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Evaluation of major constraints to revegetation of lead/zinc mine tailings using bioassay techniques

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Abstract

The residues from the extraction of lead/zinc (Pb/Zn) ores of most Pb/Zn mines are permanently stored in tailings ponds, which require revegetation to reduce their environmental impact. This can only be done if the main constraints on plant establishment are evaluated. This can readily be done by field and greenhouse studies.

To test this, the properties of different tailings from Lechang Pb/Zn mine located at the north of Guangdong Province in southern China have been studied. Physical and chemical properties including concentrations of metals (Pb, Zn, Cd and Cu) in the tailings and soils collected from different sites have been measured. The results showed that tailings contain low nitrogen (0.016–0.075%), low-organic matter (0.58–1.78%), high salt (3.55–13.85 dS/m), and high total and diethylene-tetramine-pentaacetic acid (DTPA)-extractable metal concentrations (total: 1019–1642 $\mu\text{g g}^{-1}$ Pb, 3078–6773 $\mu\text{g g}^{-1}$ Zn, 8–23 $\mu\text{g g}^{-1}$ Cd, and 85–192 $\mu\text{g g}^{-1}$ Cu; DTPA-extractable: 59–178 $\mu\text{g g}^{-1}$ Pb, 21–200 $\mu\text{g g}^{-1}$ Zn, 0.30–1.5 $\mu\text{g g}^{-1}$ Cd, and 4.3–12 $\mu\text{g g}^{-1}$ Cu). Aqueous extracts of tailings/soils (10%, 20% and 30%, w/v) from different sites were prepared for testing their effects on seed germination and root elongation of a vegetable crop *Brassica chinensis* and a grass species *Cynodon dactylon*. It was found that root elongation provided a better evaluation of toxicity than seed germination. The ranking of toxicity using root elongation was: high-sulfur tailings > tailing dam > sparsely vegetated tailings > densely vegetated tailings > mountain soil for both plants. This order was consistent with DTPA-extractable Pb contents in the tailings and soils. *B. chinensis* seedlings were then grown in the mixtures of different proportions of tailings and farm soil for 4 weeks, and the results (dry weights of seedlings) were in line with the root elongation test. All these demonstrated that heavy metal toxicity, especially available Pb, low content of nutrient, and poor physical structure were major constraints on plant establishment and colonization on the Pb/Zn mine tailings. © 2002 Published by Elsevier Science Ltd.

Keywords: Pb/Zn mine; Toxicity; Root elongation; Yield; *Brassica chinensis*; *Cynodon dactylon*

1. Introduction

Apart from the aesthetic and economic problems associated with large areas of derelict land, tailings dumps can be important sources of water pollution and of wind-borne, metal-containing dusts (Freedman,

1995). In the northern part of Guangdong Province, China, about 1700 thousand ha of farmland, which accounted for 7.3% of the total cultivated land in this area, are contaminated by heavy metals released from mining activities (Shu, 1997). Chemical and physical techniques are available for dust control and stabilization against water erosion, but the long-term objective of waste rehabilitation can only be realistically achieved by the use of vegetation as a basis for landscaping, stabilization and pollution control (Bradshaw and Johnson, 1992; Freedman, 1995).

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However, vegetation establishment on mine tailings is always difficult (Ernst, 1988; Johnson et al., 1994). In addition to the high level of acidity, Pb/Zn mine tailings may also contain toxic concentrations of metals, such as Pb, Zn and Cd, low levels of major plant nutrients, poor physical structure, and excess salinity (Ernst, 1988; Bradshaw and Johnson, 1992; Shu, 1997). In addition, different mine wastes have different constraints for re-vegetation; the chemical composition can vary vertically and laterally in the same tailings pond (Shu, 1997). In order to successfully reclaim mine tailings, it is essential to assess the physical, chemical, and biological factors pertaining to mine wastes, in order to gain a full understanding of constraints and opportunities (Johnson et al., 1994). Day and Ludeke (1979) also indicated that since most mineral wastes are very low in plant nutrients, careful attention must be given to their correct fertilization prior to planting.

