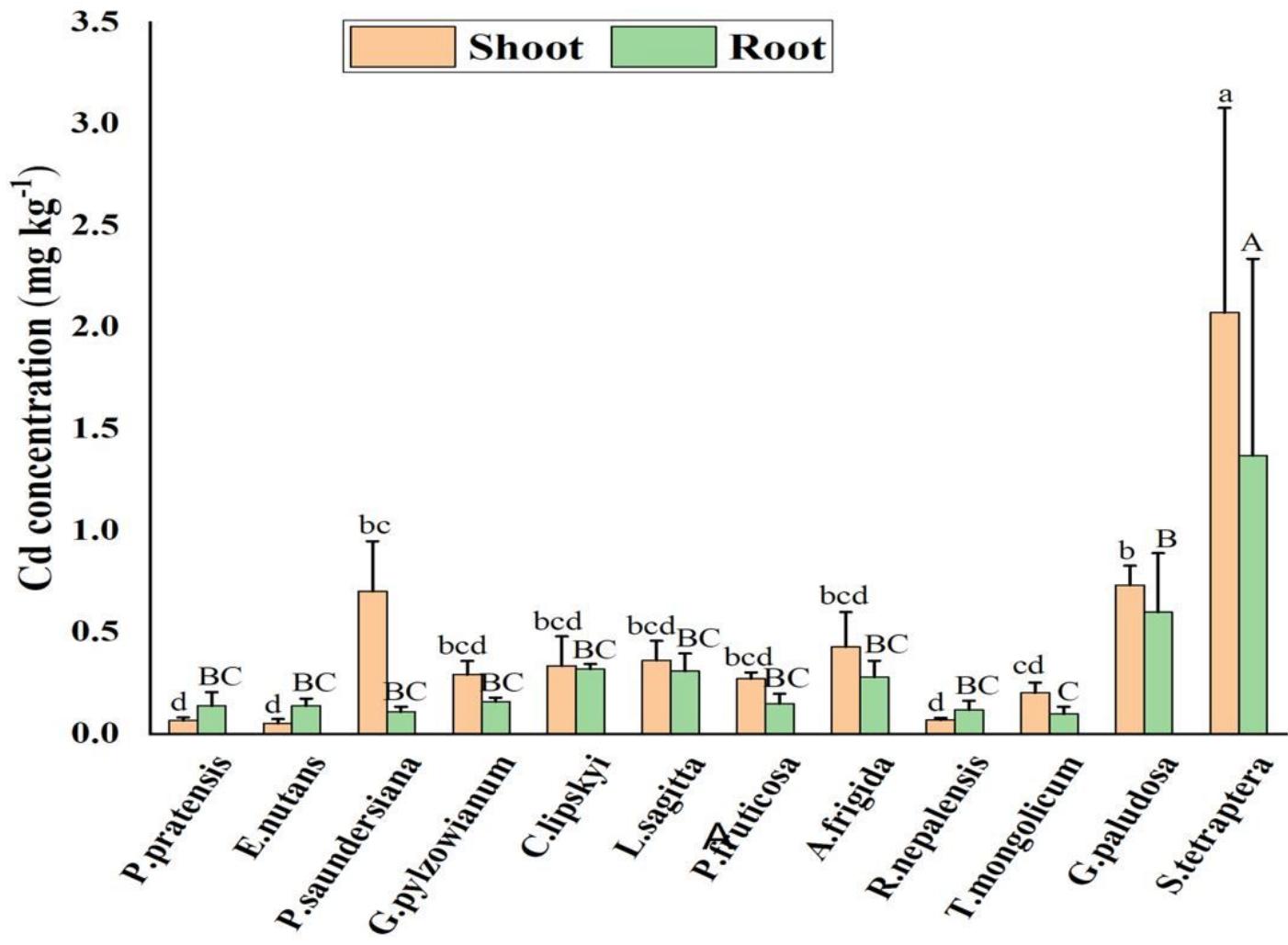
**Figure 1**

Native plant species in the mining area



**Figure 2**

As concentration in 12 native plant species from the mining area. Note: The different lower letters and upper letters indicate groups that are marked differences at the  $p < 0.05$  in the shoots and roots, respectively.



