

Influence of Compost and Chemical Fertilizer on Multi-Metal Contaminated Mine Tailings Phytostabilization by *Atriplex nummularia*

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ABSTRACT

Heavy metals in mine tailings induce severe environmental contamination of terrestrial ecosystems. They are hazardous to human health and must be cleaned up. However, ex-situ procedures are costly and soil-destroying. Phytoremediation approaches might be a cost-effective and environmentally friendly option. Phytostabilization of mine tailings, which employs plants, is a commonly used technique for preventing the spread of contaminants and particles from the site. Nutrient-deficient mine tailings must be amended to increase plant growth and phytoremediation performance. This study aims to investigate the tolerance of *Atriplex nummularia* to high heavy metal levels (Pb, Zn, and Cu) and the effects of compost and chemical fertilizer on biomass generation and heavy metal uptake. Halophyte species have been commonly employed for the phytoremediation of soil polluted with heavy metals. A pot experiment was undertaken with four treatments: T1 (agricultural soil), T2 (mine tailings), T3 (mine tailings mixed with compost), and T4 (mine tailings with chemical fertilizer). Results showed that both amendments demonstrated a significant beneficial effect on growth and biomass production. For all treatments, metals mostly accumulated in the roots, with only a small amount transferred to the shoots. Compost application resulted in a higher Pb concentration in roots than chemical fertilizer. The results of this study suggest that *Atriplex nummularia* can be used in phytostabilization for these types of mine tailings. However, long-term field data is needed to improve understanding of the *Atriplex nummularia* tolerance to high concentrations of heavy metals, as well as their uptake and translocation to aerial components.

Keywords: amendments, *Atriplex nummularia*, mine tailings, phytoremediation.

INTRODUCTION

Numerous countries have recognized in recent decades that abandoned metal mining activities have a substantial negative impact on the environment (Elmayel et al., 2020; Peco et al., 2021). Deposit operators in the mining industry were not compelled to complete environmental

impact assessments or to restore the site upon closure. As a result, many sites were abandoned, leaving large amounts of waste in place. In Morocco, more than 200 abandoned mines exist, posing significant environmental impacts and health risks to the surrounding communities. In the absence of a post-closure plan, abandoned mines can be toxic. The main issue is caused by

mining activity that was carried out using inefficient technologies, which resulted in a relatively large amount of waste containing large amounts of toxic metals (Dybowska et al., 2006; Lee et al., 2014; Gil-loaiza et al., 2017).

Among mine wastes, tailings are known to have the largest environmental impact, as they have the highest concentrations of toxic elements (Dudka and Adriano, 1997). Long-term tailings storage can result in resource depletion and land waste (Ji et al., 2018; Anning et al., 2019). In arid and semi-arid zones, mine tailings are often devoid of vegetation cover and constitute a source of environmental contamination due to water and wind erosion (Conesa, Faz and Arnaldos, 2006; Mendez and Maier, 2008; Wang, Zhang and Jin, 2009).

To mitigate these hazards, phytoremediation of tailings ponds is a viable and highly recommended approach. It has attracted more attention recently than conventional techniques due to the low cost of implementation and the environmental benefits (Shi et al., 2018; Soman et al., 2020). While physical and chemical treatments modify soil qualities irrevocably, phytoremediation typically improves the physical, chemical, and biological conditions of mining areas (Li, Wang, et al., 2019; Yan et al., 2020). The main disadvantage of phytoremediation is the prolonged treatment duration, which may vary from months to years (Ghori et al., 2015; Agomoh, Hao and Zvomuya, 2018).

Phytoremediation also needs special attention since tailings frequently present unfavorable conditions for plant growth, resulting in asphyxiation, dieback, and plant mortality. Mine tailings exhibit unfavorable chemical and physical properties, including high concentrations of heavy metals (HM) and salts, low organic matter content, poor water retention capacity, and uneven nutrient rates, all of which inhibit plant growth (Acosta et al., 2018; Xiao et al., 2018; Wei et al., 2021a). The selection of suitable species capable of achieving the strategy's aims is a critical factor (Lee et al., 2014; Peco et al., 2021). Numerous studies have shown halophytic plants' endurance to many forms of stress, including the presence of high amounts of HM (Nedjimi and Daoud, 2009; Milić et al., 2012; Amari, Ghnaya and Abdely, 2017). As a result, these species may be employed to remediate polluted substrates, such as mine tailings.