In China there are over 8000 national and 230 000 private mining companies presently operating (Young, 1988), producing 60 million ton mining wastes annually (Shu, 1997). The Lechang Pb/Zn Mine Operation (lat 24°40' N, long 113°20' E) is located in the Pb/Zn mine zone in the north of Guangdong Province, southern China. The climate is sub-tropical and the annual rainfall is about 1500 mm. The operation started in 1959 and is a conventional underground mining operation covering an area of 1.5 km². It produces approximately 30 000 ton of tailings annually with a dumping area of 60 000 m² (Ye et al., 2000). Most of the dumping area is bare and lacks vegetation cover.

The Lechang site was chosen for testing assessment techniques. Tailings toxicity and other major constraints for plant establishment were assessed by a seed germination/root elongation test and an early seedling growth test, using *Brassica chinensis* and *Cynodon dactylon* as test species. Smith (1991) reported that only three vascular plant toxicity tests developed by the USEPA are currently approved for laboratory use: (1) duckweed (*Lemna*) acute toxicity test; (2) seed germination/root elongation toxicity test; and (3) early seedling growth toxicity test. It has also been reported that root elongation test is a simple and sensitive technique for detecting toxicity of heavy metals (Wong and Bradshaw, 1982; Godbold, 1994). *B. chinensis* has a high-germination rate and fast root growth (Wong and Lau, 1983), whilst *C. dactylon* is one of the most common turf grasses in southern China (Ye et al., 2000).

2. Materials and methods

2.1. Site description

Four tailings sites (A, B, TD and SH) at the Lechang Pb/Zn mine area, one mountain site (M) next to Site B,

and one clean site (OF) located at an organic farm in Hong Kong were selected.

Site A is a tailings disposal area, previously a pond close to a roadside, with a relatively high-plant cover, and a substantial amount of undecomposed leaf litter. *Bidens bipinnata*, *Erigeron acer* and *Vitex negundo* are the dominant species at this site. Some trees (e.g., *Cinnamomum burmannii*, *Cinnamomum camphora* and *Rhus chinensis*) and shrubs (e.g., the dominant *V. negundo*) occur. Site B is a tailings pond of which the central portion is bare except for three small patches of *C. dactylon*. It has a slippery and reddish brown surface, with *Impatiens cylindrica* and *R. chinensis* growing around the margin. Site TD is a tailings heap with black tailings on the sides of the heap, with a good growth of *Bidens bipinnata*. Site M is a mountain site with normal soil adjacent to Site B with a luxuriant growth of vegetation, and a high diversity of plant species, with many tree species, e.g. *R. chinensis* and *Pinus massoniana*. Site HS is an area of fresh tailings with a high-sulfur content, without any vegetation. Site OF is an area cultivating crops from an organic farm in Hong Kong.

2.2. Sample collection and preparation

Samples of tailings and soils were randomly collected from the selected sites in June 1995. The soil used for cultivating vegetable crops from the organic farm was used as a control and also as tailings ameliorant. Seeds of *B. chinensis* and *C. dactylon* were purchased from a local commercial seed store. The soils and tailings for the analysis of general properties were air-dried for 2 weeks and passed through 2-mm mesh sieve.

2.3. Tailings and soil analysis

Tailings and soil samples from Sites A, B, TD and M were subject to physical and chemical analysis. pH (solid:distilled water = 1:2) was determined using a Beckman pH meter and electrical conductivity (EC; solid:distilled water = 1:2) using an Orion 160 EC meter (Grimshaw, 1989). Total organic carbon (C) and total nitrogen (N) contents were measured using a PE 2400, CHNS analyzer. Total phosphorus (P) was extracted by perchloric acid digestion, and then determined using the molybdenum blue method (Olsen and Sommers, 1982). Tailings/soil texture was analyzed using the hydrometer method (Allen et al., 1974). The total and diethylene-tetramine-pentaacetic acid (DTPA)-extractable Pb, Zn, Cd and Cu contents were determined using flame atomic absorption spectrometry (AAS) after extraction with conc. HNO₃ + conc. HClO₄, 5:1, v/v (Baker and Amacher, 1982) and DTPA [(1.976 g DTPA + 14.29 g triethanolamine + 1.47 g CaCl₂ · 2H₂O) dissolved in 980 ml deionized H₂O, and made up to 1 l, pH 7.30] (Lindsay and Norvell, 1978) respectively. Tailings col-

lected from Site HS and control soil collected from the organic farm were also analyzed for pH, EC, texture, total and DTPA-extractable contents of Pb, Zn, Cd and Cu using the methods described above.