**Figure 3**

Cd concentration in 12 native plant species from the mining area. Note: The different lower letters and upper letters indicate groups that are marked differences at the  $p < 0.05$  in the shoots and roots, respectively.

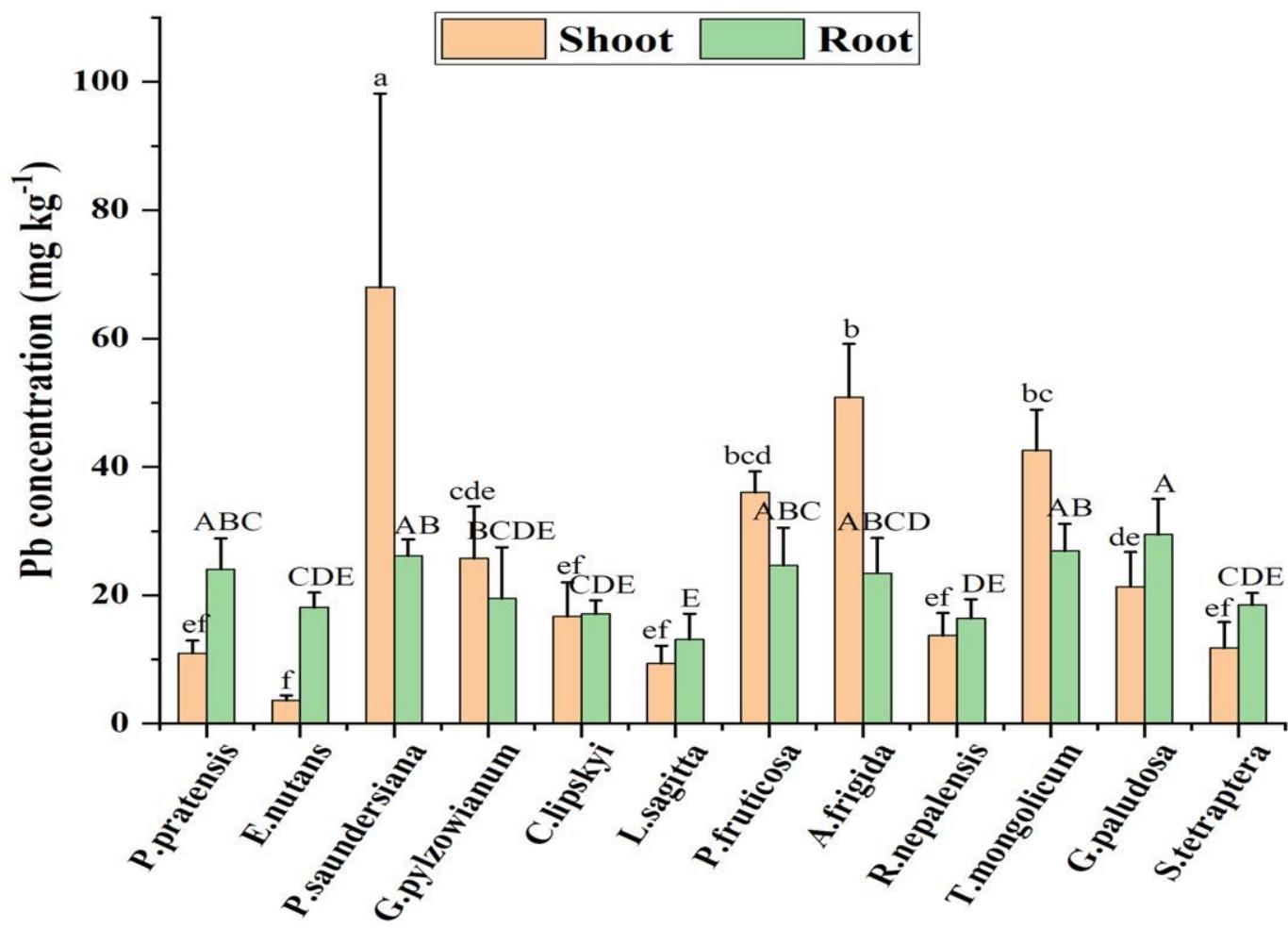
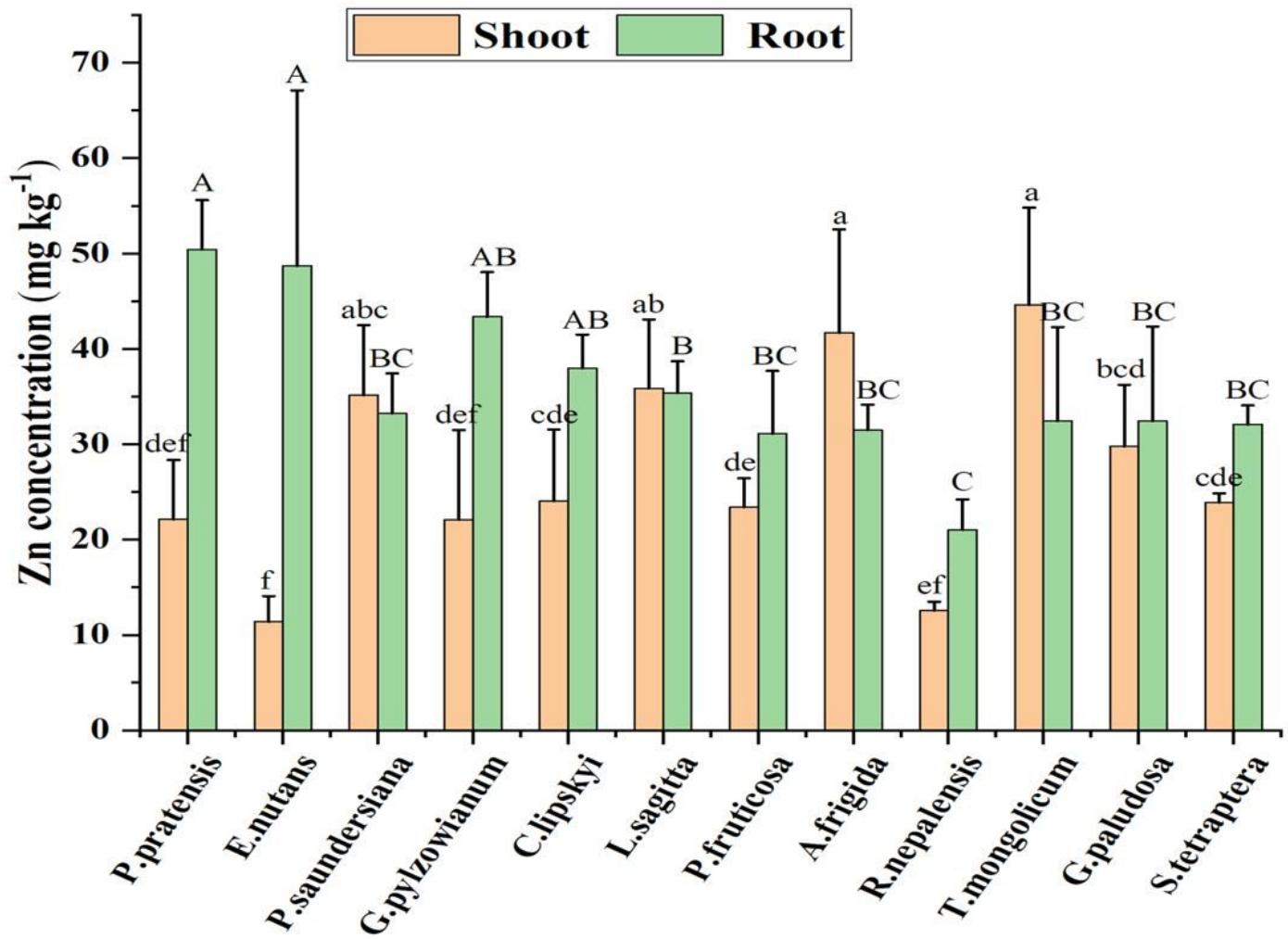