Among the most widespread halophyte in the world, the genus *Atriplex* (Chenopodiaceae) contains several species well adapted to arid and

semi-arid climatic conditions. The genus *Atriplex* has about 200 species that occur in most parts of the world. This shrub is the largest and most diverse of the Chenopodiaceae family. Species in this family are halophytes with a high tolerance to aridity and salinity (Bilal et al., 1990). They are a rich source of protein and carotene. They have the property of producing abundant foliar biomass with a deep root system adapted to the poor structure and characteristics of polluted substrates (Eissa, 2014). These species also naturally produce high amounts of oxalic acid, which can perform positive functions in HM stress tolerance mechanisms (Lutts et al., 2004; Kachout et al., 2012). *Atriplex* halophyte species have been recommended for phytoremediation in mining regions (Mendez, Glenn and Maier, 2007; Eid and Eisa, 2010; Sai Kachout et al., 2010). Some species can withstand high quantities of HM in soil (Manousaki et al., 2008) and transfer small amounts of roots to shoots (Sai Kachout et al., 2010) while others may be used as hyperaccumulators in phytoremediation (Nedjimi and Daoud, 2009).

The present research is intended to investigate the resistance of the *Atriplex nummularia*, halophyte species, to high levels of tree HM (Pb, Zn, and Cu), as well as the effect of amendments (compost and chemical fertilizer) on their biomass production and ability to accumulate and translocate HM.

MATERIALS AND METHODS

Substrates (mine tailings and agricultural soil)

Mine tailings were collected from tailing ponds at the Zaida lead-mine in High Moulouya, Morocco. The agricultural soil was obtained from a farm in the Beni Mellal agricultural zone. Each substrate was air-dried for 10 days before being homogeneously mixed and sifted in the laboratory using a 2 mm sieve to remove coarse elements and plant debris. The pH was determined using the potentiometric method (soil/water ratios of 1/2.5). A conductivity meter was used to test the electrical conductivity of a saturated paste of soil (USSL, 1954). The Walkley-Black (1934) and Olsen & al. (1954) techniques were used to analyze soil organic matter and available phosphorus concentrations, respectively.

Total metal concentrations in tailings and agricultural soil were determined by Inductive

Couple Plasma - Atomic Emission Spectroscopy (ICP-AES). At around 120°C, the substrates were digested with concentrated acid solutions (1 mL nitric acid 70% + 10 mL fluorhydric acid). Perchloric acid (5 mL for plant tissues and 10 mL for soil) was applied after drying and evaporated at 160°C. After drying, minerals were dissolved in 70% nitric acid (1 mL) and 38% hydrochloric acid (3 ml). The volume was finished with deionized water after the solutions were filtered (H₂O MQ).

Experimental design

A pot experiment was performed with *Atriplex nummularia*. It consisted of four treatments, each replicated six times. The experiment was laid out on a completely randomized design since experimental conditions were uniform and the experiment size was very small. The four treatments were:

- T1 – agricultural soil;
- T2 – mine tailings;
- T3 – mine tailings mixed with compost (200 g/kg). Before filling the pots, the soil was well mixed with compost prepared from sheep manure (Table 1);
- T4 – mine tailings with chemical fertilizer (phosphorus: 12% and nitrogen: 61%) intake at the beginning of the 9th week.

Because young seedlings' roots are more viable than those of older plants, 7-month-old seedlings were employed. They had all the same height (15 cm on average) and showed no symptoms of disease. The substrates were put in plastic pots (10 cm in diameter and 25 cm in height) after being air-dried and homogenized. The experiment was conducted in the open air at a temperature of 2°C to 36°C.

Table 1. Main properties of used compost

Parameters	Values
pH	5.83
Total organic matter (%)	17.23
Organic C (%)	12.80
N (%)	0.54
P (%)	0.25
K (%)	0.66
Mg (%)	0.25
Ca (%)	1.58
Cu (mg/kg)	6.75
Zn (mg/kg)	31.68

Plant harvesting

The plants were harvested after 21 weeks. Separated shoots and roots were thoroughly washed with distilled water and dried at room temperature. The samples were dried in an oven at 70°C for 24 hours before being ground separately with an electric grinder to a fine powder (2 mm). Heavy metal contents (Pb, Zn, and Cu) were determined by the ICP-AES method.

