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RESEARCH ARTICLE

Phytostabilization alternatives for an abandoned mine tailing deposit in northwestern Mexico

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Abstract
Purpose Past mining activities in northwestern Mexico have left a large number of abandoned mine tailings deposits, such as in San Felipe de Jesus, Sonora, that is known to be transferring metal(oid)s to nearby agricultural fields. Given the risk and the need to implement mitigation measures, in this paper, we describe the results of two experiments evaluating the phytostabilization potential of five plant species collected in the area.
Methods We evaluated the assisted phytostabilization approach using compost and nutrients and the soil capping approach using combinations of soil, gravel, clay, and tailings layers.
Results The assisted experiment revealed that seedlings were unable to establish under unamended treatments and only *Ricinus communis* showed potential under this approach. Compost and nutrients reduced the accumulation of As, Pb, Mn, and Zn in leaves of *R. communis*, but some were above the maximum tolerable levels for domestic animals. Under the capping approach, *R. communis* also showed better performance under some combinations of soil, gravel, and tailings layers than the other species. The accumulation of As, Pb, and Mn in leaves was below the maximum tolerable levels for domestic animals, indicating that soil capping has greater potential in this abandoned tailing deposit.
Conclusion The capping approach has more phytostabilization potential than the use of amendments, reducing the risk of incorporating metal(oid)s in the trophic web.

Keywords Assisted phytoremediation · Metal(oid)s · Mining footprint · Mining legacy · Rio Sonora · Soil capping

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Introduction

The generation and abandonment of mine tailings (MTs) are some of the most hostile byproducts of mining (Cross et al. 2017). MTs represent a worldwide problem with an enormous global impact, as they generally remain exposed and unvegetated, subject to eolian dispersion or fluvial erosion, for tens to hundreds of years. During this time, MTs transfer potentially toxic elements (PTE) over several hectares leaving a toxic footprint on ecosystems that may affect ecosystem health and human welfare (Mendez and Maier 2008; Kim et al. 2012; Cross et al. 2017; Djebbi et al. 2017).

Phytostabilization is a form of remediation that uses plants to stabilize tailings deposits and their contaminants in the rooting zone, with minimal accumulation in above-ground organs, preventing the transfer into adjacent ecosystems and the incorporation into local trophic webs (Kennen and Kirkwood 2015). The plant canopy serves to reduce dust emission (Gil-Loaiza et al. 2018) while the root system promotes soil aggregation and stabilization, reducing fluvial erosion and immobilizing pollutants through adsorption (Mendez and Maier 2008). Two major phytostabilization approaches used for mine tailings remediation are:1) assisted in situ*,* adding soil amendments (i.e. compost, biochar) to promote plant establishment in often harsh conditions -like acid or highly compacted and polluted soils-; 2) capping at the top of tailings with soil, lined at the base with layers of clay, gravel or geomembranes, to reduce the infiltration and capillary fringe, then planted to stabilize the cap (Johnson and Hallberg 2005; Santini and Fey 2016). Both approaches have differences in costs and management inputs in the short and long-term (Santini and Fey 2016; Gil-Loaiza et al. 2016). In the long-term, the capping approach faces several challenges such as the integrity of the capping layers (Santini and Fey 2016), the risk of the capillary ascent of contaminants, and subsequent plant mortality (Menzies and Mulligan 2000), and its sustainability (Lottermoser et al. 2009). In contrast, in situ remediation enhance soil formation, potentially changing into a substrate that allows a self-sustainable vegetation cover by increasing organic C, N and nutrients and modifying unfavorable substrate properties such as extremes of pH, EC and alkalinity (Bray et al. 2018; Santini and Fey 2018), which improves the soil function for plant support.

Achieving a self-sustainable plant community on mine tailings, whether using the assisted or capping approach requires previous knowledge about plant species and processes that affect their performance in such substrates. Two critical steps are the identification of suitable plant species with phytostabilization potential and the barriers that restrict plant establishment (Ginocchio et al. 2017; Arvizu-Valenzuela et al. 2020). Phytostabilization in arid and semiarid environments requires drought- and metal-tolerant plant species. Frequently, the best candidate plants are native species that may be adapted to the local conditions and reduce the risk of introducing invasive species (Mendez and Maier 2008). Spontaneous plant colonization on or species growing around mine tailings deposits offers good candidate plant species to be tested (Ginocchio et al. 2017; Santos et al. 2017). However, in highly modified substrates, if native species cannot tolerate the physicochemical properties of the tailings deposit, non-native species could be an option if they are not invasive and provide desirable levels of phytostabilization (Hobbs et al. 2009).

The case of San Felipe de Jesús

Past mining activities in northwestern Mexico have left large amounts of abandoned mine tailing deposits (Jimenez et al. 2006; SEMARNAT 2021), like those located at San Felipe de Jesús, Sonora (Fig. 1c). Mining in the area started around 1900 with large fluctuations in metal production; mined metals were mainly lead and zinc, with minor production of gold, silver, and copper. In 1973, a flotation plant was built with a capacity to process 100 tons/day (Roldan-Quintana 1979). This plant processed ore from several regional mines until 1991 when production ceased (Tietz 2018). Total production from this period (1973–1991) was around 104,000 tons at average grades of 10.4% zinc, 2.6% lead, 0.3% copper, and 75.7 g of silver per ton. Ore processing left a tailings deposit adjacent to the flotation plant, between San Felipe and Aconchi (Espinoza-Madero 2012).

The tailings pile (Fig. 1c) is around 200 × 300 m, and covers an area of 16,300 m^2 with heights varying from 2 to 5 m (Espinoza-Madero 2012; Del Rio-Salas et al. 2019); the deposit is reddish (oxidized) in the external surface and greyish (mostly unoxidized) in deeper zones. Fluorescent minerals develop as white-colored crusts on the surface during the dry season, with their composition being contingent upon the specific type of tailings, predominantly sulfates of calcium (Ca), iron (Fe), magnesium (Mg),

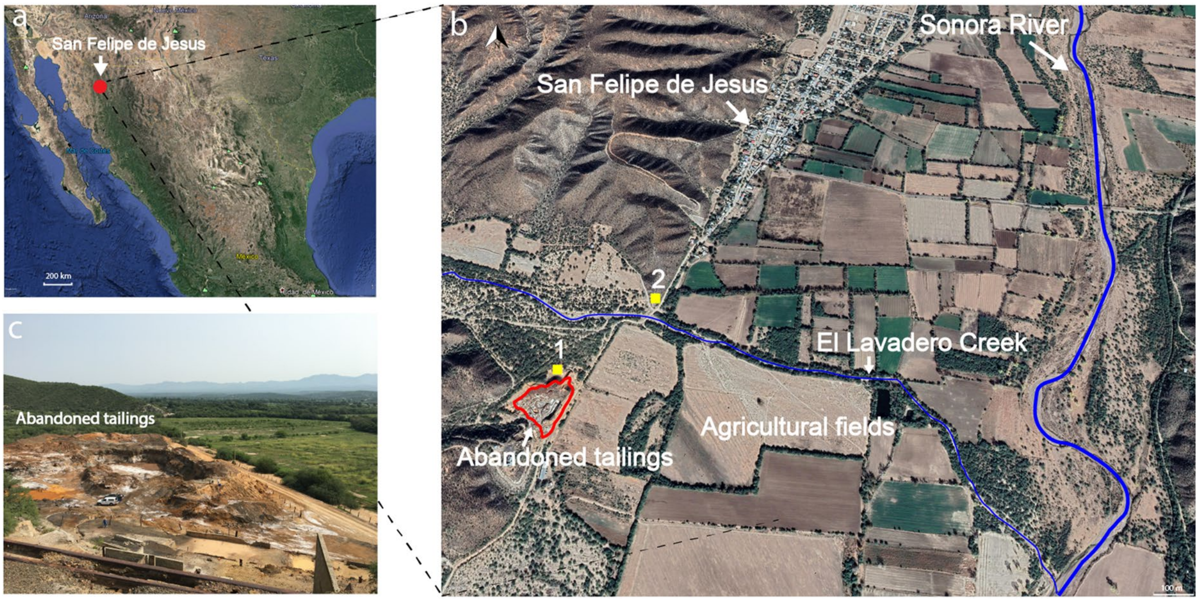

Fig. 1 **a** Location of San Felipe de Jesus in northwestern Mexico. **b** The study area showing the location of the abandoned mine tailings, the town of San Felipe de Jesús, agricultural fields and sites where we analyzed soil samples. Site 1 indicate an adjacent site where a soil profile was described and site 2 indicate the natural soil site that was used as control for the experimental treatments. **c** General view of the abandoned tailings of San Felipe

and potassium (K) (described in Del Rio-Salas et al. 2019); the pH and electrical conductivity (EC) values range from 3.7 to 6.5 and from 68.0 to 415.7 µS/cm respectively, among samples from oxidized, unoxidized materials and efflorescent minerals. Minerals found in oxidized and unoxidized samples from the tailings deposit consist of silicates, sulfates, carbonates, sulfides, and oxides. Most important PTE in the pile include Pb in concentrations ranging from 6857 to 26,944 mg/kg, As from 221 to 25,177 mg/kg, Zn from 1854 to 176,589 mg/kg, Cu from 83 to 491 mg/kg, Sb from 56 to 955 mg/kg, Cd from 15 to 904 mg/kg, Mn from 6502 to 57,851 mg/kg and Ti from 356 to 1309 mg/kg (Del Rio-Salas et al. 2019).

Since abandonment in the early ‘90s, no vegetation has been observed colonizing the tailings. Thus, this pile has been an important source of local pollution as it is subject to wind erosion during the dry season, transporting metal-enriched dust to the town of San Felipe and nearby agricultural soils (Fig. 1b). In addition, water erosion transfer metals during the heavy summer rains, because the tailings are connected with the Sonora River through a nearby stream known as ¨El Lavadero¨ (Fig. 1b), which comes from Sierra Aconchi (Del Rio-Salas et al. 2019; Loredo-Portales et al. 2020).

