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Lead and Copper Removal from Mine Tailings Using *Lycium chilense* and *Haplopappus foliosus*

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Abstract: In Chile, the budget for managing environmental liabilities such as abandoned tailings impoundments is limited. Using native and endemic plant species to remove heavy metals from tailings represents a low-cost alternative. Ex situ phytoremediation experiments were conducted over a period of seven months. The endemic species *Lycium chilense* and native species *Haplopappus foliosus* were used to remove copper and lead from mine tailings. The results indicate that both species can concentrate levels of Cu and Pb higher than the toxicity threshold in the roots and aerial parts, and present high removal efficiency for Cu higher than 50%. In both species, the concentrations of the target elements are higher in the roots than in the aerial parts. *Haplopappus foliosus* presents the best performance, accumulating higher concentrations of Cu and Pb than *Lycium chilense*, and presenting a bioconcentration of over one for Cu.

Keywords: heavy metals; tailings; copper; lead; phytoremediation

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1. Introduction

Chile ranks number three worldwide in tailings impoundments, with 757 registered as of 2022; of these, 112 are active, 467 are inactive, 173 are abandoned, and 5 are under construction [1]. Emblematic examples of problematic mine tailings impoundments include Andacollo, Illapel, and La Higuera, where the population suffers from irreversible pollution [2].

Copper mine tailings are the residual waste material produced during the extraction and processing of copper ore and often contain significant amounts of copper, as well as other potentially toxic elements (PTEs), which can contaminate the environment and eventually make their way into the food chain [3,4]. Every year, more than 10 billion tons of tailings are discharged from mining activities [5].

PTEs such as copper and lead can leach into the soil, reaching the groundwater and surface water when tailings are improperly stored or managed [6]. Lead can enter the human body and wildlife through accidental ingestion or via the food chain [7]. It is a neurotoxic metal and can produce a number of harmful effects, especially in children. Copper is a metal that can be toxic to aquatic life in high concentrations. In humans, exposure to high levels of copper can cause various health problems, including gastrointestinal distress and damage to the liver and kidneys. Long-term exposure to low levels of copper may also contribute to the development of chronic diseases such as Alzheimer's and Parkinson's [8].

The Dutch Soil Standards have established a concentration of 85 mg·kg^{-1} as the target value for lead and 530 mg·kg^{-1} as the intervention value; for copper, the values are 36 mg·kg^{-1} as the target value and 190 mg·kg^{-1} as the intervention value [9].

In Chile, where copper mining is a significant industry, the management of abandoned mine tailings is overseen by municipalities, which have a limited budget for dealing with the problem; this is why using a cost-effective metal-removal process from soils as a form of phytoremediation is of paramount importance.

Phytoremediation is a process that uses plants to remove, transfer, stabilize, or destroy contaminants in the soil. Its effectiveness has been demonstrated in several studies [10,11], and the use of native or endemic flora—given their availability and climatic adaptability—is essential for the success of the technique.

Some studies exist which are related to the ability of certain Chilean species to aid in the phytoremediation of tailings. For example, the accumulation characteristics of *Atriplex nummularia* for Mn, Pb, and Zn and *Schinus molle* in the cases of Cu, Mn, Pb, and Zn, respectively, from mine tailings with different amendments have been highlighted [12,13]. Lazo et al., 2020, analyzed the possibility of removing Cu and Pb using four species—among which, *Solidago chilensis* showed potential for the phytoextraction of Mo and the phytostabilization of Cu [14]. The same authors highlighted the ability of *Cistanthe grandiflora* and *Puya berteroniana* to accumulate Cr and Zn in their roots, with bioconcentration factors of close to 1.5 [15].

The uptake of Pb by most plants, close to 90%, is characterized by higher amounts of metal accumulated in the roots and only a small part translocated and accumulated in the plant's aerial parts [16,17]. In the case of Cu, most plants that tolerate the element are excluders, and translocation from the roots to aerial parts is limited [18].

Efforts to remediate contaminated sites, such as re-vegetating tailings storage areas to reduce erosion and contaminant leaching, can help mitigate the risks associated with PTE contamination from mine tailings [19,20]. Some species such as *Schinus polygamus* and *Atriplex deserticola* have been studied to determine their ability to accumulate copper; both species can attain over 1.2 $g \cdot kg^{-1}$ in their leaves [21]. Studies in Chilean soil related to lead phytoremediation have used the species *Atriplex halinus*, reaching concentrations of around 360 $mg \cdot kg^{-1}$ in the roots and between 32 and 42 $mg \cdot kg^{-1}$ in the plant's aerial parts [22]. Other native plants studied for phytoremediation of an industrial area in Valparaíso are *Oenothera picensis*, *Sphaeralcea velutina*, and *Argemone subfusiformis*; all of these present phytoremediation factors that suggest their potential for use in the removal of Pb [23].