Substrates were recovered at the end of the experiment. Physico-chemical properties and heavy metal concentrations were determined using the same analytical approach.

Phytoremediation efficiency

To determine plant phytoremediation effectiveness, the bioaccumulation factor (BAF) and translocation factor (TF) were computed using the equations below (Usman et al., 2020):

$$\text{BAF} = \frac{\text{concentration of metal in plant tissue}}{\text{concentration of metal in soil}} \quad (1)$$

$$\text{TF} = \frac{\text{concentration of metals in shoots}}{\text{concentration of metals in roots}} \quad (2)$$

Statistical analysis

Data on heavy metal contents were first checked for normal distribution using the Shapiro-Wilk test and the equality of variances using the Levene test. If these assumptions are verified, then a descriptive statistic like the mean and a parametric statistical test like analysis of variance (ANOVA) can be used. Otherwise, a robust statistic like the median and a non-parametric statistical test like Kruskal-Wallis should be used. In case of significant differences between levels of factors, overall tests are followed by posthoc tests, either Duncan multiple range test after ANOVA or Dunn-Bonferroni test after Kruskal-Wallis. For all the statistical analyses, the significance level was set to 0.05. All statistical computations were done using the SPSS software, version 25 (IBM Corp., Armonk, NY, USA).

RESULTS

Substrate characterization

The physico-chemical properties and heavy metal contents of substrates (tailings and agricultural soil) are shown in Table 2. A silty-clay texture

Table 2. Properties of substrates used in the experiment

Parameter	Tailings	Agricultural soil
Sand (%)	87.40	16.50
Limon (%)	5.00	45.00
Clay (%)	7.60	38.50
pH	8.03	8.22
Electrical conductivity ($\mu\text{S}/\text{cm}$)	32.70	16.90
Organic matter (%)	0.08	2.61
Pb (mg/kg)	6632.00	3.80
Zn (mg/kg)	142.00	35.70
Cu (mg/kg)	121.00	11.40

characterized agricultural soil, while mine tailings had a sandy texture (7.6% clay, 5% silt, and 87% sand). Both substrates have an alkaline pH, with a clear difference in organic matter content (0.08% for tailings and 2.61% for agricultural soil). The tailings contain high levels of heavy metals (Pb = 6632 mg/kg; Zn = 142 mg/kg; Cu = 121 mg/kg), while the levels in the agricultural soil do not exceed those in the uncontaminated standard soil.

Plant growth

Observing growth and development

Table 3 summarizes observations gathered over the 21 weeks of *Atriplex nummularia* development. Despite high amounts of Pb (6632 mg/kg), Zn (142 mg/kg); and Cu (121 mg/kg), seedlings grown on mine tailings (T2) exhibited no signs of toxicity, such as wilting, necrosis, or chlorosis. The shoots, on the other hand, have decreased. The mixing of mine tailings with compost (T3) led to wilting of the seedlings at the beginning of the experiment,

but after recovery, good growth was recorded. Wilting can be explained by the increased bioavailability of HM and subsequent phytotoxicity. Because the tailings have a sandy texture, they have a limited water retention capacity, explaining why they require more frequent watering than agricultural soil, which has a silty-clay texture and hence retains more irrigation water. The addition of compost to the mine tailings (T3) boosted their water retention capacity, reducing the quantity of water brought in by irrigation.

Shoots development

Figure 1 depicts the weekly progression of the average stem height of plants grown on each of the four treatments. The *Atriplex nummularia* development curves may be separated into two periods:

- Period 1 – within the first seven weeks after transplanting, all plants seem to stop growing. This can be explained by the transplant shock.
- Period 2 – the seedlings' growth restarted after the eighth week for all treatments. The shoot's height developed steadily and consistently, with a notable variation across the four treatments. Plants cultivated on tailings (T2) were less elongated than seedlings grown on other substrates. The addition of compost and fertilizer had a positive effect on shoot height. At the end of the experiment, the shoot height of T4 was 54 cm.