Although mining was important in the past, currently agriculture and cattle raising are the most economically important regional activities (Del Rio-Salas et al. 2019). Agriculture is practiced along the flood plains of the Sonora River (Roldan-Quintana 1979) using irrigation water extracted from wells, a water spring (Huepac), or directly from the river. Major crops include groundnuts, maize, and garlic for human consumption and alfalfa and barley for livestock (SIAP 2020). A recent study of 900 ha of agricultural soils from San Felipe detected several hotspots with a high concentration of Pb, Zn, Mn, As, and Cu (Gonzalez-Mendez et al. 2022). Furthermore, some elements from the agricultural soils around the tailings deposit are phytoaccessible (Loredo-Portales et al. 2020) and might accumulate in crops, representing a potential risk for domestic animals consuming forage crops and for human consumption of food crops. Therefore, the goal of this study was to select five local plant species to evaluate their phytostabilization potential for the abandoned mine tailings, using soil amendments and a capping approach as mitigation measures to reduce the transfer of the PTEs into a nearby environment.

Material and methods

Study area

San Felipe de Jesus is located in northwestern Mexico (12 R 573360.35 m E, 3303426.53 m N) (Fig. 1a). The regional climate is arid (BSO), with a mean annual temperature of 21.1 °C, a maximum of 40 °C during the summer, and a minimum of 2.6 °C during the winter (Brito-Castillo et al. 2010). Most of the rainfall occurs from July to September in short spells, with average annual precipitation around 481 mm (Servicio Meteorologico Nacional 2020). The Sonora River is 0.5 km far from the tailings deposit. The natural vegetation is thorn scrub composed of legumes trees and cacti (Martinez-Yrizar et al. 2010). Local soils include Regosols, Fluvisols, and Phaeozems (INEGI 2005). We selected two sites: one on the periphery of the tailings (point 1 in Fig. 1b) and a natural soil (not affected by the tailings and not used for agriculture) around 360 m far from the tailings (point 2 in Fig. 1b). Natural soils near the mine tailings are Cambic Regosols (IUSS working group WRB 2015), with a 15 cm thick A horizon, poor in total carbon (6 g Kg^{-1}) and total nitrogen (0.5 g Kg^{-1}), sandy clay loam texture, covering a stratum of more than 25 cm of sand derived from alluvial material. The pH ranges from 7.31 to 7.65, and electrical conductivity goes from 2.47 to 0.61 dS m^{-1}. The mean bulk density is 1.2 g cm^{-3}. Additionally, the erosion of mine tailings has promoted their particles' illuviation through the nearby soils forming a thick layer (60 cm) of artefacts (mine particles) mixed with the natural alluvial material; therefore, these soils were classified as Spolic Technosols according to WRB (2015). This artefact stratum is covered with a thin A horizon poor in total carbon (1 g Kg^{-1}), the Technosol's texture ranges from a clay loam at the top of the field to sandy loam at the bottom, and the pH and electrical conductivity go from 3.1 to 3.9, and 189.6 to 145.9 dS m^{-1}, respectively through the soil profile. The mean bulk density is 1.4 g cm^{-3} and a high content of the studied PTE. Table 1 lists some physical and chemical properties of the natural soils and tailings-affected soils. Major minerals in the tailings deposit consist of metal sulfides and sulfates such as beudantite ($PbFe_3(OH)_6SO_4AsO_4$), sphalerite (ZnS), arsenopyrite (FeAsS), and szmikite ($MnSO_4$) that can release PTE into the surrounding environment (Del Rio-Salas et al. 2019; Morales-Perez et al. 2021). A detailed description of the mineralogy of this tailings deposit is provided by Del Rio-Salas et al. (2019).

Table 1 Physical and chemical properties of the topsoil and mine tailings (0–30 cm)

Soil property	Natural Soil	Tailing affected soil	Mine tailings
pH (in water)	7.5	3.3	2.83
EC (dS m^{-1})	1.5	151.5	2.6
Bulk density (g cm^{-3})	1.2	1.4	2.6
TC (g kg^{-1})	6	1.0	0.9
TN (g kg^{-1})	0.5	ND	0.1
As (mg/kg)	47.9	3876.7	1033.1
Mn (mg/kg)	446	2400.5	3867.6
Pb (mg/kg)	120.5	4202.5	2901.7
Zn (mg/kg)	322.3	1923.5	5826.6

ND Not determined

Field survey of plant species

After the area around the deposit and a nearby roadside were explored, 12 common species were identified (Online Resource Table 1), from which the five most abundant species with mature seeds were selected. Seeds were collected in paper bags and stored under Laboratory conditions until used in experiments. The species were identified using a published flora (Felger et al. 2001) and the database from the network of Herbaria of northwestern Mexico (http://herbanwmex.net/portal). Three species are woody perennial trees with a relatively deep rooting system: *Prosopis velutina*, *Parkinsonia praecox,* and *Acacia farnesiana*. The other two species were non-native, herbaceous and have a shorter life cycle: *Ricinus communis* and *Nicotiana glauca*. Although non-native, they are not invasive in the area and were used in case the selected native species had a poor phytostabilization potential.

Mine tailings and substrate characterization

Substrate sampling

Tailings samples were taken from the oxidized surface. A sample of top tailings (0–30 cm) was taken from five holes augered by hand at the corner and center of a 50 cm side square to form a composite sample. Samples from the natural soil were taken around 360 m (NE) far from the tailings (point 2 in Fig. 1b), from an area with natural vegetation and presumably with less influence of the tailings. Soil samples were taken in the same way as the tailings ones.

Total carbon (C) and nitrogen (N) were analyzed by complete combustion (CNHS/O 2400 Perkin Elmer), using acetanilide as a calibration standard. For PTE analysis, both soil and tailings samples were digested using the EPA 3050b method (USEPA 1996) and analyzed by ICP-OES (Perkin-Elmer Optima 8300 DV). Three samples were used for C and N, and four for PTE analysis.

Soil amendment

Compost made of local sources was used for the assisted phytostabilization approach. Detailed information about the compost elaboration and its effect on tailings properties and plant growth is available on Arvizu-Valenzuela et al. (2020). Compost properties are: total carbon = 6.67%, total nitrogen = 0.58%, available phosphorous = 0.0093%, carbon/nitrogen ratio = 11.49, pH = 8.44 and electrical conductivity = 4.01 dS/m.

Experimental evaluation of phytostabilization potential

Assisted phytostabilization experiment

Plant responses to different concentrations of compost and tailings material, with or without additional nutrients, were evaluated in pots under full sunlight outside UNAM facilities in Hermosillo, Sonora. The five plant species with sufficient seeds for all experimental treatments were used: *Acacia farnesiana* (= *Vachellia farnesiana*), *Parkinsonia praecox*, *Prosopis velutina* (= *Neltuma velutina*), *Ricinus communis* and *Nicotiana glauca*.

A completely randomized design with two factors, namely compost concentration and nutrients, was used (Fig. 2A). The first factor had three levels of compost concentrations (0, 20 & 30% w:w), thoroughly mixed with oxidized tailings material (100, 80 & 70%) and a control treatment using natural soil, with five replicates. Compost-tailings mixes (0:100; 20:80; 30:70 compost: tailing) and the natural soil control with additional nutrients (Fig. 2A) were used for the second factor, with five replicates for each. Nutrients were thoroughly mixed in each treatment using Osmocote plus

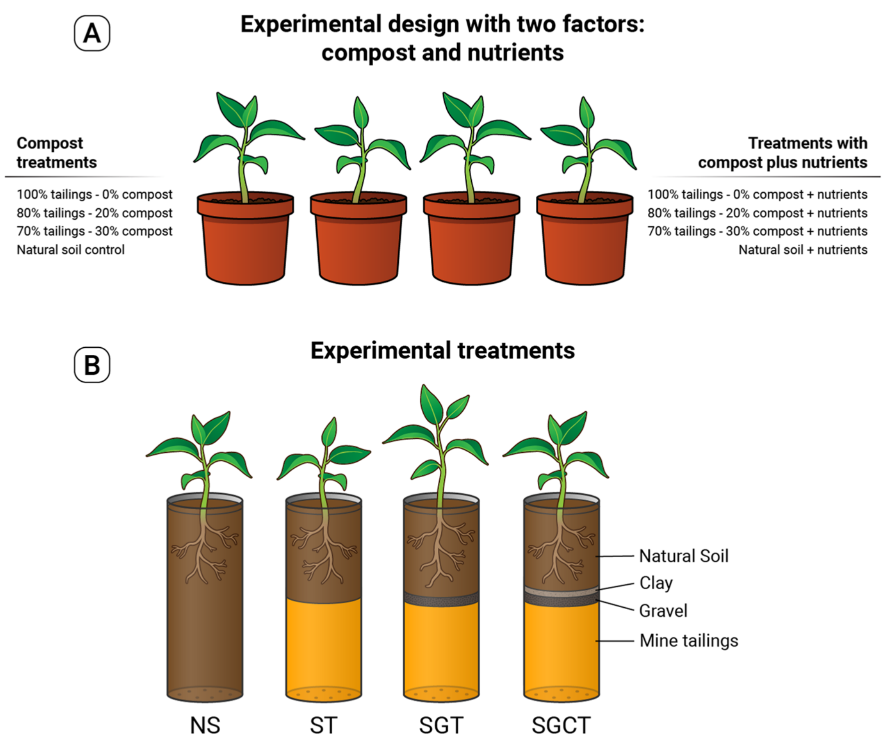

Fig. 2 **A** Experimental design used to evaluate compost concentration and nutrients on plant performance. **B** Experimental design used to evaluate plant responses to different combinations of layers of soil, tailings material and gravel and clay filters. NS: natural soil; ST: soil and tailings layer in direct contact; SGT: soil and tailings layer with a gravel filter between layers; SGCT: soil and tailings layers with a clay and gravel filter between layers

(N: 15%; P: 9%; K: 12%) at the dosage recommended by the commercial product (5 g/pot).