This work is focused on the study of removing copper and lead from copper mine tailings through ex situ experiments using two species of plants, *Lycium chilense* and *Haplopappus foliosus*, to find plant species with the ability to stabilize or extract the target metals. Both species grow naturally in zones with mining activity and are possible candidates for remediation. This study complements previous research in which the same species were used to remove Cr, Ni, and Zn. The experiments lasted seven months, seeking to determine the species' phytoremediation factors. Finally, the bioconcentration, translocation factors, and removal efficiency in tailings enriched with liquid organic fertilizer are evaluated.

2. Materials and Methods

2.1. Plants

The experiments were carried out using two species, *Haplopappus foliosus* and *Lycium chilense*, which can be found in the central zone of Chile. Both species have ornamental value and no frost resistance. *Haplopappus foliosus* is a very abundant endemic shrub distributed between the Atacama and O'Higgins Regions; it grows on the coast and inland as far as the humid air from the sea reaches. *Lycium chilense* Miers ex Bertero is a native shrub that can be found between the Valparaíso and Maule Regions at low altitudes from 0 to 500 m in interior valleys and coastal areas, and between 500 and 2000 m in coastal mountains [24].

2.2. Tailings Sample Preparation

A tailings sample of approximately 550 kg was provided by Minera Las Cenizas. The localization of the impoundment is 32°28′16.1″ S, 71°05′00.2″ W and it has a projected capacity of 3 million tons of paste tailings. An image of the tailings impoundment site is presented in Figure 1. After drying the sample at 105 °C until it reached a constant weight, it was ground and homogenized using a ball mill and ASTM N°18 mesh. The pH was determined according to the 9045D EPA Method [25] and the elemental analysis was performed by inductively coupled plasma-optical emission spectroscopy (ICP-OES), using a Perkin Elmer ICP Optima 2000DV with a detection limit of between 0.005 and 0.01 ppm.

Figure 1. Tailings impoundment property of Minera Las Cenizas.

2.3. Process Parameters

The translocation and bioconcentration factors were obtained to evaluate the process using Equations (1), (2) and (3), respectively. The translocation factor TF indicates the ability to mobilize the target element from the roots to the shoots. The bioconcentration factor BCF_{roots} indicates the ability to accumulate the target element in the roots, and BCF_{aerial} indicates the ability to accumulate it in the plant's aerial parts.

$$TF = \frac{\text{Metal in the aerial parts of the plant}}{\text{Metal in the roots}} \tag{1}$$

$$BCF_{roots} = \frac{\text{Metal in the roots of the plant}}{\text{Metal in the tailings}} \tag{2}$$

$$BCF_{aerial} = \frac{\text{Metal in the aerial parts of the plant}}{\text{Metal in the tailings}} \tag{3}$$

When TF < 1, the specific plant would exclude the target metal, and when TF > 1, the plant would have the ability to translocate the target metal from its roots to its shoots. In the case of BCF, a value of higher than 1 corresponds to a plant being able to accumulate the target metal in a determined part of the plant [26,27]. The removal efficiency was calculated to obtain the total mass of the target metal removed from tailings, according to Equation (4):

$$RE\% = \frac{C_i - C_f}{C_i} 100\% \tag{4}$$

where C_i and C_f are the initial and final concentrations of the element in the tailings.

2.4. Phytoremediation Tests

Ex situ experiments were carried out at the Universidad Técnica Federico Santa María (33°02′05″ S, 71°35′43″ W). Each plant was planted in 3.1 kg of dry tailings contained in a pot. Liquid commercial organic stimulant from the algae *Ascophyllum nodosum* and water were supplied weekly. After seven months, the plants were analyzed for copper, lead, and molybdenum by ICP-OES, following the same procedure described by Lazo et al., 2023 [28].

A Merck certified multi-elemental standard solution was used to prepare an eight-point calibration curve from 0 to 8000 ppm for the quantitative determination of elements.

Control samples consisting of the two species planted in pots with natural soil and the addition of water and the same organic stimulant were used as references.