2.4. Toxicity tests

2.4.1. Seed germination and root elongation test

Tailings from Sites A, B, TD and HS and soil from Site M were used for the toxicity test. Different concentrations of aqueous extracts (10%, 20%, 30% w/v) were prepared by blending the appropriate weight of tailings or soil samples in distilled water respectively with an electric shaker at 100 rpm for 1 h. The extracts were then filtered through a Whatman No. 42 filter paper. Values of pH and EC, and Pb, Zn, Cd and Cu contents in the extracts were determined.

Twenty seeds of *B. chinensis* and *C. dactylon* were placed on alkathene beads in glass petri dishes (diameter: 12 cm) respectively. Six ml of the appropriate extract was added to each petri dish, and 6 ml of distilled water was used as a control treatment. There were three replicates for each treatment and species. The experiment was conducted under a 16-h light/8 h dark cycle at a temperature of 24 ± 4 °C in a growth chamber. Treatments were augmented with 0.5 ml of extract daily. The percentages of seed germination and root length of germinated seeds were recorded at days 4, 7 and 14 (USEPA, 1992). ECG₃₀, the effective concentration to reduce root growth (elongation) by 30%, was also calculated according to the root elongation from seedlings grown in control and treatment extracts.

2.4.2. Seedling growth test

Tailings from Sites A, B, TD and HS and soil from Site M were used for the seedling growth test. Different proportions of tailings or soil (10%, 25%, 50% and 100% w/w) were thoroughly mixed with the appropriate weight of farm soil from Site OF. Farm soil alone was used as control, and triplicate treatments were prepared. pH, EC, texture, total contents (HNO₃ and HClO₄) and DTPA-extractable contents of Pb, Zn, Cd and Cu in the mixtures were determined using the methods described above.

Six seeds of *B. chinensis* were sown in each pot (diameter: 6 cm, height: 7 cm). The pots were arranged in a randomized block design and watered daily, and 25% Hoagland's solution (Hewitt, 1966) was added weekly. Pots were placed in a greenhouse, with temperature varying between 25 and 35 °C, for 4 weeks. At the end of the second week, three seedlings were thinned out and three healthiest seedlings were left.

Plants were harvested after 4 weeks. Roots were washed three times with deionized water to remove the associated soil particles. Plant tissues were dried to

constant weight at 70 °C and the total dry weights were recorded.

2.5. Statistical analysis

The data were analyzed using a SPSS statistical package on an IBM personal computer (Little and Hills, 1978). One-way analysis of variance (ANOVA) was carried out to compare the means of different treatments. Where significant F values were obtained, differences between individual means were tested using Tukey-HSD tests at 0.05 significance level.

3. Results and discussion

3.1. General properties of tailings and soils

The general properties of tailings and soils are presented in Table 1. The pH values of tailings at Sites A, B, TD and HS were near neutral (pH 7.4, 6.5, 7.5 and 7.6, respectively). Comparing with the other sites within the Lechang mine, the pH of tailings at Site B was more variable, ranging from 2.8 to 7.9. The soil collected from mountain site (M) and the organic farm (OF) were acidic (pH 5.2 and 4.8, respectively). pH values ranging between 5.8 and 9.0 were reported in four other Pb/Zn mine tailings in southern China by Shu (1997). pH values of the soils at Sites M and OF fell within the range for normal red soils in southern China. Despite its known high-sulfur content, the pH of HS tailings was still high, probably because of its recent origin.

EC values of tailings collected from Sites A, B, TD and HS were 6.0, 7.7, 5.4 and 3.9 dS/m, respectively, significantly higher than those of soils from Sites M and OF. The highest EC value (13.8 dS/m) was found at one location in Site B, associated with poor growth of *C. dactylon*. Salinity is a common feature in tailings of high pyrite and carbonate content (Nielson and Peterson, 1972). At an EC of 4 dS/m, yields of many crops will be restricted due to inhibition of plant growth and seed germination (Wild, 1993). High-salt levels may also adversely affect plant metabolism and/or membrane permeability (Greenway and Munnus, 1980). Therefore, salinity in the Lechang tailings may be one of the major constraints to vegetation establishment. The EC of HS tailings was low, perhaps again because of its recent origin.