The experiment was set in medium size plastic pots (diameter: 16 cm and height: 12 cm) in a bench under full sunlight at UNAM facilities. Three seeds of each plant species were planted per pot on August 25, 2017, and each pot was started to be irrigated on a daily basis. Germination was recorded 2–3 days after seeding and we kept only one seedling per pot. Plant performance was evaluated through different measures and plants were harvested 64 days after planting in order to estimate biomass accumulation, as the major period of growth for seedlings of perennial plant species in this region is during July, August and September, when 80% of the annual rainfall occur.

Capping experiment

A completely randomized design was used, where treatments corresponded to layers of different materials: natural soil, tailings material, clay, and gravel. Plant responses to different combinations of layers of soil, tailings material, gravel and clay filters (Fig. 2B) were evaluated using the same five species. Four treatments were used employing PVC tubes (length: 40 cm and internal diameter: 11 cm) with small draining holes at the base: a) a layer of natural soil on top (21 cm) in direct contact with a layer of tailings material below (17 cm): **ST**; b) a layer of natural soil on top (19 cm), a layer of gravel (2 cm) below the soil and on top of a layer of tailings material (17 cm) on the lower portion: **SGT**; c) a layer of soil on top (17 cm), a layer of gravel (2 cm) below, a layer of clay (bentonite, 2 cm) below and a layer of tailings material (17 cm) on the lower portion of the tube: **SGCT** and d) a control treatment with just one layer of natural soil (38 cm): **NS** (Fig. 2B). Gravel diameter varied from 1 to 1.5 cm while bentonite was from a commercial source. Experimental evaluation of the capping approach in mine remediation have used capping layers as substrate for plant growth at depths from 15 to 50 cm (Mohan et al. 1997; Santini and Fey 2018). Therefore, our soil layer falls under the range that has been previously used.

The experiment was set on a bench under full sunlight outside UNAM facilities in Hermosillo, Sonora with tubes being held within plastic boxes. Three seeds were planted in each tube on August 28, 2018, and were irrigated daily. Germination was scored 2–3 days after seeding, keeping only one seedling per tube. Plant performance was evaluated during the experiment, and plants were harvested 67 days after planting to estimate accumulated biomass.

Plant harvest and sampling growing substrate

Plants from each pot or tube were harvested, including the root system and rinsed first in running water and later in a 0.1% HCl solution using distilled water. Each plant was separated into leaves, stems and roots in paper bags. The growing substrate from each pot or tube influenced by roots was collected by shaking vigorously to collect the growing substrate. Both the separated plants and the substrate samples were air-dried during two weeks.

Evaluation of performance in experimental plants

Plant responses to different treatments in each experiment were measured through different parameters: germination, seedling establishment, leaf area, photosynthesis, chlorophyll fluorescence and biomass accumulation.

Seed germination and seedling establishment Germination was calculated as the percentage of emerging seedlings taking into account that three seeds were originally planted. Seedling establishment was calculated as the percentage of established plants from the one emerged seedling that was kept on each pot.

Leaf area The leaf area of each individual from all experimental treatments was measured as an estimation of plant growth. Measurements were done immediately after plant harvest in fresh leaves with a LI-3100 (LICOR Inc.) leaf area meter and expressed in cm^2.

Photosynthesis As an estimation of the physiological performance, CO_2 assimilation of plants growing under the different experimental treatments was measured. Photosynthetic rates were measured early during the morning on fully expanded leaves without evidence of senescence, using a LI-6400 portable IRGA with a standard leaf chamber (LICOR Inc.).

Chlorophyll fluorescence Direct chlorophyll fluorescence induced by continuous excitement of plants growing under different treatments was measured as an estimation of the stress of the photosynthetic apparatus. Leaves were previously acclimated to dark conditions during 10–30 min before being exposed to 650 nm light at 3000 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for 1–10 seconds and simultaneously measuring and storing the values of emitted fluorescence. Measurements were taken during the morning and the afternoon, using a pocket PEA chlorophyll Fluorimeter from Hansatech Instruments.

Biomass accumulation As an estimation of plant growth, once plants were dry, leaves, stems and roots of each individual from each treatment were weighted to the closest mg using an analytical balance. The sum of each plant organ represented total biomass.

Concentration of potentially toxic elements (PTE) in plants and growing substrate Dry samples of leaves, stems and roots of each plant were ground in an agate mortar and sieved through a 210-µm sieve. Ground samples were sent to a certified laboratory (Australian Laboratory Services, Vancouver, Canada) for analysis of PTE (As, Mn, Pb & Zn) using method VEG-41. A 1-g aliquot was coldly digested with nitric acid for 8 h before being transferred to a hot block for 15 minutes at 85 °C followed by 2 h at 115 °C. The samples were subsequently cooled and brought up to volume with HCl. The resulting solution was mixed thoroughly and analyzed by inductively coupled plasma mass spectrometry (ICP-MS). The accuracy and precision of the analysis (± 10%) were determined using NIST-1515 and NIST-1575a standards. For the experiment using soil caps, samples were analyzed by triplicate; for the organic amendment experiment, samples were also analyzed by triplicate and when biomass was not sufficient from three plants, only by duplicate.

Given that total PTE concentration does not necessarily indicate phyto availability (Proto et al. 2023), the phyto-accessible fraction of the growing substrate was determined using digestion by low molecular weight organic acids (LMWOA, Cruz-Jimenez et al. 2020). Dry samples were ground in an agate mortar and sieved through a 210-µm sieve. The LMWOA solution was prepared according to Cieslinski et al. (1998), using acetic (2898 mM), succinic (194 mM), oxalic (43 mM), malic (39.8 mM), tartaric (26.3 mM), fumaric (12 mM) and citric acid (6 mM). Solution was adjusted at pH 4 using nitric acid. The concentration of As, Mn, Pb and Zn was determined by triplicate using ICP-OES (Perkin-Elmer Optima 8300 DV with autosampler S10) at LANGEM UNAM facilities.

Bioaccumulation factors The bioconcentration (BCF) and translocation factors (TF) were calculated using the concentration of PTE in plants and the growing substrate. The bioconcentration factor represents the relationship between the PTE concentration in roots with respect to the substrate:

$$BCF = C_{root}/C_{substrate}$$

where C_{root} is the concentration in roots and $C_{substrate}$ is the concentration in the growing substrate (Ali et al. 2013). The translocation factor (FT) represents the relationship between the PTE concentration in the above-ground organs to the root:

$$FT = C_{above-ground}/C_{root}$$

where $C_{above\text{-}ground}$ is the concentration in above-ground organs and C_{root} is the concentration in roots (Ali et al. 2013).

Maximum tolerable levels by domestic animals. – It was evaluated whether the leaf values of As, Mn, Pb, and Zn in experimental plants reached the maximum tolerable levels (MTL) by domestic animals (National Research Council 2005). The MTL of a mineral is the dietary level above which there is an impact on performance and pathological signs of toxicosis (National Research Council 2005). Observed values were compared with MTL for cattle, horses, and rodents to evaluate the toxicity risk to animals that could consume leaves and potentially transfer PTE to the trophic network.

Statistical analysis Plant responses to different treatments in both experiments were also analyzed with generalized linear models (GLM). Response variables were declared normal or binomial depending on the nature of the variable. For all analyses, likelihood ratio tests evaluated the significance of potential predictors. The influence of compost, nutrients, and their interaction was tested in the experiment using organic amendment. When significant differences were detected between treatments, contrast tests were used to identify which treatments were different. All statistical analyses were performed using JMP version 11.0 (SAS Institute 2013).

Results

Mine tailings and substrate characterization

Some physical and chemical properties of superficial samples from the natural soil, the tailing-affected soil, and oxidized tailings are shown in Table 1. The mine tailings possessed the harshest conditions with lower pH, total carbon and nitrogen content, high bulk density, and Zn and Mn content, which could restrict plant establishment. Although the tailing-affected soil is less compacted (bulk density of 1.4 g cm^{-3}) than the mine tailings, the conditions are still hard for plant survival, especially with a very acid pH (3.3), a poor carbon content, and a higher As and Pb concentration. The natural soil presents an almost neutral pH, is less compacted (bulk density of 1.2 g cm^{-3}), and has higher C, N, and lower PTE concentrations, which could facilitate plant establishment. Based on this finding, the natural soil was selected as a control treatment for the experiments, and the oxidized mine tailings as the substrate subject to remediation.

Assisted phytostabilization experiment: Plant response to compost and nutrients

Seed germination and seedling establishment Large variation in germination among species and treatments was recorded (Fig. 3A). Seed germination followed the trend *R. communis* > *P. velutina* > *A. farnesiana* > *P. praecox* > *N. glauca*. For *N. glauca*, we did not record any germination for any treatment; therefore, we do not report further results for this species. In contrast, for *R. communis* germination was 100% for all treatments (Fig. 3A). For *R. communis*, the amendment and nutrients had no significant effect as compost concentration ($P=1.00$), adding nutrients ($P=1.00$) and their interaction ($P=1.00$) were not significant. Similarly, for *P. velutina*, germination varied from 87 to 100% among treatments, without a significant effect associated with compost ($\chi^2=6.69$, df=3, $P=0.08$), nutrients ($\chi^2=0.20$, df=1, $P=0.89$) and their interaction ($\chi^2=0.62$, df=3, $P=0.89$). For *P. praecox* and *A. farnesiana*, germination ranged from 20 to 100% with a significant effect associated with compost concentration for *P. praecox* ($\chi^2=36.46$, df=3, $P<0.0001$) and *A. farnesiana* ($\chi^2=38.05$, df=3, $P<0.0001$). In contrast, adding nutrients ($\chi^2=0.47$, df=1, $P=0.49$ for *P. praecox* and $\chi^2=0.47$, df=1, $P=0.49$ for *A. farnesiana*) and their interaction ($\chi^2=0.47$, df=3, $P=0.92$ and $\chi^2=0.15$, df=3, $P=0.15$, respectively) were not significant.