2.5. Statistical Analysis

In order to confirm any differences between the phytoremediation performance, a set of hypothesis tests were conducted, which considered separately: the metal concentration in the roots and the aerial parts of the plant, the translocation factors, and the bioconcentration factors in the roots and the aerial parts of the plant, with *Haplopappus foliosus* as species i and *Lycium chilense* as species j. Each statistical test was assessed in this order:

(1) An F-test between species at the parameter variance as given in Equation (5). $f_{0,u,v}$ is the test statistical indicator between each plant variance with u degrees of freedom in the numerator (corresponding to n_{i-1}) and v degrees of freedom in the denominator (corresponding to n_{j-1}). If the p-value is less than the significance level, the results are statistically significant.

$$p\text{-Value} = P(F > f_{0,u,v}) = \int_{f_{0,u,v}}^{\infty} f(x)dx \quad (5)$$

(2) A T-test between species with the parameters as given in Equation (6), where $t_{0,DF}$ is the test statistical indicator between each plant parameter with DF degrees of freedom. The calculation of degrees of freedom, and the indicator for each case, depends on the results of the F-test, as displayed in Table 1.

$$p\text{-Value} = P(T > t_{0,DF}) = \int_{t_{0,DF}}^{\infty} T(x)dx \quad (6)$$

where π is the mean of the analyzed result, with DF degrees of freedom. If the p-value is less than the significance level, the results are statistically significant. The entire analysis was performed with a significance level (SL) of 5%.

Table 1. T-test calculation formulas according to the F-test.

Results F-Test	DF for T-Test	Statistical for T-Test
p-Value < α	$\left[\dfrac{\left(\frac{s_i^2}{n_i}+\frac{s_j^2}{n_j}\right)^2}{\frac{\left(\frac{s_i^2}{n_i}\right)}{n_i-1}+\frac{\left(\frac{s_j^2}{n_j}\right)}{n_j-1}}\right]$	$t_{0,DF} = \dfrac{\lvert\pi_i-\pi_j\rvert}{\sqrt{\frac{s_i^2}{n_i}+\frac{s_j^2}{n_j}}}$
p-Value > α	$n_i + n_j - 2$	$t_{0,DF} = \dfrac{\lvert\pi_i-\pi_j\rvert}{\sqrt{\left(\frac{(n_i-1)s_i^2+(n_j-1)s_j^2}{n_i+n_j-2}\right)\left(\frac{1}{n_i}+\frac{1}{n_j}\right)}}$

3. Results

3.1. Initial Metal Concentrations in Tailings

In Table 2 is presented the characterization of the initial tailings sample, and the main parameters include the corresponding standard deviation. Since the sample corresponds to paste tailings, the percentage of solids in the sample is quite high.

As can be seen from Table 2, the copper concentration in the tailings sample is much higher than the value indicated by Kumar et al., 2019 [29], who suggest a concentration of 20 mg·kg^{-1} in the soil as the limiting value. Additionally, this exceeds the values indicated in the Dutch List [9], where the target value for copper in soils is 36 mg·kg^{-1} and the intervention value for copper in soils is 190 mg·kg^{-1}. The concentration detected in the sample is eight-times higher than the intervention concentration. The lead concentration in the same sample also exceeds the level established for the Dutch List [9]. In addition, Usman et al. (2020) [30] indicate that the growth of most plants is severely reduced at a lead concentration in soil of higher than 30 mg·kg^{-1}. The molybdenum concentration is within the background concentration range for normal soils.

Table 2. Characterization of the tailings sample provided by Minera Las Cenizas.

Parameter	Value	Unit
Specific gravity	2.6 ± 0.3	-
pH	7.3 ± 0.1	-
Solid % (weight)	82 ± 1	%
Granulometry d_{50}	0.046 ± 0.001	µm
As	90 ± 5	mg·kg^{-1} dry weight
Hg	Under detection limit	
Cu	1582 ± 78	
Pb	228 ± 3	
Zn	870 ± 32	
Ni	95 ± 3	
Mo	3.9 ± 0.2	
Cd	Under detection limit	
Cr	155 ± 5	

3.2. Metal Concentration in Plants

At the beginning and end of each experiment, the control samples of the plant species were analyzed for Cu, Mo, As, and Pb. The concentrations of Cu and Mo plus the standard deviation are presented in Table 3. In the case of As and Pb, all concentrations were under the detection limit.

Table 3. Initial and final amounts of Cu and Mo in aerial parts and roots in control samples.