Total N contents of the tailings from Sites TD, B and HS were significantly lower than those of soils from Sites OF and M. Soil from Site OF and tailings from Site TD contained the highest total P (0.51% and 0.44%, respectively), more than twice that of the tailings at Site B (0.18%). Total organic C contents of soils at Sites M and OF (3.66% and 3.30%, respectively) were significantly higher than those from tailings at Sites SH, B and TD

Table 1
General properties of tailings and soils collected from Lechang Pb/Zn mine sites and control site (mean $\pm$ s.e., $n = 5$)

Sites	pH	EC (dS m ⁻¹)	Total N (%)	Total P (%)	Total organic C (%)	Texture		
						Clay (%)	Silt (%)	Sand (%)
A	7.4 $\pm$ 0.02a*	6.0 $\pm$ 0.17ab	0.07 $\pm$ 0.002bc	0.35 $\pm$ 0.02abc	1.88 $\pm$ 0.71ab	23.3 $\pm$ 1.33a	56.7 $\pm$ 5.33a	20 $\pm$ 1.85e
B	6.5 $\pm$ 0.68ab	7.7 $\pm$ 1.1a	0.03 $\pm$ 0.02cd	0.18 $\pm$ 0.08c	0.58 $\pm$ 0.20c	9.7 $\pm$ 0.85c	51.0 $\pm$ 4.71a	39.3 $\pm$ 3.52d
TD	7.5 $\pm$ 0.03a	5.4 $\pm$ 0.02bc	0.02 $\pm$ 0.001d	0.44 $\pm$ 0.003ab	0.75 $\pm$ 0.10bc	7.7 $\pm$ 0.56c	29.4 $\pm$ 2.52bc	62.9 $\pm$ 5.23bc
M	5.2 $\pm$ 0.08b	0.18 $\pm$ 0.02d	0.14 $\pm$ 0.01b	0.28 $\pm$ 0.05bc	3.66 $\pm$ 0.47a	26.3 $\pm$ 1.61a	26.4 $\pm$ 2.23bc	47.3 $\pm$ 3.42cd
HS	7.6 $\pm$ 1.1a	3.9 $\pm$ 0.24c	0.03 $\pm$ 0.003cd	0.27 $\pm$ 0.03bc	0.35 $\pm$ 0.20c	0.00 $\pm$ 0.00d	10.7 $\pm$ 0.85d	89.3 $\pm$ 5.62a
OF	4.8 $\pm$ 0.08bc	0.16 $\pm$ 0.01d	0.44 $\pm$ 0.04a	0.51 $\pm$ 0.07a	3.30 $\pm$ 0.21a	16.7 $\pm$ 1.22b	17.7 $\pm$ 1.19cd	65.6 $\pm$ 3.45b

A: densely vegetated tailings, B: sparsely vegetated tailings, TD: tailing heap, M: mountain site, HS: high-sulfur tailing area, OF: farm soil.

* Different letters in the same column indicate significant difference at $p < 0.05$ according to Tukey-HSD test.

(0.35%, 0.58% and 0.75%, respectively). For the growth of rice, soil with total N $> 0.2\%$ was considered high, 0.1–0.2% moderate and $< 0.1\%$ low (Zhijiang Agricultural University, 1991). It was also reported that total P in soil below 0.08–0.1% would limit plant growth (Zhijiang Agricultural University, 1991). Therefore, N contents in the tailings of Sites A, B and TD were inadequate for plant growth (Table 1). The organic matter content as reflected by total organic C content, was lower in the tailings when compared with the surface horizons of most natural soil (usually 3–5%), especially at Sites B, TD and HS. The higher N and total organic C contents of tailings in Site A compared to Sites B and TD may contribute to the greater plant diversity at the former site. Shu (1997) studied the floristic diversity in relation to soil characteristics at a Pb/Zn mine complex in southern China, and found that the soil of the species-rich area had a higher plant nutrient value than species-poor area. The high-organic matter content in Site A was due to many fallen leaves. This can be a strategy by which plants exclude accumulated metals.

Tailings from Site A (23.28% clay, 56.72% silt and 20.00% sand) and Site B (9.72% clay, 51.00% silt and 39.28% sand) were silty loam. Tailings from Sites TD (7.72% clay, 29.36% silt and 62.92% sand) and HS (0.00% clay, 10.72% silt and 89.28% sand) (Table 1) were sandy loam. The HS tailings contained no clay fraction. The mountain soil was classified as a loamy soil (26.28% clay, 26.44% silt and 47.28% sand).