Roots development

The main characteristics of root systems are summarized in Table 4. Most of them were colonized at the full depth of the pots used as well as

Table 3. Observations collected when growing *Atriplex nummularia* on various substrates

Parameters	T1	T2	T3	T4
Signs of toxicity	None	None	<ul style="list-style-type: none"> • Wilting of 4 seedlings from the 8th week • Recovery of two seedlings during the 9th week 	None
Coloring	Greyish	Greyish	Greenish	Greyish
Rod	Erect and rigid	Erect and rigid	Not trained	Erect and rigid
Ramification of aerial parts	++	+	+++	+++
Sheets	Rigidity	+++	++	++++
	Size	+++	+	+++
	Number	++	+	+++
Need for water	++	++++	+++	+++

Note: + – low; +++ – average; ++++ – high; +++++ – very high.

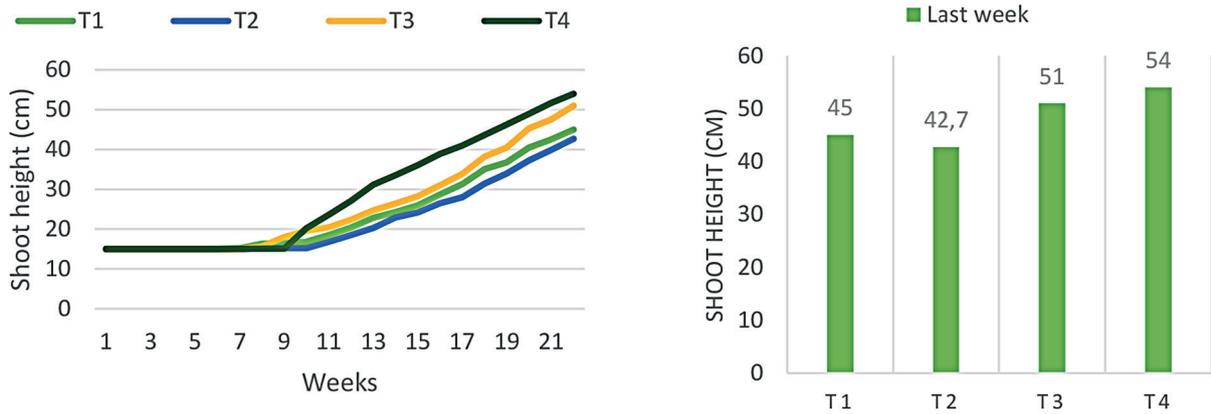


Figure 1. Evolution of shoot height of *Atriplex nummularia* under various treatments

the lateral surfaces. The average root lengths measured are approximately 21.5 cm for T1, 18 cm for T2, 21 cm for T3, and 24 cm for T4. Roots showed differences in their development and architecture between plants grown on the agricultural soil and those grown on tailings. These had a massive root system with a well-differentiated taproot and a very thin and shorter secondary network relative to the main root while plants grown on the agricultural soil developed a sparsely dense root system with long and stiffer secondary roots. This can be attributed to the different textures of the two substrates.

Biomass production

Figure 2 shows the wet and dry biomass of *Atriplex nummularia* shoots and roots produced

by the four treatments. Compared to control treatment (T1), *Atriplex nummularia* did not show any visible symptoms of metal toxicity or nutrient deficiency when grown in the tailings (T2). The amendment of mine tailings (T3 and T4) increased wet and dry biomass compared to control (T1) and mine tailings (T2). The greatest shoot and root biomass were observed in the tailings amended with chemical fertilizer (T4).

HM accumulation

Results of normality show that this assumption was checked for the four treatments only for Cu in shoots and soil (Table 5); for all the other situations, data did not follow a normal

Table 4. Roots length and density of *Atriplex nummularia* in the different treatments after 21 weeks

Features	T1	T2	T3	T4
Main root length (cm)	21.5	18.0	21.0	24.0
Lateral roots length (cm)	18.0	9.5	14.5	19.0
Density	Low	Strong	Average	Very strong

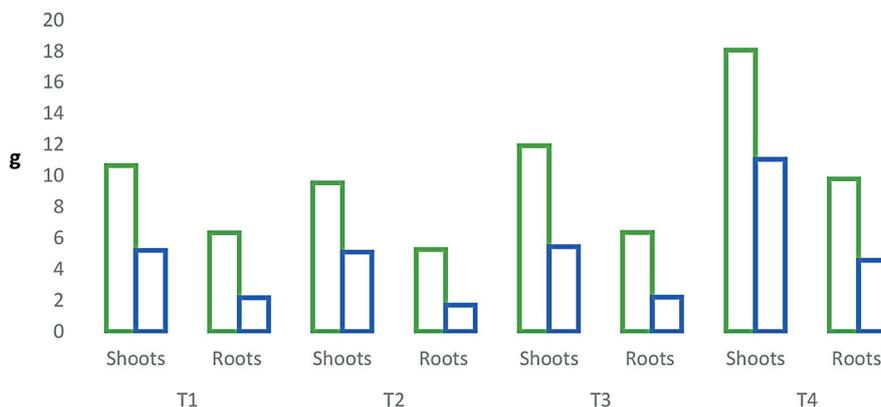


Figure 2. Wet and dry biomass of shoots and roots under different treatments

Table 5. Verification of assumptions of normality and equality of variances, choice of appropriate statistical test, and its significance

