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ORIGINAL PAPER

Physico-chemical characteristics and heavy metal concentrations of copper mine wastes in Zambia: implications for pollution risk and restoration

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Abstract Soil characterization is a vital activity to develop appropriate and effective restoration protocols for mine wastelands while insights into the total content of heavy metals in the soil is an important step in estimating the hazards that the metals may pose to the vital roles of soil in the ecosystem. This study addressed the following research questions: (1) To what extent do the physico-chemical characteristics vary between mine waste sediments and the nearby forest soil? (2) Are the concentrations of heavy metals high enough to be considered as toxic? and (3) Are heavy metals present in mine waste sediments potential sources of pollution? We hypothesized that the physico-chemical characteristics of mine waste sediments are less favorably for plant establishment and growth while the concentrations of heavy metals are very high, thus restricting the success of revegetation of mine waste lands. Mine waste sediments were sampled following a diagonal transect across tailings dams, overburden dump sites and the local forest soil from the top layer (0–20 cm) using a closed auger. Samples were analyzed for arsenic, barium, lead, cadmium, cobalt, copper, chromium, nickel, vanadium, and zinc as well as for soil physico-chemical properties. The mine waste sediments were dominated by silt whilst the forest soil by sand particles, with significantly high bulk density in the former. Both the forest soil and overburden sediments were acidic than the alkaline tailings dam sediment. Total organic carbon and nitrogen contents were significantly low in mine wasteland substrates but the concentration of Ca and Mg were significantly higher in tailings dam substrate than the forest soil. The concentrations of available P, K and Na were similar across sites. The mean concentrations of heavy metals were significantly ($p < 0.01$) higher in mine waste sediments than the forest soil; except for cadmium ($p = 0.213$). The order of contamination by heavy metals on the tailings was Cu > Co > Ba > Ni > As > Zn > Pb > Cr > V > Cd, and that on the overburdens was Cu > Co > Ba > Ni > Zn > Cr > Pb > V > As > Cd. The pollution load index (PLI) was nearly twice higher for the tailings dam (8.97) than the overburden (5.84). The findings show that the copper mine wastes (the tailings dams and overburden waste rock sites) are highly contaminated by heavy metals; which, in turn, might pose serious hazards to human health and agricultural productivity. In addition, poor macro-nutrient availability, substrate compaction and soil acidity (particularly on overburden sites) coupled with toxic level of heavy metals would be the main challenges for successful phytostabilization of copper mine wastelands.

Keywords Contamination factors · Overburden material · Phytostabilization · Pollution load index · Tailings dam

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Introduction

There is a global concern regarding the high input and flow of heavy metals and metalloids in the biosphere; elements which on a global perspective should normally be present in very low concentrations (Monterroso et al. 2014). While heavy metals are present in the environment naturally, anthropogenic activities, such as mining, tend to increase their occurrence to toxic levels. Mining and processing of metal ores, such as copper, can be a significant source of environmental pollution; thereby affecting environmental quality and ecosystem services (Zhuang et al. 2009). In addition, mining causes extensive environmental destruction in the form of alteration of landscape, deterioration of vast land areas, extinction of wildlife and clearance of vegetation (Lima et al. 2016; Ezeaku and Davidson 2008).

Heavy metals are elements that exhibit metallic properties and include the transition metals, the lanthanides, actinides and some metalloids (Gautam et al. 2011). Although some heavy metals, such as iron, boron, manganese, zinc, copper and molybdenum, are micronutrients essential for plant growth, high concentrations of all heavy metals are toxic and are regarded as pollutants (Chehregani et al. 2004). Soils heavily contaminated by heavy metals, such as Cu, Pb, Zn and Ni, restrict plant growth, cause leaf chlorosis and alteration of the activity of many key enzymes of various metabolic pathways. Contaminated soils also adversely affect the number, diversity and activity of soil organisms, inhibiting soil organic matter decomposition and N-mineralization processes (Wong 2003; Gowda et al. 2010).

The waste materials from the abandoned mine or from decommissioned waste sites, when exposed to processes of weathering over time, may lead to development of a soil type referred to as mine soil (Sencindiver and Ammons 2000) which is generally a young soil. The presence of heavy metals in these metalliferous soils in very high concentrations negatively affects the quality of soil and destroys their functional ecosystems (Zhang and Ke 2004); leaving these wastelands devoid of vegetation for extended periods of time. Furthermore, mine wastelands have generally poor water holding capacity, low organic matter content, nutrient deficiency and low microbial activity (O'Dell et al. 2007). Thus, mine waste materials, such as tailings dam and overburdens, are one of the main environmental problems in post-mining landscapes. In the absence of adequate closure management, metalliferous mine tailings and overburden materials pose serious hazards to human health and agricultural productivity through surface or groundwater pollution, offsite contamination via aeolian dispersion and water erosion, and uptake by vegetation and bioaccumulation in food chains (Tutu et al. 2008; Kuter 2013).