The data presented in Table 1 show that organic matter, N content and physical structure of the tailings were poor for plant establishment. Nutrient deficiency is common in mine spoils (Smith and Bradshaw, 1979; Pichtel et al., 1994; Shu, 1997), making plant establishment difficult. Organic matter not only acts as a reservoir of essential macro-nutrients, but also provides a food resource for invertebrates and microorganisms that support the decay process and thus help nutrient recycling (Johnson et al., 1994). Low-organic matter may lead to leaching of nutrients, especially when water infiltration is rapid. Therefore, adding inorganic fertilizer alone to the mine spoils is inadequate. The use of organic matter can improve the physical structure (Ye et al., 1999).

Total and DTPA-extractable concentrations of Pb, Zn, Cd and Cu in the tailings are shown in Table 2, and the results were similar to those obtained from an abandoned Pb/Zn tailings pond in New Mexico, USA (Sidle et al., 1991) and Shuikoushan Pb/Zn mine tailings, Hunan, China (Shu, 1997). Total concentrations of Pb, Zn, Cd and Cu in the tailings were much higher than in the soils of Sites M and OF. Total Pb concentration in Site A was the highest among the studied sites. However, DTPA-extractable Pb content was significantly lower at Site A than at the other tailings sites (HS, B and TD). DTPA-extractable Pb contents for the studied sites were

Table 2
Total and DTPA-extractable concentrations ($\mu\text{g g}^{-1}$) of Pb, Zn, Cd and Cu in tailings and soils collected from Lechang Pb/Zn mine sites and control site (mean $\pm$ s.e., $n = 5$)

Sites	Pb		Zn		Cd		Cu	
	Total	Extractable	Total	Extractable	Total	Extractable	Total	Extractable
A	1642 $\pm$ 53a*	59 $\pm$ 2.4d	5021 $\pm$ 218b	115 $\pm$ 5.4b	14 $\pm$ 0.28b	1.5 $\pm$ 0.04a	192 $\pm$ 15a	12 $\pm$ 0.05a
B	1260 $\pm$ 205bc	85 $\pm$ 2.0c	5620 $\pm$ 290d	106 $\pm$ 11b	8.0 $\pm$ 0.37d	0.9 $\pm$ 0.04c	117 $\pm$ 1.5b	6.5 $\pm$ 0.42b
TD	1019 $\pm$ 30c	112 $\pm$ 3.5b	6773 $\pm$ 234a	200 $\pm$ 11a	23 $\pm$ 0.25a	1.1 $\pm$ 0.09b	139 $\pm$ 4.3b	4.3 $\pm$ 0.04c
M	71 $\pm$ 3.8d	26 $\pm$ 1.9e	248 $\pm$ 2.3e	3.3 $\pm$ 0.34d	1.2 $\pm$ 0.53e	0.13 $\pm$ 0.01d	11 $\pm$ 0.60d	0.79 $\pm$ 0.02d
HS	1453 $\pm$ 6.9ab	178 $\pm$ 4.8	3078 $\pm$ 180c	21 $\pm$ 1.5c	11 $\pm$ 0.57c	0.30 $\pm$ 0.001d	85 $\pm$ 3.8c	4.6 $\pm$ 0.28c
OF	25 $\pm$ 1.5e	14 $\pm$ 0.83f	43 $\pm$ 3.3e	0.84 $\pm$ 0.02e	0.20 $\pm$ 0.10e	ND	4.6 $\pm$ 0.23e	0.58 $\pm$ 0.01d

A: densely vegetated tailings, B: sparsely vegetated tailings, TD: tailing heap, M: mountain site, HS: high-sulfur tailings, OF: farm soil, ND: not detectable.

* Different letters in the same column indicate significant difference at $p < 0.05$ according to Tukey-HSD test.

in the following order: HS > TD > B > A > M > OF. Tailings from Sites A and TD contained the highest total and DTPA-extractable Zn and Cd concentrations. Tailings from Site A also contained the highest total and DTPA-extractable Cu. Soil collected from Site OF only contained $4.6 \mu\text{g g}^{-1}$ total Cu which indicated this soil suffered from potential Cu deficiency (Table 2).