Heavy metals	Parts	Normality for treatments				Equality of variances	Statistical test	Significance
		T1	T2	T3	T4			
Cu	Shoots	0.057	0.830	0.900	0.089	0.064	ANOVA	0.110
	Roots	< 0.001	0.486	0.234	0.418	0.016	KW	0.083
	Soil	0.826	0.208	0.815	0.089	< 0.001	KW	0.027
Pb	Shoots	0.005	0.002	0.172	0.013	0.233	KW	0.008
	Roots	< 0.001	0.089	0.453	0.425	0.038	KW	0.018
	Soil	0.040	0.673	0.403	0.413	0.051	KW	0.001
Zn	Shoots	0.007	0.200	0.254	0.025	0.203	KW	0.039
	Roots	0.028	0.656	0.813	0.524	0.513	KW	0.025
	Soil	< 0.001	0.147	0.770	0.260	0.797	KW	0.005

Note: ANOVA – analysis of variance; KW – non-parametric Kruskal-Wallis test.

distribution. In addition, for the two former cases, equality of variances was met only for Cu in shoots (Table 5) for which ANOVA was used; for all the other cases, the non-parametric Kruskal-Wallis was used (Table 5).

Soil

All the three heavy metal contents in soil differed significantly between the four treatments with p-values of 0.027, 0.001, and 0.005 for Cu, Pb, and Zn, respectively (Table 5). Cu contents were the lowest for agricultural soils (T1), mine tailings with compost (T3), and mine tailings with chemical fertilizer (T4) whereas it was the highest for mine tailings alone (T2) (Table 6). Regarding Pb, the order was, from the lowest to the highest content, T1, T3, and T2 and T4, with no significant differences between the two last treatments (Table 6). Finally, for Zn, T1 had the lowest content as opposed to the other three treatments that had the highest content. In conclusion,

all the three heavy metal contents were the lowest for agricultural soils (T1) whereas the order differed for the second to the last positions.

Shoots

The uptakes of heavy metals by the shoots and roots of *Atriplex nummularia* in different treatments are shown in Table 6 and Figure 3. First of all, for Cu, there is no significant difference between the four treatments, for shoots, with a p-value of 0.110 (Table 5). Regarding Pb, there is a significant difference between the treatments with a p-value of 0.008 (Table 5) with the lowest median content for T1, followed by T4, and finally T2 and T3, the last two treatments did not differ (Table 6). Finally, for Zn, there is also a significant difference between the treatments with a p-value of 0.039 (Table 5) with T1 and T2 having the lowest contents and T3 and T4 having the highest contents (Table 6). Compared to unamended tailings (T2), the application of compost increased the uptake of Zn by the shoots and

Table 6. Mean and median values of heavy metal contents

Heavy metals	Parts	Mean				Median			
		T1	T2	T3	T4	T1	T2	T3	T4
Cu	Shoots	14.0	10.2	9.5	15.8	11.0	10.0	10.0	15.0
	Roots	27.2	73.8	45.0	59.5	19.0	69.5	41.0	57.5
	Soil	20.6	71.7	27.2	19.4	19.7 a	87.8 b	27.2 a	18.9 a
Pb	Shoots	28.0	58.2	45.8	89.5	22.0 a	49.0 b	41.5 b	77.0 c
	Roots	245.5	1303.3	944.8	1550.8	114.0 a	1085.5 b	852.5 b	1645.0 c
	Soil	10.9	4248.0	1777.0	3994.6	10.0 a	4277.5 c	1737.7 b	3971.4 c
Zn	Shoots	44.8	49.7	77.8	70.2	38.9 a	47.0 a	67.4 b	63.8 b
	Roots	48.1	79.6	65.0	109.5	35.5 a	73.2 b	58.8 a	105.0 b
	Soil	55.8	168.8	167.1	171.7	44.4 a	176.3 b	164.3 b	170.4 b

Note: Different letters indicate significant differences between treatments following the Dunn-Bonferroni posthoc test.