Metal Content		*Haplopappus foliosus* mg·kg^{-1} Dry Weight	*Lycium chilense* mg·kg^{-1} Dry Weight
Mo in aerial parts	Initial	0.21 ± 0.02	0.110 ± 0.007
	Final	0.22 ± 0.01	0.174 ± 0.008
Mo in roots	Initial	0.220 ± 0.008	0.144 ± 0.003
	Final	0.225 ± 0.006	0.154 ± 0.007
Cu in aerial parts	Initial	11.05 ± 0.07	10.45 ± 0.05
	Final	10.881 ± 0.002	10.894 ± 0.007
Cu in roots	Initial	12.77 ± 0.02	10.990 ± 0.002
	Final	13.05 ± 0.05	11.565 ± 0.007

The final concentration of Mo, Pb, and Cu in the aerial parts and the roots of *Haplapappus foliosus* and *Lycium chilense* after seven months of growth while planted in tailings are presented in Table 4.

At the end of the growth period, the concentration of Cu in the plant tissues of both species surpassed the value of 30 mg·kg^{-1} dry matter, indicated as "satisfactory" by Kumar et al., 2021 [31], as can be seen from Table 4. Additionally, Oorts, 2013 [32] suggests that the onset of Cu toxicity in the aerial parts of the plants occurs between 4 and 15 mg·kg^{-1} dry matter. In the roots, the critical concentrations of Cu are between 100 and 400 mg·kg^{-1} dry matter [33,34]. For *Haplopappus foliosus*, the concentrations of Cu in its roots (847 mg·kg^{-1} dry matter) and aerial parts (261 mg·kg^{-1} dry matter) were higher than for *Lycium chilense*. The same trend was observed for Pb and Mo.

Table 4. Concentration of Mo, Pb, and Cu in aerial parts and roots of *Haplopappus foliosus* and *Lycium chilense* after seven months of growth while planted in tailings.

Metal Content	*Haplopappus foliosus* mg·kg^{-1} Dry Weight	*Lycium chilense* mg·kg^{-1} Dry Weight
Mo in aerial parts	1.004 ± 0.006	0.699 ± 0.007
Mo in roots	4.11 ± 0.07	5.13 ± 0.04
Pb in aerial parts	12.80 ± 0.08	3.72 ± 0.06
Pb in roots	93.1 ± 0.9	34.0 ± 0.3
Cu in aerial parts	261 ± 2	92 ± 1
Cu in roots	847 ± 5	599 ± 4

The Pb concentration in the roots of both species exceeded the value indicated by Usman et al. (2020) [30] for the onset of toxicity, where *Haplopappus foliosus* presents the highest concentration. Moreover, in the case of the two studied species, it was observed that the lead concentration in the roots was almost ten-times higher than the concentration in the aerial parts.

In the case of molybdenum, the final concentrations were higher than the initial ones, but still considered within normal values for plants. The concentration of As in the aerial parts and roots of the plant was under the detection limit.

In the same way, the tailings sample was analyzed after and before the experiment. The final concentrations of the elements are presented in Table 5.

Table 5. Final concentration of the metals in tailings.

Metal Content	*Lycium chilense* mg·kg^{-1} Dry Weight	*Haplopappus foliosus* mg·kg^{-1} Dry Weight
Mo	2.64 ± 0.02	3.30 ± 0.05
Pb	194.6 ± 0.1	186.9 ± 0.1
Cu	740.7 ± 0.2	703.3 ± 0.3

4. Discussion

4.1. Final Metal Concentrations in Plants

After seven months of plant growth, the Cu, Mo, and Pb concentration in the roots was higher than in the aerial parts of the plant for both species. Higher roots/aerial concentrations ratios were obtained with *Lycium chilense* compared to *Haplopappus foliosus*.

At the end of the experiments, it was observed for both species that Mo was the least concentrated metal and Cu the most concentrated one. In addition, the metal content in the roots was considerably higher than in the aerial parts for both species, showing a between three to nine-times higher concentration in the roots. The results of the statistical tests for the metal concentrations are shown in Table 6.

Table 6. Statistical tests for metal concentration in the plant parts after phytoremediation.