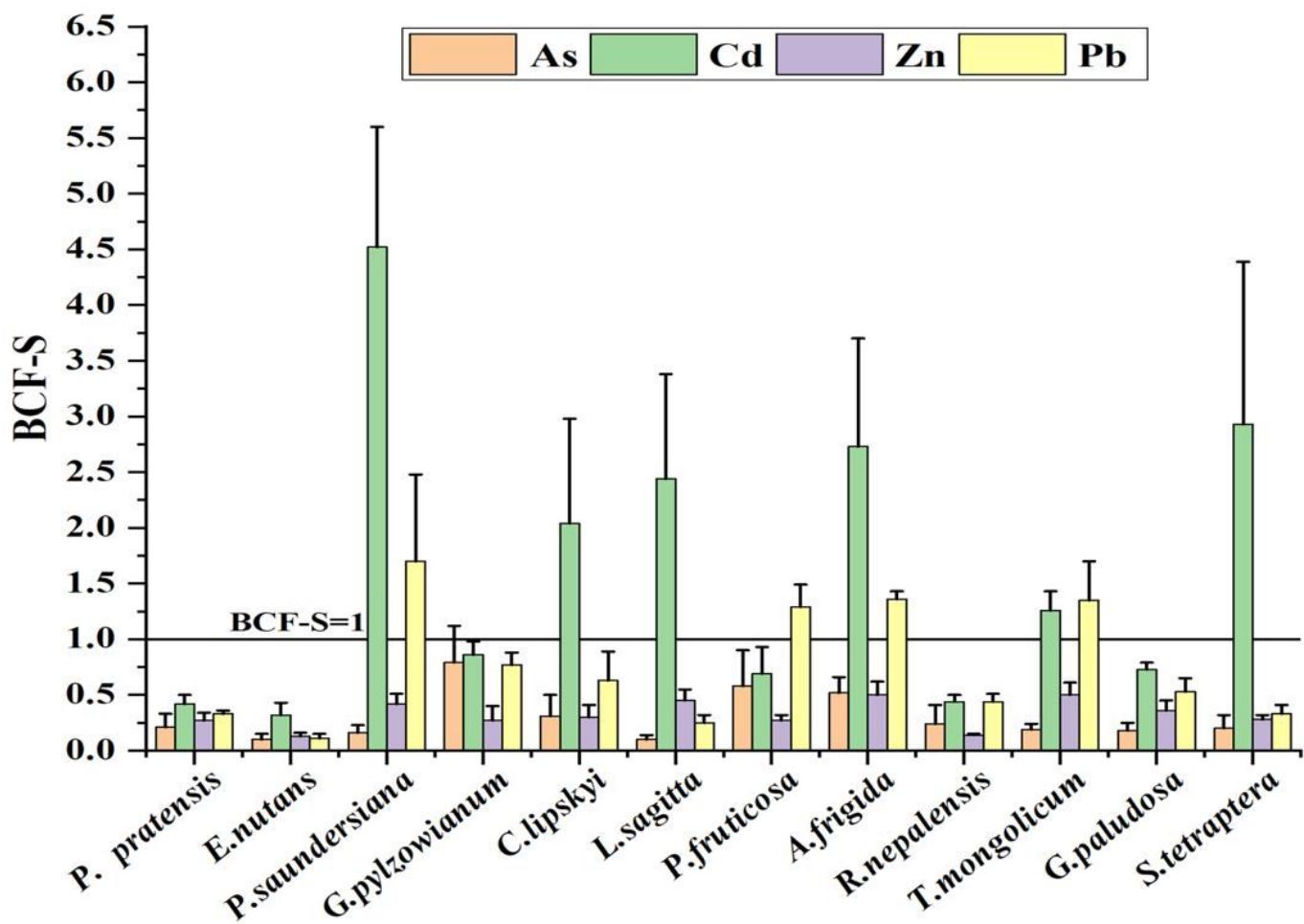
Figure 4

Pb concentration in 12 native plant species from the mining area. Note: The different lower letters and upper letters indicate groups that are marked differences at the  $p < 0.05$  in the shoots and roots, respectively.