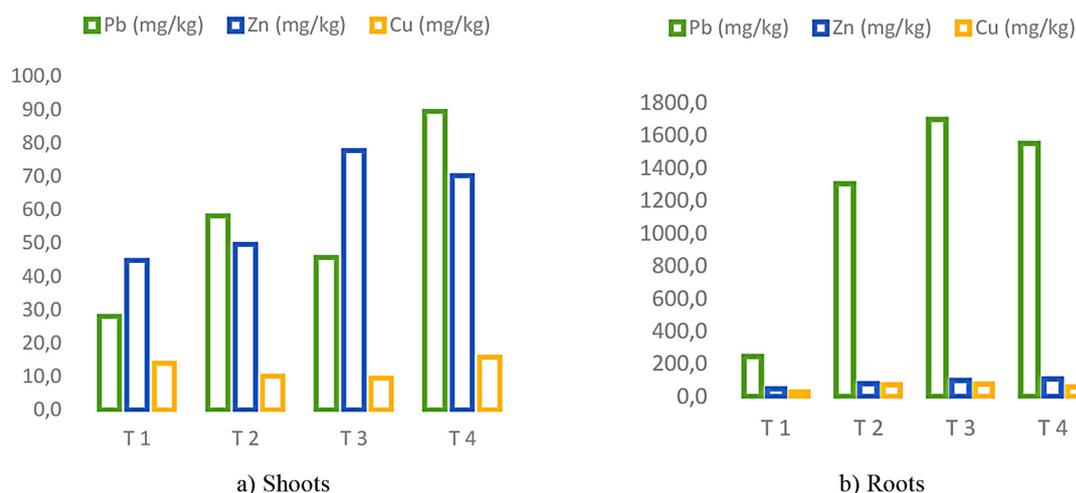


Figure 3. Effect of amendments on heavy metal contents in shoots and roots

reduced that of Pb while the application of chemical fertilizer increased the uptake of the three metals (Pb, Zn, and Cu) by the shoots.

Roots

As for shoots, there is no significant difference between treatments for Cu uptake by *Atriplex nummularia* roots with a p-value of 0.083 (Table 4). Lead uptake differed significantly with a p-value of 0.018 (Table 4): T1 had the lowest content, followed by T2 and T3 whereas T4 had the highest content (Table 5). Finally, Zn uptake was significantly different between treatments with a p-value of 0.025 (Table 4) with the lowest contents corresponding to T1 and T3 and the highest contents corresponding to T2 and T4 (Table 5). For the 4 treatments, the roots accumulated high levels of Pb compared to the other two metals, with a difference between the 4 treatments. The highest uptake of the three heavy metals was obtained by plants grown on tailings amended with chemical fertilizer (T4), followed by those grown on tailings without amendment, then those amended by chemical fertilizer, and finally those grown on agricultural soil. For all HM, the concentrations in the roots are much higher than those accumulated by the shoots, in particular for Pb, whose contents in the roots are 17 times higher than those in the shoots.

DISCUSSION

Plant growth

Mine tailings of Zaida are characterized by low pH, sandy texture, lack of organic matter,

and high levels of HM, especially Pb (Table 2). The same properties were recorded by previous studies (Saidi, 2004; Elhimer, 2012; Iavazzo et al., 2012). These characteristics are common to tailings worldwide and many authors reported that this is the major challenge for tailings phytoremediation (Mendez and Maier, 2008; Acosta et al., 2018; Xiao et al., 2018; Wei et al., 2021b). In this study, *Atriplex nummularia* presented the ability to grow on unamended mine tailings and to endure unfavorable conditions (Figures 1 and 2). This plant showed no signs of toxicity during cultivation on these unamended substrates. The same finding had been made by Eid (2011) who reported that this species accumulates HM without any reduction in biomass production.

Several studies noted that halophyte plants, such as *Atriplex*, are often tolerant to other types of stress, such as high levels of HM (Lutts et al., 2004; Manousaki et al., 2008; Parraga-Aguado et al., 2014; Pardo, Bernal and Clemente, 2017) and are ideal candidates for phytoremediation of heavy metal polluted soils (Manousaki and Kalogerakis, 2011). Indeed, the mechanisms involved in salinity tolerance are the same that operate in tolerance to HM.