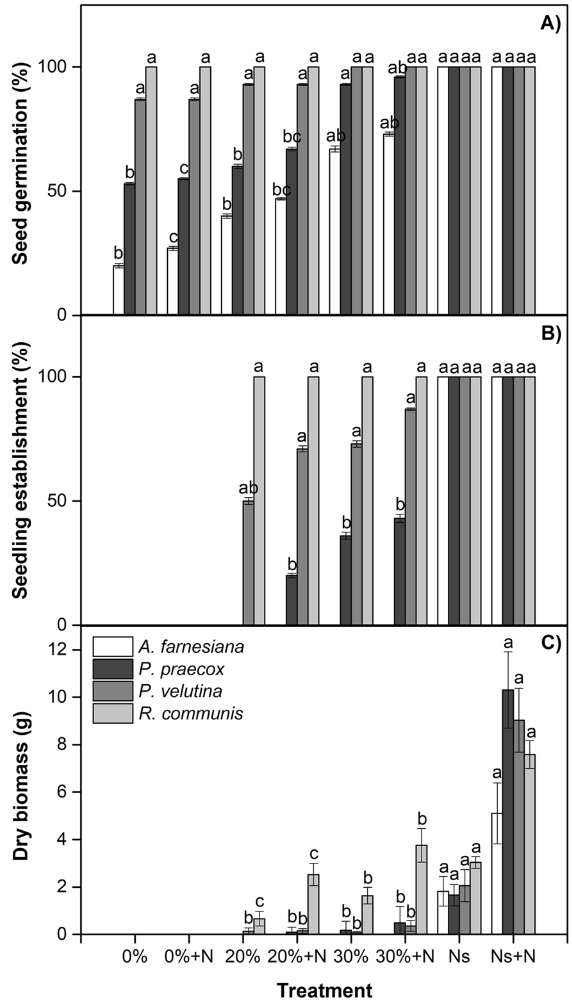

Fig. 3 Seed germination (**A**), seedling establishment (**B**) and total biomass accumulation (**C**) for the different species grown under different experimental treatments using compost and nutrients. 0%: 100% tailing material and 0% compost, without and with nutrients (N); 20%: 80% tailing material mixed with 20% compost, without and with nutrients (N); 30%: 70% tailing material mixed with 30% compost, without and with nutrients (N); NS: natural soil treatment without and with nutrients (N). Values represent means ± one standard deviation. Different letters indicate means with significant differences between treatments within species

For seedling establishment, large variation among species and treatments was also recorded (Fig. 3B). For all evaluated species, no seedling was able to establish under the 0% compost treatment, that is under 100% tailings material (Fig. 3B). For *A. farnesiana*, seedlings survived only on the natural soil treatment. For *R. communis*, seedling establishment was 100% for all treatments except under the 0% compost treatment. For this species, compost concentration (P = 1.0), adding nutrients (P = 1.0) and their interaction (P = 1.0) did not have a significant effect on seedling survival. For *P. velutina* and *P. praecox*, seedling establishment varied from 0 to 100% among treatments. For these two species, compost concentration had a significant effect on seedling survival ($\chi^2 = 10.08$, df = 2, P = 0.006 for *P. velutina* and $\chi^2 = 31.49$, df = 2, $P < 0.0001$ for *P. praecox*). In contrast, adding nutrients ($\chi^2 = 1.15$, df = 1, P = 0.28 and $\chi^2 = 0.40$, df = 1, P = 0.52, respectively) and the interaction ($\chi^2 = 0.65$, df = 2, P = 0.72 and $\chi^2 = 0.27$, df = 2, P = 0.87, respectively) did not have a significant effect on seedling establishment. For *A. farnesiana*, no seedling survived on the amended treatments.

Biomass accumulation Established plants showed clear differences among treatments and species in accumulated biomass after 64 days of growth (Fig. 3C). Maximum biomass values were recorded for the species that germinated under the natural soil treatment. In general, *R. communis* accumulated greater biomass in the amended treatments than the other species. *A. farnesiana* only survived in the natural soil control treatment whereas *P. velutina* and *P. praecox* were able to accumulate very low values of biomass (< 1 g) on the 20 and 30% compost treatments. In contrast, *R. communis* was able to produce larger values of biomass in those compost treatments (Fig. 3C).

R. communis was the species that had the best performance under the amended treatments. Increasing compost concentration had a significant effect on accumulated biomass ($\chi^2 = 80.23$, df = 2, $P < 0.0001$), as adding nutrients ($\chi^2 = 75.14$, df = 1, $P < 0.0001$) and the interaction was also significant ($\chi^2 = 33.33$, df = 2, $P < 0.0001$). The natural soil control had the greatest values of accumulated biomass (Fig. 3C). Similarly, for *P. velutina* and *P. praecox*, increasing compost concentration in the substrate had a significant effect on biomass ($\chi^2 = 91.86$, df = 2, $P < 0.0001$ and $\chi^2 = 65.60$, df = 2, $P < 0.0001$, respectively) as well as adding nutrients ($\chi^2 = 52.16$, df = 1, $P < 0.0001$ and $\chi^2 = 36.84$, df = 1, $P < 0.0001$, respectively) and the interaction was also significant ($\chi^2 = 66.73$, df = 2, $P < 0.0001$ and $\chi^2 = 50.36$, df = 2, $P < 0.0001$, respectively). Overall, the natural soil control was the treatment where all species accumulated greater biomass (Fig. 3C).

Based on the overall biomass accumulation, *R. communis* was the species with the best performance. The other species accumulated biomass mainly on the natural soil control treatment and very low values on the amended treatments. Thus, *P. velutina*, *P. praecox,* and *A. farnesiana* did not produce sufficient biomass to measure other parameters and estimate the concentration of PTE in their organs. For these reasons, in the following section, we just report the performance of *R. communis*.

Leaf area, photosynthesis, and chlorophyll fluorescence After 64 days of growth, a significant effect of compost ($\chi^2 = 33.49$, df = 2, $P < 0.0001$) and nutrients ($\chi^2 = 32.84$, df = 1, $P < 0.0001$) was recorded in leaf area of *R. communis* (Fig. 4A), whereas the interaction was not significant ($\chi^2 = 5.56$, df = 2, $P = 0.06$). Maximum leaf area values were recorded under the natural soil treatment with nutrients. Similarly, a significant effect of compost ($\chi^2 = 31.09$, df = 2, $P < 0.0001$) and nutrients ($\chi^2 = 6.59$, df = 1, $P = 0.01$) was found on photosynthetic rates (Fig. 4B), but the interaction was not significant ($\chi^2 = 0.25$, df = 2, P = 0.88). As in other parameters, maximum assimilation was recorded under the natural soil treatment with nutrients. Chlorophyll fluorescence measurements during the morning and the afternoon for the different treatments varied from 0.72 to 0.82 (Fig. 4C). No significant differences were found between compost treatments during the morning ($\chi^2 = 1.16$, df = 2, $P = 0.55$) or during the afternoon ($\chi^2 = 1.28$, df = 2, $P = 0.52$). Similarly, the effect of adding nutrients was not significant during the morning ($\chi^2 = 3.49$, df = 1, $P = 0.06$) or the afternoon ($\chi^2 = 2.09$, df = 1, $P = 0.14$) and the interaction was neither significant ($\chi^2 = 3.03$, df = 2, $P = 0.21$ and $\chi^2 = 0.57$, df = 2, $P = 0.74$).

Phytostabilization potential

Concentration of potentially toxic elements (PTE) With some exceptions, adding compost and nutrients to the substrate reduced the concentration of As, Pb, Mn, and Zn in plant organs of *R. communis*. In all cases, the concentration of PTE was lowest in the natural soil treatment (Fig. 5). As previously described, it was not possible to estimate PTE accumulation in the unamended (100% tailings) treatment as no seedling was able to establish.

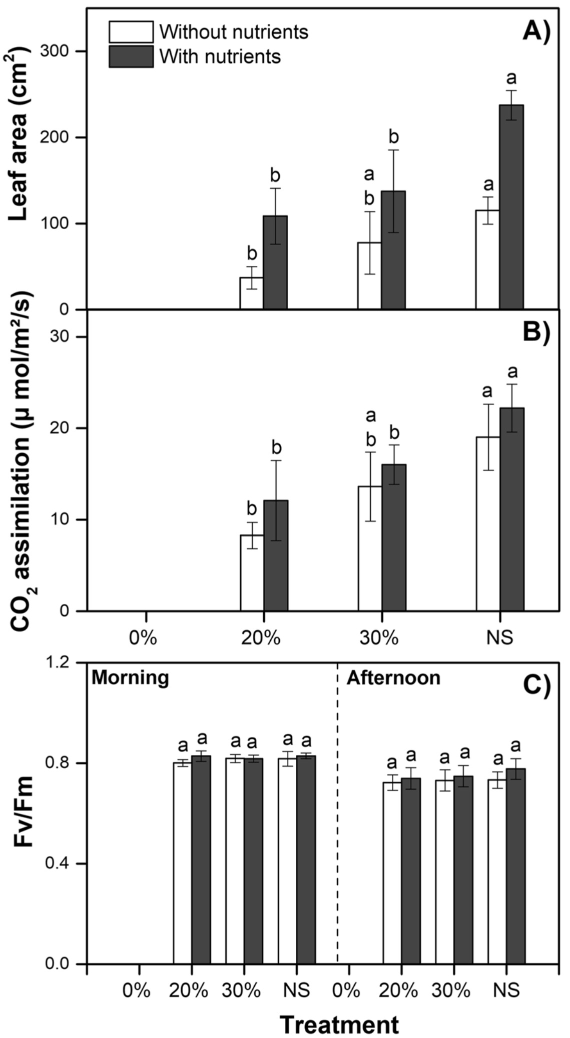

Fig. 4 Leaf area (**A**), photosynthetic rates (**B**) and chlorophyll fluorescence (**C**) values of *R. communis* grown under different experimental treatments using compost and nutrients. Values represent means ± one standard deviation. For chlorophyll fluorescence values for morning and afternoon are shown. Different letters indicate means with significant differences between treatments