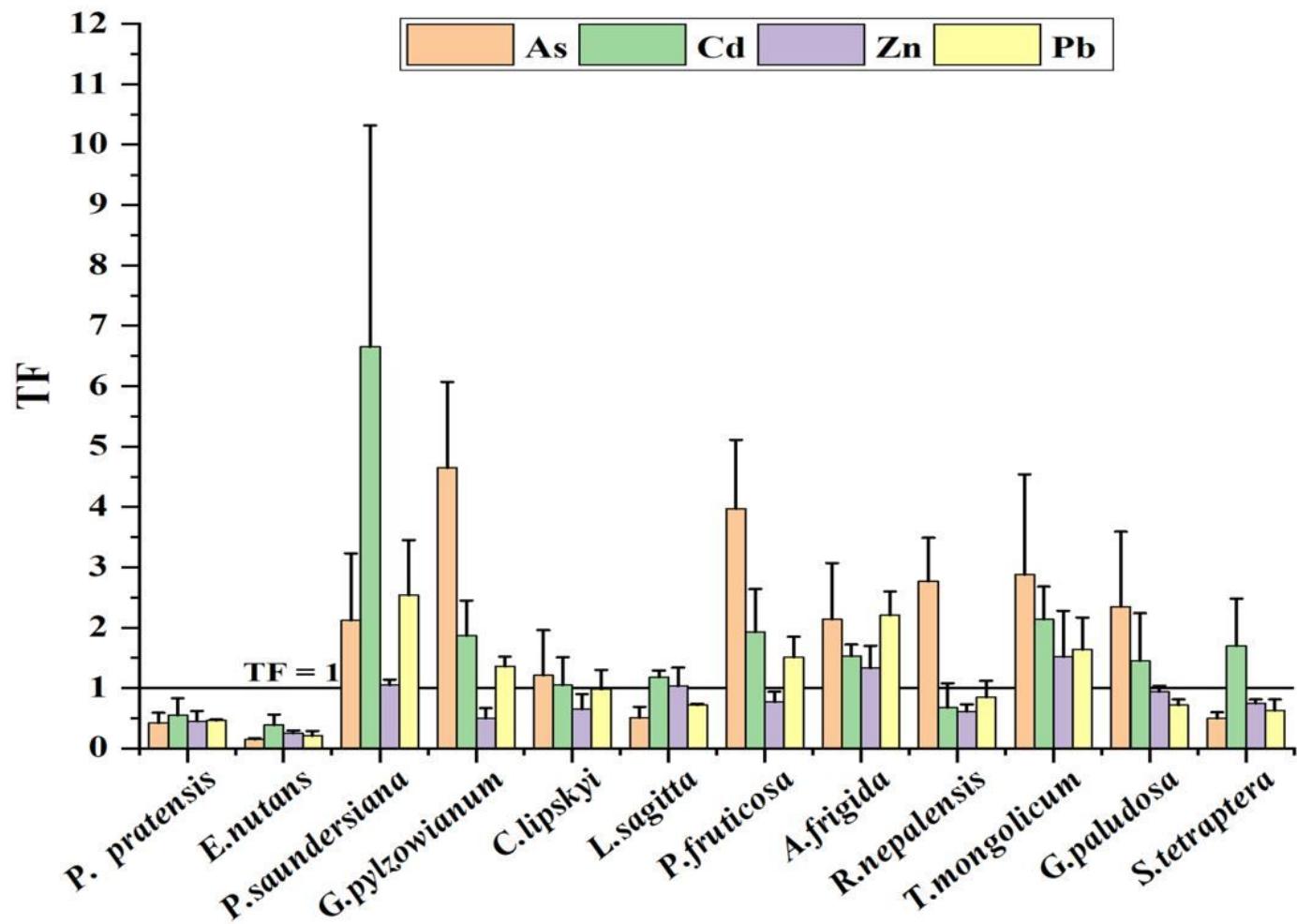
**Figure 5**

Zn concentration in 12 native plant species from the mining area. Note: The different lower letters and upper letters indicate groups that are marked differences at the  $p < 0.05$  in the shoots and roots, respectively.



**Figure 6**

The BCF-S (mean  $\pm$  SD) of 12 native plant species collected from the mining soils.



**Figure 7**

The TF (mean  $\pm$  SD) of 12 native plant species collected from the mining soils.

## Supplementary Files

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