After transplanting *Atriplex nummularia*, all plants stopped growth in the first 8 weeks of the pot experiment before resuming at the 9th one (Figure 1). (Eid and Eisa, 2010) found that when *Atriplex nummularia* was transplanted with two other species (*Sporobolus virginicus* and *Spartina patens*), the latter two species responded and grew faster than *Atriplex*. They attributed the difference to the adventitious root systems of *Sporobolus* and *Spartina* plants, which grow more

quickly after transplantation than *Atriplex*'s fasciculated root system. Seedlings that were grown in the agricultural soil (T1) had higher biomass production (shoots and roots) than those grown in mine tailings without any amendment (T2) (Table 4, Figure 2). (Sai Kachout et al., 2010) showed that the length of *Atriplex* roots was significantly inhibited by HM. The level of inhibition depended on the type and concentration of the metal. Similar results were reported by Shi et al. (2011) who studied the growth of 5 species (*Amorpha fruticosa* (Linn) Nash, *Vitex trifolia* Linn. var. *simplicifolia* Cham, *Glochidion puberum* (Linn.) Hutch, *Broussonetia papyrifera*, and *Styrax tonkinensis*) on treatment residues. Their experience has shown that roots have been inhibited, which has reduced biomass production by plants.

To promote substrate conditions for plants establishment, the addition of amendments to mine wastes has been a strategy widely employed (Acosta et al., 2018; Pérez et al., 2021). In the present study, two types of amendment were used, compost and chemical fertilizer. Results showed that both forms of amendments enhance the development of shoots and roots biomass production (T3 and T4) (Figures 1 and 2). Our findings are in agreement with many previous studies that have documented positive plant responses to fertilization. Eissa (2014) showed that applying compost to another species of *Atriplex* boosted biomass production and nutritional value of plants and that fresh and dry biomass grown as the dose of compost introduced increased. Chemical fertilizers are an easily accessible source of nutrients that have an immediate and direct influence on plant development (Gonzalez and Cooperband, 2002), which may be attributed to the high concentration of nutrients and the presence of hormones that function as growth promoters (Bernal-Vicente et al., 2008).

Several authors reported that the presence of HM in soil decreases chlorophyll synthesis (Cheng, 2003; Pietrini et al., 2003). However, no difference in leaf staining was seen in this trial between agricultural soil and tailings. Manousaki et al. (2008) reported the same conclusion when they tested the effects of Cd and Pb on the *Atriplex halimus* species.

Roots play a key role in plant growth and development, and any changes can have a direct effect on other plant parts (Biernacki and Lovett-Doust, 2002). It also plays a crucial role in phytoremediation following increased soil particulate aggregation and uptake or stabilization of

HM (Brunner et al., 2008) and sandy particles. Substrate texture was shown to influence developing root morphology and architecture. Seedlings grown on mine tailings showed high total root volume compared to agricultural soil. On the same *Zaida* residues, Saidi (2004) showed that *Vetiveria zizanioides* Linn. had developed a massive root system on these contaminated substrates. The same observation was highlighted by El Himer et al. (2013) who carried out a phytoremediation experiment of these substrates by the plant *Jatropha curcas* L. These authors also showed that the development of the root system of cultivated plants is strongly influenced by the texture of the substrates.

Effect of amendments on heavy metal uptake

Heavy metal concentrations were found to vary across the shoots and roots of *Atriplex nummularia* (Figure 3). These results are correlated with those of (Lotmani et al., 2011) who showed that *Atriplex halimus* accumulates more HM in roots than in the upper parts. (Kachout et al., 2012) investigated the accumulation of HM by *Atriplex hortensis* and *Atriplex rosea*. They indicated that *Atriplex* accumulates HM in roots and that low concentrations of these elements are transported to the shoots.

The application of amendments to mine tailings increased the concentrations of Pb, Zn, and Cu in the shoots as well as in the roots of the plants (Figure 3). Many studies have reported that the addition of organic matter amendments enhances heavy metal uptake by plants (Seo et al., 2008; Acosta et al., 2018; Li, Zhang, et al., 2019; Samsuri et al., 2019). It can be explained by the increase of plant biomass, the larger root surface area facilitated by the nutrition supply (Li, Zhang, et al., 2019), and the behavior control of HM in the soil (Tariq et al., 2016).