The relationship between growth of established plants and metal contents in tailings or soil might be complicated by the time available for growth since deposition of tailings in each area has ceased. Difference in the age of the tailings may have affected plant establishment. However, Site A with a dense plant cover, had higher contents of total Pb, Zn, Cd and Cu, and extractable Cd and Cu than those of Site B with small patches of *C. dactylon*. The dense vegetation at Site A may be due to higher total organic C, N, and lower extractable Pb contents. It is commonly known that when organic matter and other mineral nutrients are in abundant supply, Pb toxicity does not occur (Woolhouse, 1983; Wild, 1988). Lead toxicity occurs most commonly on waste heaps from mining operations where organic matter and nutrient contents of the soil are low. The results presented here suggest that higher extractable Pb, lower nutrients (especially P and N) and organic C may be the main factors that affect plant growth on Site B. It has been indicated that high concentrations of toxic metals are the major cause of sparse vegetation cover of metalliferous mine waste and phosphorus concentrations are the immediate determinant, firstly because P is an important nutrient, and secondly it acts as a complexing agent for heavy metals and reduce their toxicity (Smith and Bradshaw, 1979).

3.2. Toxicity tests

3.2.1. Seed germination and root elongation tests

The results from the analysis of water extracts of tailings/soil show that dilution of the extracts (10%, 20%, and 30%, tailings (w)/water (v)) dramatically lowered the soluble salt content (EC values). However, dilution of extracts resulted in unchanged pH values. The results also show that the metal contents in water extracts of tailings were quite low, comparing with the DTPA-extractable portion (data not presented here). It has also been noted that only a small proportion of Pb, Zn, Cd and Cu in tailings could be extracted by water (Ye et al., 1999). However, heavy metals may inhibit root elongation and delay seed germination of a large variety of species even at very low concentrations (Wong and Bradshaw, 1982). For example, $0.1 \mu\text{g ml}^{-1}$ Zn or Cu in nutrient solution could significantly reduce growth (fresh weight of whole seedling) of *Sinapis alba* (De-Kock, 1956). The present results here showed that tailings from the tailings heap (TD) and high-sulfur tailings (HS) contained higher water-soluble Pb (0.18

and $0.33 \mu\text{g ml}^{-1}$ Pb in extracts of 30% TD and 30% HS tailings, respectively), and Zn (0.52 and $0.45 \mu\text{g ml}^{-1}$ Zn in extracts of 30% TD and 30% HS tailings, respectively) than the other tailings samples.

Germination percentages of *B. chinensis* and *C. dactylon* seeds treated with different tailings/soil extracts

were recorded at days 4, 7 and 14 (data not presented here). The results showed that there were no significant differences in germination rate among the different treatments for both species. Similar results were reported when seeds of *Agropyron elongatum* and *Trifolium repens* were germinated in the Pb/Zn tailings

Fig. 1. Root elongation ($n = 40$) of *B. chinensis* and *C. dactylon* in extract of different tailings and soils. Control: distilled water. Percentages indicate concentrations of the extracts (w/v). A: densely vegetated tailings, B: sparsely vegetated tailings, TD: tailings heap, M: mountain site, and HS: high-sulfur tailings.

amended with different amounts of lime and fertilizer (Ye et al., 1999).

Comparison of root elongation of *B. chinensis* and *C. dactylon* grown in different concentrations of the extracts of the tailings and soils showed that *B. chinensis* had a longer root length than *C. dactylon* (Fig. 1). It was apparent that *B. chinensis* was more sensitive to metal toxicity in the extracts than *C. dactylon*. Drastic inhibition of root elongation of *B. chinensis* was observed in extracts (10%, 20%, and 30%) of HS tailings. In the same plant, root elongation in extracts of the mountain soil was similar to OF soil (control), indicating the soil at Site M was not toxic to *B. chinensis*. The toxicity ranking of extracts for *B. chinensis* was: high-sulfur tailings (HS) > tailings heap (TD) > sparsely vegetated tailings (B) > densely vegetated tailings (A) > mountain soil (M). A similar trend was also observed for *C. dactylon* (Fig. 1).

Table 3 shows the root length of plants given in Fig. 1, expressed as ECG₃₀. The results confirmed that the rankings of toxicity for both *B. chinensis* and *C. dactylon* were similar to toxicity ranking of the extracts mentioned above.

3.2.2. Seedling growth test

The mixtures of different ratios of farm soil (OF) with the tailings resulted in changes of texture, decreases of pH, EC, and metal concentrations (data not presented here). In general, concentrations of total and extractable metals (Pb, Zn, Cd and Cu) in the mixtures were significantly reduced after mixing with 50% and above 50% farm soil in the tailings. The decrease of pH in the mixtures was due to acidic nature of the farm soil, whereas the decrease of EC and metal contents was due to dilution effects.