Currently, large amounts of mine wastes are of serious environmental concern in Zambia, where there are about 791 million tons of tailings covering 9125 ha of land and 1899 million tons of overburden materials covering 20,646 ha, as well as an estimated 77 million tons of waste rock covering 388 ha and 40 million tons of slag covering 279 ha of land (Sikaundi 2013). Despite the occurrence of huge mine generated wastelands in Southern-Central Africa (Venkateswarlu et al. 2016), little information is available, particularly in Zambia, regarding the physico-chemical characteristics as well as the distribution and concentration of heavy metals across these wastelands. Previous studies have mainly focused on heavy metal accumulation and its biological impact (Yabe et al. 2011, 2012; M'kandawire et al. 2012; Kapungwe 2013; Nakayama et al. 2013) and heavy metal accumulation in soils and sediments (Ikenaka et al. 2010).

The objectives of this study were to quantify the heavy metal contamination and pollution load in different mine waste sediments and to characterize their physical and chemical properties. The research questions addressed were: (1) To what extent do the physico-chemical characteristics vary between mine waste sediments and the nearby forest soil?, (2) Are the concentrations of heavy metals high enough to be considered as toxic?, and (3) Are heavy metals present in mine waste sediments potential sources of pollution? We hypothesized that the physico-chemical characteristics of mine waste sediments are less favorably for plant establishment and growth while the concentrations of heavy metals are very high, thus restricting the success of revegetation of mine waste lands. The results from this study will allow identifying factors that limit restoration of post-mining landscape using phytostabilization method, which involves the use of plant species and soil amendment measures to immobilize heavy metals through absorption and accumulation by roots, adsorption onto roots, or precipitation within the rhizosphere (Mendez and Maier 2008; Bolan et al. 2011).

Materials and methods

Study area

The study was undertaken on Copper Mine wastelands in Chingola District, Zambia (Fig. 1). The study site is located between longitude and latitude 12°32′ South and 27° 51′ East and one of the oldest copper mining towns of Zambia. The area receives an average of 1000 mm of rainfall annually (Environmental Council of Zambia 2000) and has three distinct season; rainy season (November–