Translocation and bioaccumulation of HM

The translocation factor (TF) expresses the ability of the plant to transfer metals to its shoots (Conesa, Faz and Arnaldos, 2006; Sun et al., 2008), while the bioaccumulation factor (BAF) is the best indicator for determining the potential for plant phytoaccumulation of HM (Li, Luo and Su, 2007; Subpiramanyam, 2021).

Table 7 presents the TF and BAF in plants. TF was less than 1 for all HM. The transport of

Table 7. Translocation and bioaccumulation coefficients for HM in plants

Parameters	TF			BAF		
	Pb	Zn	Cu	Pb	Zn	Cu
T2	0.04	0.62	0.14	0.20	0.56	0.61
T3	0.03	0.79	0.12	0.26	0.70	0.63
T4	0.06	0.64	0.27	0.23	0.77	0.49

the 4 elements studied is very limited under the 4 treatments, in particular for Pb and Cu. These results are correlated with those obtained by (Greger, 2004) and Seregin and Kozhevnikova (2006), who showed that in a plant, Zn is more mobile and thus easily transferred to the shoots than Pb, which remains complex at the root level. This difference can be explained by the fact that Zn is an essential plant component (Broadley et al., 2007), while Pb is toxic (Kachout et al., 2010).

According to (Li, Luo and Su, 2007), hyper-accumulator species must have a BAF greater than 1. From the results reported in Table 4, *Atriplex nummularia* cannot be considered a hyper-accumulator plant. For the 3 metals and in the 4 treatments, the BAF value did not exceed 1. The addition of compost had a positive effect on the bioaccumulation of the 3 elements, while chemical fertilizer only affected Pb and Zn. Soil pH is an important factor of bioavailability of HM in soils due to its influence on soil solubility (Burgos et al., 2006). Woody plants grown on alkaline substrates (7.72 and 8.26) rich in Pb, Zn and Cu had low BAF and TF values (Shi et al., 2011). The slight increase in BAF in treatments T2 and T4 can be explained by the effect of fertilizers on the decrease in substrate pH.

Phytostabilization potential

Phytostabilization is the employment of plants to physically stabilize pollutants by limiting erosion, leaching, and runoff, or chemically through accumulating in the roots or precipitation in rhizosphere soils (Acosta et al., 2018). In the majority of mine sites, processing residues from mineral extraction activities are devoid of vegetation cover (Mendez and Maier, 2008), which is a potential source of environmental contamination due to their high HM concentrations (Conesa, Faz and Arnaldos, 2006; Wang, Zhang and Jin, 2009). Establishing a plant cover on these tailings can physically stabilize them by minimizing the spread of sandy particles through wind and even water erosion (Mendez

and Maier, 2008). It can also chemically stabilize contaminants.

As stated by (Mendez and Maier, 2008), a plant may be utilized for phytostabilization if its TF and BAF values are less than 1. Results from this experiment showed that *Atriplex nummularia* is a good candidate for the phytostabilization of mine tailings containing high levels of heavy metals, especially Pb. *Atriplex nummularia* can accumulate high levels of HM in roots with a low rate of translocation to shoots. Williams et al. (1994) and Jordan et al. (2002) showed that *Atriplex* spp. accumulate HM in the roots, and are therefore good candidates for phytostabilization. (Kachout et al., 2012) indicated that phytostabilization of mine tailings with *Atriplex* in arid and semiarid regions has promising potential and that plant establishment on mine tailings is possible, and when successful helps to reduce erosion processes and enhance soil properties.

CONCLUSIONS

Atriplex nummularia is excellent for phytostabilization of mine tailings in arid and semi-arid areas. This species showed high tolerance to polymetallic contamination and accumulated large amounts of heavy metal, which had been immobilized in roots. The application of compost and chemical fertilizer promoted plant growth and heavy metal uptake. *Atriplex* species have a high nutritional value and are well appreciated by animals, which can contribute to the development of breeding activities and subsequently to the socio-economic development of the region. However, additional experiments must be conducted to investigate the accumulation of HM in the shoots of *Atriplex nummularia*. Therefore, other pot and field experiments should focus on the long-term phytostabilization process and transfer of contaminants along the food chain, also other amendments should be tested for more cost-effective phytoremediation.

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