Adding compost and nutrients to the growing substrate reduced the accumulation of As in plants: the concentration of As in organs of *R. communis* showed significant differences between compost treatments, with lower leaf ($\chi^2 = 15.93$, df = 2, $P = 0.0003$), stem ($\chi^2 = 15.35$, df = 2, $P = 0.0005$) and root ($\chi^2 = 32.96$, df = 2, $P < 0.0001$) concentration as compost concentration increases (Fig. 5). Similarly, the addition of nutrients was also associated with significant differences between treatments as the concentration of As decreased in leaves ($\chi^2 = 11.45$, df = 1, $P = 0.0007$), stems ($\chi^2 = 10.26$, df = 1, $P = 0.0014$) and roots ($\chi^2 = 10.58$, df = 1, $P = 0.0011$) with nutrients (Fig. 5). The interaction between factors was also significant ($\chi^2 = 8.12$, df = 2, $P = 0.01$ for leaves, $\chi^2 = 12.76$, df = 2, $P = 0.001$ for stems and $\chi^2 = 18.19$, df = 2, $P = 0.0001$ for roots). In general, the greatest concentration of As was recorded in roots and with few exceptions, the lowest was detected in stems (Fig. 5A and B).

Adding compost also reduced the accumulation of Mn in plants (Fig. 5). There were significant differences in Mn concentration between compost treatments with lower concentration as compost increased for leaves ($\chi^2 = 23.25$, df = 2, $P < 0.0001$), stems ($\chi^2 = 17.80$, df = 2, $P = 0.0001$) and roots ($\chi^2 = 13.41$, df = 2, $P = 0.001$). Adding nutrients had a significant effect only on the concentration in stems ($\chi^2 = 10.62$, df = 1, $P = 0.001$), but not in leaves ($\chi^2 = 0.79$, df = 1, $P = 0.37$) and roots ($\chi^2 = 1.42$, df = 1, $P = 0.23$). The interaction between factors was also significant only for the concentration in stems ($\chi^2 = 6.31$, df = 2, $P = 0.04$), but not in leaves ($\chi^2 = 0.25$, df = 2, $P = 0.87$) and roots ($\chi^2 = 0.77$, df = 2, $P = 0.67$). Similar to As, the greatest concentration of Mn was recorded in roots and the lowest in stems (Fig. 5).

Compost and nutrients also reduced the concentration of Pb in plant organs. Significant differences were recorded between treatments, as Pb decreased with increasing compost levels in leaves ($\chi^2 = 11.90$, df = 2, $P = 0.002$), stems ($\chi^2 = 20.34$, df = 2, $P < 0.0001$) and roots ($\chi^2 = 29.26$, df = 2, $P < 0.0001$). The addition of nutrients had a significant effect, decreasing the Pb concentration in stems ($\chi^2 = 8.80$, df = 1, $P = 0.003$) and roots ($\chi^2 = 3.84$, df = 1, $P = 0.04$), but not in leaves ($\chi^2 = 1.17$, df = 1, $P = 0.27$). The interaction was significant only in stems ($\chi^2 = 7.90$, df = 2, $P = 0.01$), but not in leaves ($\chi^2 = 0.06$, df = 2, $P = 0.97$) and roots ($\chi^2 = 1.49$, df = 2, P = 0.47). As in other elements, the greatest concentration was recorded in roots and with few exceptions, the lowest was found in stems (Fig. 5).

Compost also reduced the accumulation of Zn in plant organs. Significantly lower concentrations were recorded as compost levels increased, in leaves ($\chi^2 = 18.33$, df = 2, $P = 0.0001$), stems ($\chi^2 = 16.64$, df = 2, $P = 0.0002$) and roots ($\chi^2 = 21.54$, df = 2, $P < 0.0001$). In contrast, adding nutrients had a significant increase only in the concentration of Zn in stems ($\chi^2 = 5.79$, df = 1, $P = 0.01$), but not in leaves ($\chi^2 = 0.70$, df = 1, $P = 0.39$) and roots ($\chi^2 = 1.53$, df = 1,

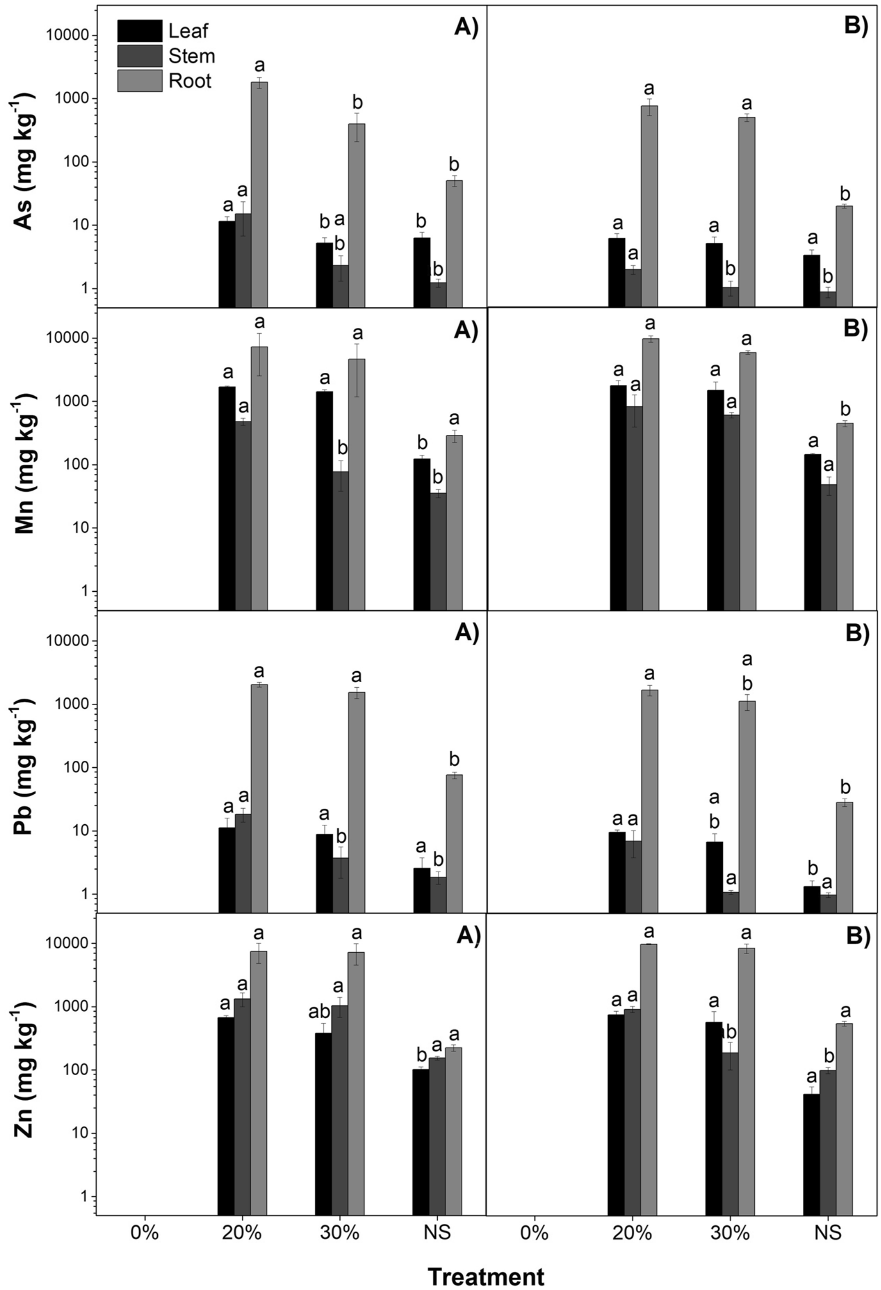

Fig. 5 Mean concentration of PTE (As, Mn, Pb and Zn) in plant organs (leaves, stems and roots) of *R. communis* grown under different experimental treatments using compost (**a**) and nutrients added to compost treatments (**b**). Values represent means ± one standard deviation. Different letters indicate means with significant differences between treatments

$P=0.21$). In this case, the interaction was not significant ($\chi^2=1.53$, df = 2, $P=0.46$, for leaves, $\chi^2=2.87$, df = 2, $P=0.23$ for stems and $\chi^2=0.53$, df = 2, $P=0.76$). The greatest concentrations of Zn were recorded in roots and with few exceptions, the lowest in leaves (Fig. 5).

Bioaccumulation factors The bioconcentration factor (BCF) was greater than 1 for all PTE and treatments (Table 2). In contrast, the translocation factor (TF) was lower than 1 for all PTE and treatments. The phytoaccesible fraction of the analyzed PTE in the growing substrate is shown in Online Resource Table 2.

Maximum tolerable levels (MTL) by domestic animals Mean concentration of the studied PTE in the above-ground biomass is shown in Table 3. The observed concentration of As did not reach MTL for any of the domestic animal groups. For Mn, observed values were greater than MTL for all domestic animal groups for the 20% compost (with and without nutrients) and 30% compost (without nutrients) treatments. Similarly, for Pb, recorded values were greater than MTL for the 20% (with and without nutrients) and 30% (without nutrients) compost treatments. Finally, recorded values of Zn were greater than MTL for all amended treatments. In contrast, observed values in the natural soil treatment were all lower than MTL (Table 3).