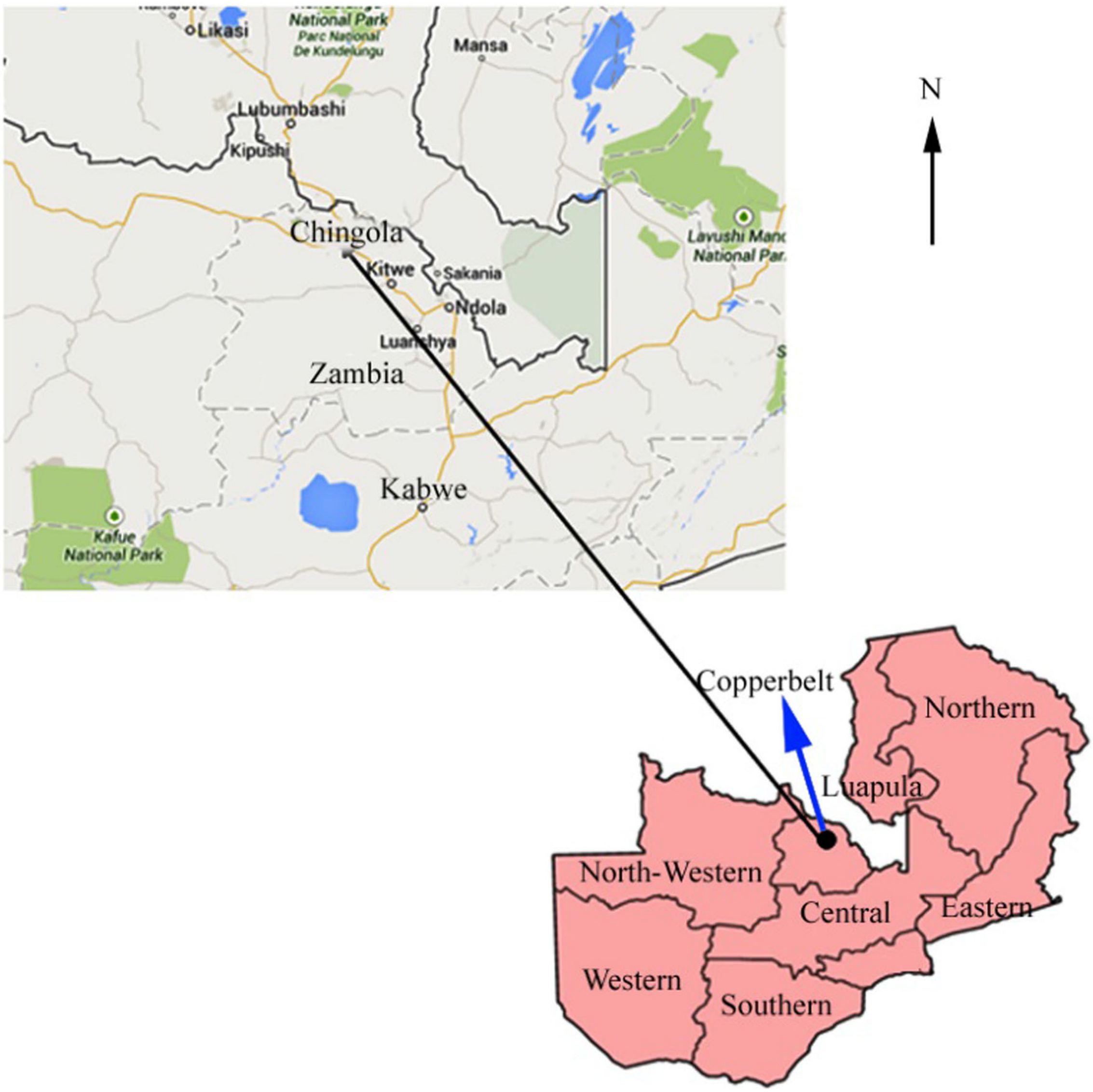

Fig. 1 Map of the study area

April), cool dry season (May–August) and the hot dry season (August–November). Due to the country's elevation, the area usually experiences a subtropical climate with mean monthly temperatures ranging from 15.8 to 15.9 °C in June and July (the coldest months) to 26.3 °C in October which is the hottest month (Environmental Council of Zambia 2000).

The underlying geology of the area is the mineralized Katanga system and the undifferentiated basement complex of mainly granites, granitic gneisses and migmatites (Environmental Council of Zambia 2000). The soils are of two distinctly different types. In the western part of the area, soils are chromic haplic Ferrasols (according to FAO classification system) which are well drained, deep to very deep yellowish red to strong brown, friable-clayey soils with a high silt/clay ratio and fairly uniform texture throughout. In the eastern part, the chromic haplic Acrisols are the dominant form, which are well drained, deep to very deep yellowish red to strong brown friable loamy to clayey soils having a clear clay increase with depth (Government of the Republic of Zambia 1991). The natural vegetation is pre-dominantly miombo woodland dominated by the genera *Brachystegia, Julbernadia* and *Isoberlina* (Syampungani et al. 2011).

Substrate sampling and analyses

Sampling was performed by following a diagonal transect across selected wastelands (tailings dam and overburden dump sites), and the local forest (control) that was in close proximity to the studied wastelands. A tailings dam is typically an earth-fill embankment dam used to store byproducts of mining operations after separating the ore from the gangue while overburden materials include the soil and rock, which are removed in order to gain access to the ore deposits. The wastelands were randomly selected from among the various sites. At every 100 m interval, five soil samples within 20 m radius were randomly collected from the top layer (0–20 cm) using a closed auger, then thoroughly mixed in a bucket to make a composite sample. A total of 12 composite samples were collected from each mine wasteland type, while six samples were collected from the local forest. At every sampling point, 2 kg of composite sample was collected and stored in a polythene bag. Samples were air dried for 48 h in the laboratory and sieved through 2-mm sieve for analysis after grinding them with a wooden mortar. The sediments were extracted by acid digestion (Sposito 1989) and further analyzed for arsenic (As), barium (Ba), lead (Pd), cadmium (Cd), cobalt (Co), copper (Cu), chromium (Cr), nickel (Ni), vanadium (V) and zinc (Zn) using inductively coupled plasma-atomic emission spectrometry (ICP-AES) in a commercial soil lab (Eurofins Environment Sweden AB).

The particle size distribution was determined by the Robinson pipette method (Sheldrick and Wang 1993) while bulk density was determined using volumetric cylinders (5-cm diameter core rings) from the top soil (0–20 cm depth). Total organic carbon content was determined according to the Walkley and Black method (Nelson and Sommers 1982), total N content was measured following the Kjeldahl method (Bremner 1996) and available phosphorus was determined by Bray 1 method (Bray and Kurtz 1945). Exchangeable cations were extracted with 1 N ammonium acetate at pH of 7. Calcium and magnesium were determined by atomic-absorption spectrophotometry, sodium and potassium by flame-emission spectrophotometry. Soil pH was measured with combined electrodes in a 1:2.5 soil/water suspension. Percentage base saturation (PBS) was calculated as a ratio of the sum of the charge equivalents of the base cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) to the CEC of the soil.