Plant growth data (Fig. 2) show that in the un-amended tailings, total dry weight yield of *B. chinensis* was the highest when grown in Site A tailings, followed by Sites B, TD, and HS tailings (Fig. 2). Fig. 2 also shows that total dry weight yield of *B. chinensis* was signifi-

cantly increased when grown in Site A tailings, mixed with 50% and above 50% farm soil. However, 50% farm soil did not significantly increase total dry weight yields of *B. chinensis* when grown in Sites B, TD and HS tailings. These results suggest tailings collected from Site A are less toxic than other tailings, which is similar to the results from the root elongation toxicity test.

Fig. 2. Dry weights (mg/plant) of *B. chinensis* seedlings grown in different tailings/soil substrata amended with agricultural soil (AS) for a period of 4 weeks (mean $\pm$ s.e., $n = 9$). (100: 100% tailings, 50: 50% tailings + 50% AS, 25: 25% tailings + 75% AS, 10: 10% tailings + 90% AS, 0: 100% AS, w/w). Different letters in the same figure indicate significant difference at $p < 0.05$ according to Tukey-HSD test. A: densely vegetated tailings, B: sparsely vegetated tailings, TD: tailings heap, M: mountain site, and HS: high-sulfur tailings.

Table 3

ECG₃₀ of tailings and soil extracts (%) on root elongation of *Brassica chinensis* and *Cynodon dactylon*

	<i>B. chinensis</i>			<i>C. dactylon</i>		
	Day 4	Day 7	Day 14	Day 4	Day 7	Day 14
A	28.7	24.7	19.9	NR	15.6	18.7
B	28.5	15.0	9.69	NR	18.5	16.2
TD	17.6	8.13	9.09	26.4	9.09	9.70
M	NR	NR	NR	NR	NR	NR
HS	9.68	6.25	6.88	8.13	7.50	6.56

A: densely vegetated tailings, B: sparsely vegetated tailings, TD: tailing heap, M: mountain site, HS: high-sulfur tailings, NR: no reduction.

3.3. Relationship between tailings properties, metal concentrations and growth responses

The results of total and DTPA-extractable metal contents in tailings, root elongation, ECG_{30} of root elongation and total dry weight yield of seedlings (Tables 2 and 3, Figs. 1 and 2) show that extractable Pb contents of the tailings appear to be related to the toxic effects of the tailings. The extractable Pb contents in the tailings are in the descending order: Site SH ($178 \mu\text{g g}^{-1}$ Pb) > Site TD ($112 \mu\text{g g}^{-1}$ Pb) > Site B ($85 \mu\text{g g}^{-1}$ Pb) > Site A ($59 \mu\text{g g}^{-1}$ Pb), while the results of root elongation, expressed as ECG_{30} , and dry weights yields of *B. chinensis* were in the opposite order. The results for Zn do not show such a clear relationship. It is commonly known that Pb does not play any essential role in plant metabolism and is toxic to plants. According to Ross (1994) the toxicity of metals in higher plants is $\text{Hg} > \text{Pb} > \text{Cu} > \text{Cd} > \text{Cr} > \text{Ni} > \text{Zn}$. Furthermore, concentrations of Pb in soil from 100–400 $\mu\text{g g}^{-1}$ were considered toxic by Kabata-Pendias and Pendias (1985). Zinc is an essential element for plant growth and its toxicity is less than Pb.

When the tailings were mixed with farm soil, the greater the proportions of farm soil in the mixture, the greater were the total plant dry weight yields. This could be due to a reduction in toxicity or improvement in nutrient availability or in soil physical properties. Amendment with soil can clearly ameliorate the phytotoxic properties of tailings.

4. Conclusions

The results of the present study suggest that constraints to plant growth on tailings from Pb/Zn mines can readily be quantified. At Lechang, high concentrations of Pb appear to restrict plant growth, characterized by the content of DTPA-extractable Pb. However, salinity may also be a problem, together with the lack of P and N. The silty and sandy texture of tailings and the lack of organic matter is also likely to restrict root growth and impose susceptibility to wind and water erosion. Amendment of soil can reduce the toxicity of tailings and could be used for reclamation practice. This investigation was, however, based on samples from five different sites. It now needs to be refined by work using a wider range of materials.

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