Capping experiment: Evaluation of plant responses

Seed germination and seedling establishment Seed germination was 100% for *R. communis*, *P. velutina,* and *P. praecox* in all treatments (Fig. 6A). For *A. farnesiana*, germination varied from 92 to 100% between treatments, whereas for *N. glauca*, no germination was observed (Fig. 6A). The statistical analysis revealed no significant differences in germination between capping treatments for all species that germinated ($P = 1.00$ for *R. communis*, $P = 1.00$ for *P. velutina*, $P = 1.00$ for *P. praecox,* and $P = 0.31$ for *A. farnesiana*).

For *R. communis*, seedling establishment was 100% for all treatments whereas for the other species that germinated, establishment ranged from 45 to 100% (Fig. 6B). Significant differences between treatments were detected for *P. praecox* ($\chi^2 = 15.91$, df = 3, $P = 0.001$) and *A. farnesiana* ($\chi^2 = 16.39$, df = 3, $P = 0.0009$) but not for *R. communis* ($P = 1.00$) and *P. velutina* ($\chi^2 = 6.78$, df = 3, $P = 0.07$). In general, seedling establishment was greater in the natural soil treatment (NS) and lower values were recorded for the SGCT treatment (Fig. 6B).

Biomass accumulation The natural soil (NS) was the treatment where biomass was greater for all species that germinated (Fig. 6C). For treatments including combinations of soil and other layers,

Table 2 Bioconcentration (BCF) and Translocation factors (TF) across different compost and nutrient treatments in plants of *R. communis* in the organic amendment experiment

Treatment	BCF				TF			
	As	Mn	Pb	Zn	As	Mn	Pb	Zn
20% compost	2.05	44.96	47.99	4.05	0.01	0.18	0.01	0.35
20% compost + nutrients	3.84	20.98	16.87	7.26	0.01	0.22	0.009	0.16
30% compost	4.41	31.57	39.69	10.79	0.02	0.19	0.007	0.19
30% compost + nutrients	4.73	13.25	55.77	7.30	0.01	0.47	0.003	0.09
Natural soil	22.63	2.87	122.58	2.14	0.14	0.80	0.06	0.03
Natural soil + nutrients	6.16	2.71	21.74	17.99	0.17	0.42	0.11	0.27

BCF relationship between PTE concentration in roots with respect to PTE in growing substrate. *TF* relationship between PTE concentration in the above-ground organs with respect to PTE concentration in roots

Table 3 PTE concentration (mg/Kg) in above-ground biomass (leaves and stems) in plants of *R. communis* grown under different experimental treatments of compost, tailing material and nutrients. For comparison, we show the maximum tolerable levels (MTL) by domestic animals (National Research Council 2005)

PTE	Treatment						MTL		
	20% compost	20% compost + nutrients	30% compost	30% compost + nutrients	Natural soil	Natural soil + nutrients	Cattle	Sheep	Rodents
As	26.5 ± 9.2	8.19 ± 1.46	7.51 ± 0.15	6.20 ± 1.88	7.51 ± 1.29	4.22 ± 0.88	30	30	30
Mn	2152 ± 19.7	2807.0 ± 1023.9	1486.2 ± 101.3	2262 ± 753.77	158.5 ± 33.3	209.8 ± 35.5	2000	2000	2000
Pb	29.4 ± 0.49	16.25 ± 5.59	12.50 ± 1.90	7.67 ± 3.25	4.41 ± 1.09	2.27 ± 0.55	100	100	10
Zn	1996 ± 391.7	1665 ± 18.3	1422 ± 738.2	963 ± 19.79	198.3 ± 1.06	141 ± 33.9	500	300	500

Maximum tolerable levels in domestic animal feed (mg/Kg) based on indexes of animal health

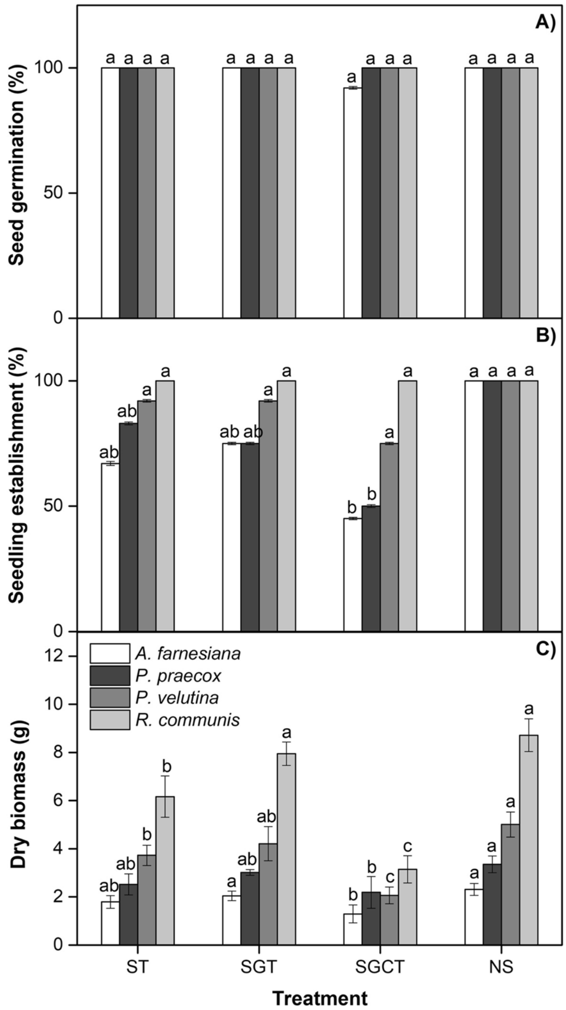

Fig. 6 Seed germination (**A**), seedling establishment (**B**) and total biomass accumulation (**C**) for the different species grown under different capping treatments, combining soil, gravel, clay and tailing layers. ST: soil layer in direct contact with tailing layer; SGT: soil layer with a gravel layer between soil and tailing layer; SGCT: soil layer with a gravel and clay layers between soil and tailing layer and NS: natural soil treatment. Values represent means ± one standard deviation. Different letters indicate means with significant differences between treatments

the combination of a gravel layer between the soil and tailings (SGT), was the treatment where plants accumulated greater biomass whereas the treatment with a gravel and clay layer between soil and tailings (SGCT) had the lower biomass (Fig. 6C). The treatment where soil and tailings were in direct contact (ST) had intermediate values of biomass. *R. communis* was the species that accumulated greater biomass than the rest of the tested species, with significant differences between treatments ($\chi^2 = 43.26$, df = 3, $P < 0.0001$). Similarly, for the other species, significant differences were detected in biomass accumulation between treatments ($\chi^2 = 14.11$, df = 3, $P = 0.002$ for *P. praecox*, $\chi^2 = 30.55$, df = 3, $P < 0.0001$ for *P. velutina* and $\chi^2 = 19.79$, df = 3, $P = 0.0002$ for *A. farnesiana*).

It was shown by our results that *R. communis* had better performance in terms of biomass accumulation and sufficient biomass was produced by it to evaluate the other parameters and measure PTE concentration. In contrast, *P. velutina*, *P. praecox,* and *A. farnesiana* did not produce sufficient biomass or leaves for evaluating the other parameters and determining PTE concentration. Therefore, we report the other parameters only for *R. communis*.

Leaf area, photosynthesis, and chlorophyll fluorescence Leaf area of *R. communis* showed significant differences between treatments ($\chi^2 = 44.07$, df = 3, $P < 0.0001$). Greater values of leaf area were recorded in the natural soil (NS) and the treatment that used a combination with a gravel layer between soil and tailings, SGT (Fig. 7A). Lower values of leaf area were recorded for the treatment without a layer between soil and tailings (ST) and the one with layers of gravel and clay, SGCT (Fig. 7A). In contrast to leaf area, no significant differences in photosynthetic rates were detected between treatments (Fig. 7B). The observed variation in chlorophyll fluorescence between treatments varied from 0.54 to 0.79 (Fig. 7C). For this parameter, no significant differences were detected between treatments during the morning ($\chi^2 = 6.27$, df = 3, $P = 0.09$), whereas a significant difference was recorded during the afternoon ($\chi^2 = 8.45$, df = 3, P = 0.03). The treatment where soil and tailings were in direct contact (ST) showed lower values (Fig. 7C).

Phytostabilization potential

Concentration of potentially toxic elements (PTE) The concentration of PTE was variable between plant organs and treatments. In terms of total concentration, the order was Zn > Mn > As > Pb (Fig. 8). Among treatments, lower concentrations were recorded in the natural soil treatment (NS) whereas higher concentrations were observed in the other treatments

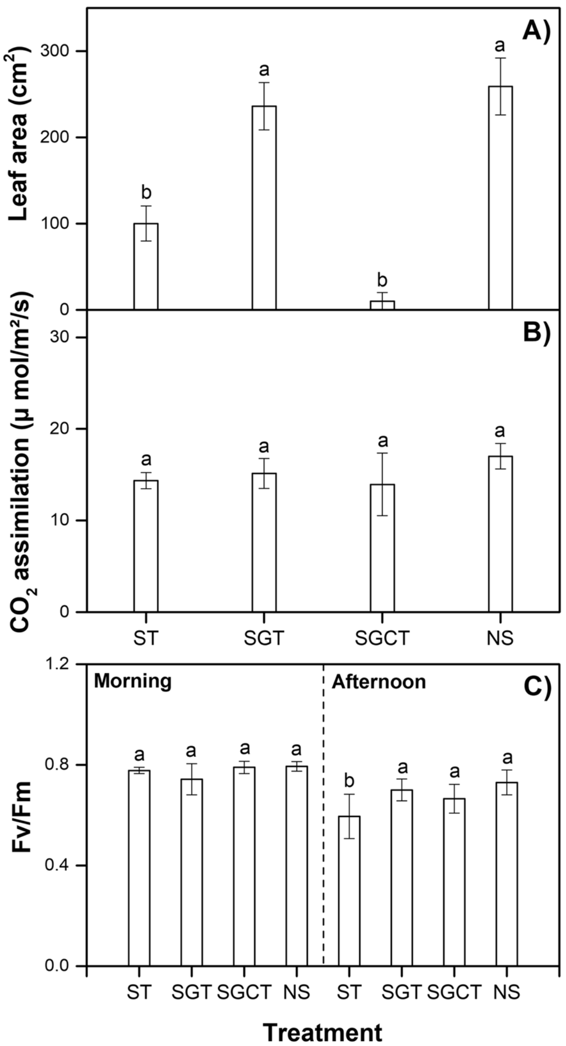

Fig. 7 Leaf area (**A**), photosynthetic rates (**B**) and chlorophyll fluorescence (**C**) values of *R. communis* grown under different capping treatments, combining soil, gravel, clay and tailing layers. ST: soil layer in direct contact with tailing layer; SGT: soil layer with a gravel layer between soil and tailing layer; SGCT: soil layer with a gravel and clay layers between soil and tailing layer and NS: natural soil treatment. For chlorophyll fluorescence values for morning and afternoon are shown. Values represent means ± one standard deviation. Different letters indicate means with significant differences between treatments

(Fig. 8). Among plant organs, greater concentrations were recorded in roots and lower concentrations were observed in leaves for Pb and Zn and stems for As and Mn (Fig. 8).