Metal Content (π)	$f_{0,u,v}$	*p*-Value for F-Test	DF	$t_{0,DF}$	*p*-Value for T-Test
Mo in aerial parts	1.188	3.76×10^{-01}	26	133.560	1.02×10^{-38}
Mo in roots	2.514	4.79×10^{-02}	23	194.379	8.58×10^{-39}
Pb in aerial parts	2.150	8.22×10^{-02}	26	349.262	1.45×10^{-49}
Pb in roots	9.792	6.07×10^{-05}	16	372.087	3.12×10^{-33}
Cu in aerial parts	1.318	3.06×10^{-01}	26	327.452	7.74×10^{-49}
Cu in roots	1.240	3.46×10^{-01}	26	157.354	1.44×10^{-40}

As can be seen from Table 6, with a confidence level of 95%, the variances for the Mo and Pb in the roots were significantly different between the two plant species. After phytoremediation, each metal was found with a different concentration in each species and each part of the plant.

Pb and Cu were more concentrated in *Haplopappus foliosus* in the roots and aerial parts of the plant compared to *Lycium chilense*. Regarding Mo, *Lycium chilense* achieved a higher concentration in the roots than in *Haplopappus foliosus*. In terms of metal accumulation, *Haplopappus foliosus* had a considerably higher potential to concentrate the analyzed metals from this mine tailing sample, except for Mo in the roots.

4.2. Assessment of Phytoremediation

The ability of the studied plants to stabilize or extract the target metals was assessed through the calculation of the translocation and bioconcentration factors, together with the removal efficiency.

The translocation factors for molybdenum, lead, and copper for *Haplapappus foliosus* and *Lycium chilense* are shown in Table 7.

Table 7. Metal translocation factors after phytoremediation for Mo, Pb, and Cu.

Metal	*Haplopappus foliosus*	*Lycium chilense*
Mo	0.245 ± 0.004	0.137 ± 0.002
Pb	0.138 ± 0.002	0.109 ± 0.002
Cu	0.309 ± 0.002	0.153 ± 0.002

At the end of the metal removal experiments, both *Happlopappus foliosus* and *Lycium chilense* showed translocation factors of lower than 1.0 for each metal. Therefore, neither of the plant species achieved sufficient affinity to mobilize the studied elements during the experimental period.

Table 8 shows the translocation factors after phytoremediation. As can be seen in the table, with a confidence level of 95%, variances for the molybdenum translocation factor were significantly different between both plant species. After phytoremediation, each metal reached a different translocation factor. *Haplopappus foliosus* obtained significantly higher translocation factors for each metal.

Table 8. Statistical tests for translocation factor after phytoremediation.

Translocation Factor (π)	$f_{0,u,v}$	*p*-Value for F-Test	DF	$t_{0,DF}$	*p*-Value for T-Test
Mo	4.008	6.94×10^{-03}	20	203.346	6.15×10^{-35}
Pb	1.332	2.99×10^{-01}	26	46.922	5.81×10^{-27}
Cu	1.480	2.36×10^{-02}	26	200.465	2.68×10^{-43}

Molybdenum, lead, and copper bioconcentration factors in the aerial parts of plants and roots for *Haplapappus foliosus* and *Lycium chilense* are shown in Table 9.

Table 9. Bioconcentration factors after phytoremediation for Mo, Pb, and Cu.

Bioconcentration Factor	*Haplopappus foliosus*	*Lycium chilense*
Mo in aerial parts	0.304 ± 0.004	0.265 ± 0.002
Mo in roots	1.25 ± 0.02	1.95 ± 0.02
Pb in aerial parts	0.0680 ± 0.0004	0.0190 ± 0.0003
Pb in roots	0.498 ± 0.005	0.175 ± 0.002
Cu in aerial parts	0.372 ± 0.002	0.124 ± 0.002
Cu in roots	1.204 ± 0.006	0.809 ± 0.006

At the end of the metal removal experiments, both *Happlopappus foliosus* and *Lycium chilense* showed bioconcentration factors of lower than 1.0 for lead; therefore, neither of the plants achieved sufficient affinity to absorb this metal in the experimental period. Regarding molybdenum, both plants were able to accumulate it in their roots, and for copper, *Happlopapus foliosus* was able to accumulate the element in its roots. The results of the statistical tests for the bioconcentration factors are shown in Table 10.

Table 10. Statistical tests for bioconcentration factors after phytoremediation.

Bioconcentration Factors (π)	$f_{0,u,v}$	*p*-Value for F-Test	DF	$t_{0,DF}$	*p*-Value for T-Test
Mo in aerial parts	2.813	3.14×10^{-02}	22	242.282	1.72×10^{-39}
Mo in roots	1.601	1.95×10^{-01}	26	102.438	9.97×10^{-36}
Pb in aerial parts	2.330	6.27×10^{-02}	26	359.338	6.91×10^{-50}
Pb in roots	10.612	3.77×10^{-05}	16	373.473	2.94×10^{-33}
Cu in aerial parts	1.462	2.43×10^{-01}	26	343.750	2.19×10^{-49}
Cu in roots	1.376	2.79×10^{-01}	26	180.559	4.05×10^{-42}

With a confidence level of 95%, variances for Mo in the aerial parts of the plant as well as Pb in the roots were significantly different between both plant species. After phytoremediation, each metal achieved a different bioconcentration factor for every species and plant part.

Concerning removal efficiencies, they were calculated for Mo, Pb, and Cu for both species. In the case of Mo, the removal efficiency was 14.5% in the case of *Haplopappus foliosus* and 31.8% for *Lycium chilense*. The values for Pb were 18.1% and 14.7%, and for Cu, 55.5% and 53.2%, respectively.

The removal efficiency for Mo was twice as high for *Lycium chilense* than for *Haplopappus foliosus*. In the case of Pb, *Haplopappus foliosus* showed a better removal performance. Finally, for Cu, the removal efficiency was similar using both species, at around 53–55%.

For copper, a BCF in the roots of higher than one was only obtained with *Haplopappus foliosus*. On the other hand, for molybdenum, a BCF in the roots of higher than one was obtained with both species; in the case of *Lycium chilense*, this value was close to two. Neither of the two plants showed significant TF values, but *Haplopappus foliosus* had a considerably higher potential to assimilate these metals from this mine tailing.

The two studied species showed the general behavior of accumulation that most plants do, where higher levels of elements are concentrated in the roots, with poor translocation [16–18]. This is observed from the values of BCF and TF for each species and element.

In the study of Lam et al., 2018 [35], the endemic Chilean species *Adesmia atacamensis* showed bioconcentration and translocation factors of less than one for growth in tailings with and without amendments. This species was able to accumulate concentrations of Cu higher than 4000 mg·kg^{-1} in roots from tailings without amendments [35]—far over the values for the species studied in this work. Additionally, Lam et al., 2017 [12] obtained promising results for Cu translocation with the native species *Schinus molle* and removal efficiencies of around 60% in tailings without amendments, close to the value obtained with both species in this work.

In Australia, Nirola et al., 2015 [27] assessed the ability of the native species *Eucalyptus camaldulensis* and *Acacia pycnantha*, growing in mining soil, to remove Cu and Pb, among other elements. The first of these showed concentrations of Cu in its leaves of higher than 5000 mg·kg^{-1} and a BCF = 3.6, which is higher than the values obtained with the species studied here.

Siyar et al., 2022 [36] analyzed five native plant species of Iran—*Cousinia congesta*, *Launacea acanthodes*, *Artemisia* sp., *Stipa* sp., and *Peganum harmala*—which were growing in a soil with 5444 mg·kg^{-1} of Cu, 26.6 mg·kg^{-1} of Mo, and 253.7 mg·kg^{-1} of Pb, among other elements. Only the first of the plants presented a BCF of close to 1.3 for Mo and Pb. In the case of TF, the value of 5.97 for Mo with *Peganum harmala* can be highlighted. The reported concentrations for Cu, Mo, and, Pb were lower than the concentrations obtained with *Haplopappus foliosus* and *Lycium chilense*, except for Pb in the aerial parts of the plant.

In general, *Haplopappus foliosus* performs better, with the ability to concentrate Cu and Pb in higher concentrations than *Lycium chilense*. Moreover, this species presents a bioconcentration factor of higher than one for Cu.

5. Conclusions

To find a more economical way than traditional methods for the remediation of abandoned mine tailings, phytoremediation with two plant species has been studied. *Haplopappus foliosus* presents a better performance than *Lycium chilense* because it can accumulate higher concentrations of Pb and Cu. Additionally, this plant species presents higher Pb and Cu removal efficiencies.

In the case of Cu, the detected concentration in both species exceeded the toxicity threshold for the roots and aerial parts of the plants indicated by different authors. In addition, the Pb concentration in the roots of both species exceeded the suggested value for the onset of toxicity. A bioconcentration factor of higher than one for Cu was obtained only with *Haplopappus foliosus*. Both species were able to remove Cu from soils with efficiencies close to 55%.

Finally, molybdenum was removed with an efficiency of 31.8% using *Lycium chilense*.

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