The accumulation of As in plant organs showed significant differences between treatments for stems (χ^2 =26.46, df=3, P <0.0001) and roots (χ^2 =20.55, df=3, P <0.0001) but not for leaves (χ^2 =7.56, df=3, P=0.05). For Mn, the concentration also showed significant differences between treatments for leaves (χ^2 =13.18, df=3, P=0.004), stems (χ^2 =24.36, df=3, P <0.0001) and roots (χ^2 =8.31, df=3, P=0.03). In Pb, significant differences were recorded between treatments for stems (χ^2 =8.26, df=3, P=0.03) and roots (χ^2 =11.12, df=3, P=0.01) but not for leaves (χ^2 =1.42, df=3, P=0.69). Finally, for Zn, the concentration showed significant differences between treatments for all organs (χ^2 =8.39, df=3, P=0.03 for leaves, χ^2 =30.17, df=3, P <0.0001 for stems and χ^2 =14.15, df=3, P=0.002).

Bioaccumulation factors For all PTE, the bioconcentration factor (BCF) was greater than 1 (Table 4). However, the translocation factor (TF) for most PTE was lower than 1, except for Mn in treatments ST and SGCT and for Zn in treatment SGCT, where they were slightly greater than 1 (Table 4). The phytoaccesible fraction of the analyzed PTE in the growing substrate is shown in Online Resource Table 3.

Maximum tolerable levels (MTL) by domestic animals The mean concentration of PTE in above-ground biomass in the natural soil treatment did not reach MTL for any of the domestic animal groups (Table 5). In contrast, values of Zn in above-ground biomass were greater than MTL for some domestic groups in treatments ST, SGT, and SGCT (Table 5).

Discussion

The analyzed mine tailings have a high bulk density (2.6 g cm^{-3}, Table 1), which is an indicator of a very compacted material where plant roots may struggle to grow. This coupled with the low pH (2.83), poor carbon and nitrogen content (0.9 and 0.1 g Kg^{-1}, respectively), and high PTE content can represent strong impediments to achieve plant establishment. The tailings affected soil show less compaction (bulk density of 1.4 g cm^{-3}), higher pH (3.3), more total carbon (1 g Kg^{-1}), but higher EC (151.5 dS m^{-1}), and PTE content similar to the mine tailings. In contrast, the natural soil is less compacted (1.2 g cm^{-3}), has a pH around neutrality (7.5), and has more C (6 g Kg^{-1}) content, which could offer a better environment for plant establishment and growth. Di Carlo et al. (2019) pointed out that rehabilitation goals

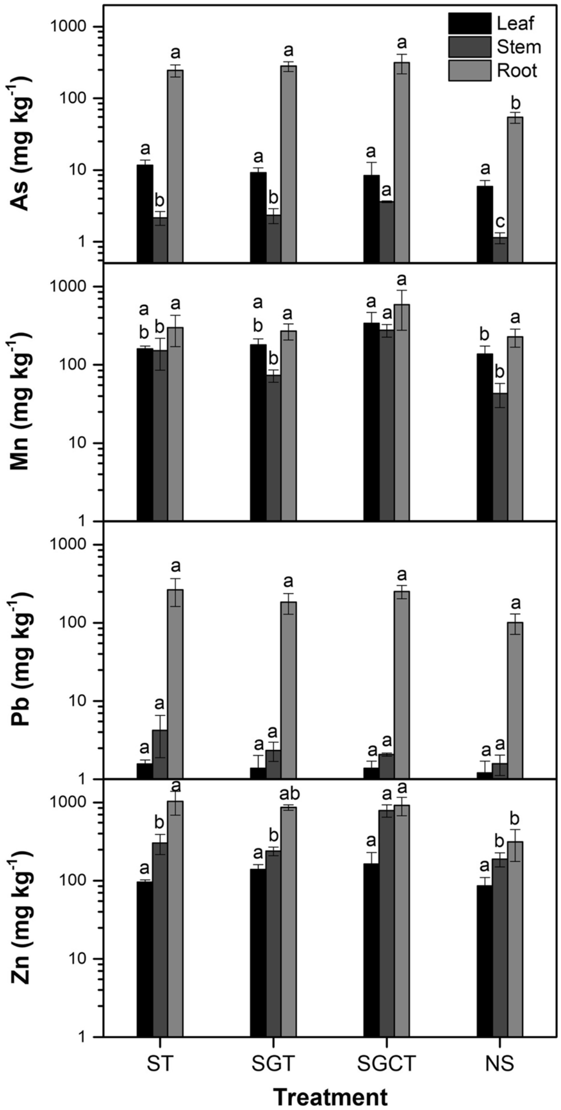

Fig. 8 Mean concentration of PTE (As, Mn, Pb and Zn) in plant organs (leaves, stems and roots) of *R. communis* grown under different capping treatments, combining soil, gravel, clay and tailing layers. ST: soil layer in direct contact with tailing layer; SGT: soil layer with a gravel layer between soil and tailing layer; SGCT: soil layer with a gravel and clay layers between soil and tailing layer and NS: natural soil treatment. Values represent means ± one standard deviation. Different letters indicate means with significant differences between treatments

for plant growth promotion in bauxite residue disposal areas include a steady-state pH between 5.5 and 9.0, an EC <4 dS m^{-1}, and a bulk density of ≤1.6 g cm^{-3}, among others. Thus, neither the analyzed mine tailings nor the tailing-affected soil is adequate for plant growth; they need a prior treatment to increase pH and OM content and decrease the EC and bulk density.

Our data on seedling establishment under different substrate treatments revealed that none of the evaluated species were able to establish in pure tailings substrate, a result that is congruent with the fact that the San Felipe deposit lack vegetation. Such pattern has been recorded in other field studies from arid or semi-arid areas of northwestern Mexico and southwestern USA (Gil-Loaiza et al. 2016; Arvizu-Valenzuela et al. 2020). Increasing compost and adding nutrients to the growing substrate allowed levels of seedling establishment that approached the natural soil treatment (Fig. 3), indicating that low organic matter (OM) and nutrients act as barriers that impede plant colonization from local seed dispersal. The addition of OM could also improve not only water retention but also the porosity of the substrate, decreasing their compaction and promoting substrate aeration that favors plant establishment. This result is consistent with other studies that evaluated plant establishment in tailings material under different substrate treatments, studied under pot or field conditions (Gil-Loaiza et al. 2016, Arvizu-Valenzuela et al. 2020). Seed germination was not inhibited under unamended tailings, but seedling establishment was identified as a critical stage affected by substrate quality. Most likely, seed dispersal is not a barrier to plant establishment (sensu Aide and Cavelier 1994) in the tailings of San Felipe as we have observed seed dispersal into this deposit (F. Molina-Freaner, pers. Obs.). Furthermore, plant growth as estimated by biomass accumulation was also significantly affected by substrate quality (Fig. 2). Growth of the three evaluated tree species under amended treatments was minimal, insufficient to measure other parameters and represented only a low fraction of the growth under the natural soil treatment (Fig. 3). Plant growth under 30% compost in the growing substrate was lower than the natural soil treatment, probably indicating that other factors such as the concentration of PTE or low pH also limit plant growth. For *R. communis*, leaf area and photosynthesis (Fig. 4) were significantly increased by adding compost and nutrients, supporting the idea that nutrients could be limiting these two parameters. Furthermore, Fv/fm fluorescence values showed no evidence of damage to the photosynthetic apparatus, probably due to a lower accumulation of PTE in leaves. Thus, our data reveal that a combination of factors acts as barriers through different plant stages that restrict plant establishment in the tailings deposit of San Felipe de Jesus, using assisted

Table 4 Bioconcentration (BCF) and Translocation factors (TF) of PTE in plants of *R. communis* grown under different experimental capping treatments (soil, tailings, gravel and clay). ST: soil layer in direct contact with tailing layer; SGT: soil layer with a gravel layer between soil and tailing layer; SGCT: soil layer with a gravel and clay layers between soil and tailing layer and NS: natural soil treatment

Treatment	BCF				TF			
	As	Mn	Pb	Zn	As	Mn	Pb	Zn
ST	15.79 ± 0.31	1.36 ± 0.47	84.12 ± 24.94	7.45 ± 1.87	0.05 ± 0.01	1.29 ± 0.91	0.02 ± 0.01	0.44 ± 0.26
SGT	14.47 ± 7.93	1.40 ± 0.49	66.85 ± 34.0	6.61 ± 1.60	0.04 ± 0.008	0.95 ± 0.14	0.02 ± 0.01	0.44 ± 0.05
SGCT	24.00 ± 12.80	3.77 ± 2.70	267.32 ± 327.14	9.27 ± 3.81	0.037 ± 0.01	1.38 ± 1.01	0.01 ± 0.003	1.07 ± 0.23
NS	18.91 ± 3.30	1.71 ± 0.39	184.13 ± 88.74	15.17 ± 11.97	0.13 ± 0.29	0.85 ± 0.32	0.03 ± 0.01	0.79 ± 0.37

BCF relationship between PTE concentration in roots with respect to PTE in growing substrate. *TF* relationship between PTE concentration in the above-ground organs with respect to PTE concentration in roots

Table 5 PTE concentration (mg/Kg) in above-ground biomass (leaves and stems) in plants of *R. communis* grown under different capping experimental treatments using combinations of soil, tailing material, gravel and clay layers. ST: soil layer in direct contact with tailing layer; SGT: soil layer with a gravel layer between soil and tailing layer; SGCT: soil layer with a gravel and clay layers between soil and tailing layer and NS: natural soil treatment. For comparison, we show the maximum tolerable levels (MTL) by domestic animals (National Research Council 2005)

PTE	Treatment				MTL		
	ST	SGT	SGCT	NS	Cattle	Sheep	Rodents
As	13.80 ± 2.66	11.51 ± 1.34	11.96 ± 4.51	7.02 ± 1.24	30	30	30
Mn	312.36 ± 78.93	252.33 ± 30.32	617 ± 107.34	180.33 ± 20.02	2000	2000	2000
Pb	5.79 ± 2.27	3.72 ± 1.01	3.44 ± 0.23	2.78 ± 0.66	100	100	10
Zn	398.5 ± 85.5	352.8 ± 19.7	952.83 ± 94.8	273.5 ± 16.75	500	300	500

Maximum tolerable levels in domestic animal feed (mg/Kg) based on indexes of animal health

phytostabilization. Plant stages and processes that were most critically affected under the evaluated treatments were seedling establishment, photosynthesis, and plant growth.

Phytostabilization of mine tailings requires metal-tolerant plants with minimal accumulation in above-ground organs to minimize the incorporation into local food webs (Mendez and Maier 2008). Our results on *R. communis* clearly showed that the concentration of PTE in above-ground organs was significantly reduced by adding compost to the growing substrate (Fig. 4). This pattern has been documented in other plant species growing under different compost treatments mixed with tailings materials (Rodriguez-Vila et al. 2014; Arvizu-Valenzuela et al. 2020), probably due to the metal immobilization by organic matter in the growing substrate (Sarathchandra et al. 2022). Similarly, adding nutrients to the growing substrate reduced the concentration of As and Pb but increased the level of Mn and Zn in above-ground organs, a pattern that may reflect the way that some nutrients are involved in plant metabolism (Dixit et al. 2015). Micronutrients such as Mn and Zn play important roles in plants and their accumulation may reflect a possible role in detoxification and reducing toxicity of non-essential metal(oid)s (Arif et al. 2016; Zhao et al. 2022). Some possible sources of Zn and Mn in these mine tailings has been already reported and includes rhodochrosite ($MnCO_3$), szmikite ($MnSO_4$.H_2O) for Mn, and sphalerite (ZnS), and sorbed specie for Zn (Del Rio-Salas et al. 2019; Loredo-Portales et al. 2020; Morales-Perez et al. 2021). Our data on bioconcentration (BCF) and translocation factors (TF) showed that although roots absorb and accumulate high concentrations of PTE, translocation of these elements into above-ground organs was low. This finding suggests that this species has phytostabilization potential (Mendez and Maier 2008). However, the concentration of Mn and Zn in above-ground organs were above MTL under amended treatments for most domestic animal groups whereas As and Pb levels were below MTL (Table 3). Thus, although compost reduces translocation, it is not sufficient to keep PTE at levels that do not represent a risk to domestic herbivores (Callery and Courtney 2015); if consumed, this species could incorporate PTE into local food webs (Vandecasteele et al. 2008). Our findings agree with those made by Proto et al. (2023), suggesting that to reduce the risk of PTE transfer into ecosystems it is necessary to couple the geochemical analysis with plant bioassay to detect toxic risk from minor elements. This risk to herbivores should be assessed using other amendments such as biochar (Gao et al. 2020) before any implementation of phytostabilization actions in this deposit.

Our data on plant performance growing on different capping treatments showed some interesting patterns that could be useful in the implementation of the soil capping approach in the tailings of San Felipe. As in the experiment with amended treatments, germination among species and capping treatments was high, except for *N. glauca* (Fig. 6). In contrast with the composting experiment, seedling establishment was relatively high for all species and treatments, except for the treatment with a layer of clay. In this treatment, it is likely that the clay layer did not allow water infiltration into the lower layer, causing stress due to flooding of the soil cap. This is probably an artifact of the experimental design using PCV tubes without lateral drainage in the gravel zone. However, this flooding problem is unlikely to occur under field conditions if the gravel and clay layers are properly implemented to allow lateral drainage (ITRC 2010). On the other hand, plant growth as estimated by biomass accumulation showed slight differences between treatments in *A. farnesiana* and *P. praecox* (Fig. 6). In contrast, clear differences between treatments were recorded for *R. communis* and *P. velutina* (Fig. 6). For this pair of species, growth of the natural soil treatment was similar to the treatment that used a gravel layer between soil and tailings material. In contrast, the treatment that used a layer of gravel and clay showed lower growth (Fig. 6). Similar to seedling establishment, it is likely that flooding caused by the clay layer induced some stress that affected plant growth. Although no significant differences between treatments were detected in photosynthesis for *R. communis*, clear significant differences were recorded for leaf area (Fig. 7). This difference was particularly evident between the natural soil and the treatment with a gravel layer with respect to treatments without a layer between soil and tailings and with a gravel and clay layer (Fig. 7). Capillary ascent in the treatment with no gravel layer can transfer PTE from the tailing layer into the soil cap, causing stress that reduces growth or plant mortality. Such transfer of PTE from a tailings layer into a soil cap has been documented to cause mortality in established plants (Menzies and Mulligan 2000) and suggests that the soil cap should use a gravel layer to avoid capillary ascent in the tailings of San Felipe. Given that the tailing deposit of San Felipe lacks an impervious layer at the base that impedes infiltration of leachates into deep layers and the aquifer, it is critically important to devise a mechanism for lateral drainage below the soil cap. The improper implementation of a device for lateral drainage could potentially threaten the integrity and sustainability of a soil capping approach in San Felipe. This is an important issue given that the concentration of soluble PTE in this deposit is high (Del Rio-Salas et al. 2019) and our knowledge about the importance of this deposit as a source of aquifer pollution is poor.

The accumulation of PTE in plant organs of *R. communis* in the soil cap experiment showed some similarities to the composting experiment, such as lower concentration in the natural soil treatment and greater concentration in roots (Fig. 8). Bioconcentration factors were greater than 1 but except for Mn, translocation factors were less than 1 (Table 4). However, Mn did not reach the maximum tolerable levels for domestic animals (Table 5). Thus, compared with the assisted phytostabilization approach, in the soil cap experiment, Mn in *R. communis* was below the MTL for domestic animals. Nevertheless, in some treatments, Zn was above MTL for some animal groups indicating that either some roots grew into the tailings layer, this element migrated through capillary ascent into the soil layer or flooding increased Zn availability. Zinc is often found in soil as absorbed ions and its mobility and phytoavailability are greater than other elements (Yan et al. 2020). Thus, implementing this approach may pose a risk to domestic animals and other options such as the use of mycorrhiza (Ultra and Manyiwa 2020) should be evaluated to reduce this potential risk.

Our data indicated that only one of the evaluated plant species, *R. communis*, showed phytostabilization potential for the tailings deposit of San Felipe. The three native tree species that were evaluated showed poor performance whereas one of the non-native species exhibited good potential to be used in both phytostabilization approaches. Such response pattern among evaluated species is common in other trials evaluating a sample of plant species in pot or field studies (Solis-Dominguez et al. 2012; Gil-Loaiza et al. 2016). When native species are unable to show phytostabilization potential, non-native species could be evaluated if they provide a desirable potential and are not invasive (Hobbs et al. 2009). This is the case of *R. communis* which showed good potential and is not regionally invasive. This species has been tested in other tailings deposits where it has shown phytostabilization potential (Ruiz Olivares et al. 2013) and can be used for oil production (Kiran et al. 2017). Although this species is promising for San Felipe, future studies should test additional native species, particularly perennial species from different life forms such as grasses, shrubs, and trees, to identify a diverse set of species that could be selected for establishing a self-sustainable plant community in this abandoned deposit.

Conclusions

1. The study identified barriers to plant establishment in an abandoned tailings deposit in northwestern Mexico, specifically related to seedling establishment and plant growth.
2. Among the five species studied, only *R. communis* showed potential for phytoremediation using assisted phytostabilization through compost in the growing substrate.
3. While compost reduced the accumulation of metal(oid)s in plant organs, the levels of some elements still exceeded the maximum tolerable levels by domestic animals, which reduces its phytostabilization potential.
4. The capping approach using a combination of soil, gravel, and tailing layers showed that *R. communis* had greater phytostabilization potential through low translocation factors.
5. Comparing the pattern of metal(oid) accumulation in plant organs, the capping approach showed more phytostabilization potential than the use of amendments, reducing the risk of incorporating metal(oid)s in the trophic web.
6. Future studies should explore field trials to evaluate the effectiveness of the capping approach in regional abandoned tailing deposits such as San Felipe.

Overall, the study suggests that the capping approach using a combination of soil, gravel, and tailing layers, and *R. communis* as the phytoremediation species, may be an effective method for remediating abandoned tailing deposits. However, further research is needed to determine the long-term effectiveness and feasibility of this approach in real-world applications.

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Declarations

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