Data analysis

To examine differences in concentrations of heavy metals and physico-chemical characteristics of substrates collected from the tailings dam, overburden dump and the natural forest sites, One-way ANOVA was performed. The mean concentrations of the heavy metals that exhibited significant difference between sites were compared using Tamhane's T2 for unequal variance ($p < 0.05$). Indices were also applied to assess the heavy metal sediment contamination. To assess the extent of contamination of the tailings and overburden sites by heavy metals, contaminant factor (C_f^i) and the degree of contamination (C_d) were computed following Hakanson (1980) as Eqs. 2 and 3:

$$C_f^i = \frac{C_{0-1}^i}{C_n^i} \tag{1}$$

$$C_d = \Sigma_{i=1}^n C_f^i \tag{2}$$

C_{0-1}^i is the mean concentration of each metal in the substrate; C_n^i is the concentration of the metal in unpolluted soil which is the baseline or background value. In our case the arithmetic mean values from the nearby natural forests were used as baseline. These indices were interpreted following Seshan et al. (2010) as follows: (1) low degree of contamination if $C_f^i < 1$ and $C_d < 7$, (2) moderate degree of contamination if $1 < C_f^i < 3$ and $7 < C_d < 14$, (3) considerable degree of contamination if $3 < C_f^i < 6$ and $14 < C_d < 28$, and (4) very high degree of contamination if $C_f^i > 6$ and $C_d > 28$.

The extent of heavy metal pollution from mining wastes were also evaluated using pollution load index (PLI), which was defined as the geometric mean of the concentration factors for the *n* metals (Tomlinson et al. 1980). The PLI was calculated using Eq. 3:

$$PLI = \sqrt[n]{CF_1 \times CF_2 \times CF_3 \times \cdots CF_n} \tag{3}$$

CF is the concentration factor, calculated as a ratio of the concentrations of the various heavy metals in wastelands to that of the natural forest and *n* is the number of heavy metals. These indices have been employed in several studies to assess pollution levels in sediments (Seshan et al. 2010) and sewage irrigation (Liu et al. 2005).

Results

Physico-chemical characteristics

The textural fractions varied significantly ($p < 0.05$) among sites (Fig. 2), where the silt fraction was higher in the overburdens and the tailing dam substrates (above 50% in both cases) than in the local forest soil (below 20%). The sand fraction was higher in the local forest (above 50%) than in both the tailings dams and the overburden sites (below 40%). In all the sites, the clay content was below 40%, but still significantly higher in the local forest soil than in mine wasteland substrates. The bulk density also varied significantly ($p < 0.05$) among sites (Table 1). The local forest soil had minimal compaction with a narrow range of bulk density (1.13–1.35 g cm^{-3}) compared to the overburdens, which had wider range (1.26–1.82 g cm^{-3}). The bulk density of the tailing was still higher than the

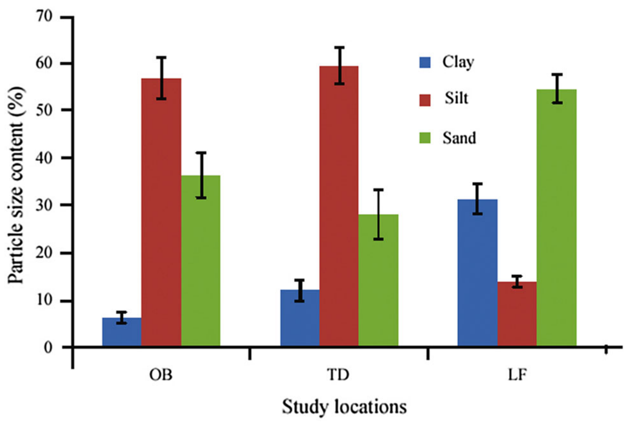

Fig. 2 Textural fractions (%) in local forest soil (LF), tailings (TD) and overburden (OB) substrates (mean ± SE)

forest soil but remained statistically similar to that of the overburdens.

The pH of mine wasteland substrates significantly differed from each other and the local forest soil (Table 1). Both the local forest soil and overburden substrate were more acidic than the tailings dam substrate, which was alkaline. The total organic carbon and nitrogen contents of the local forest soil were significantly higher than that of the mine wastelands whereas the available P content remained the same across the sites (Table 1). With regard to exchangeable cations, significant differences among sites were not detected for monovalent cations (K and Na), but divalent cations (Ca and Mg) were significantly higher in tailings substrate than overburden substrate and the local forest soil (Table 1). Even the overburden substrate had significantly higher Ca and Mg contents than the local forest soil. The base saturation exhibited similar increasing trend as divalent cations from the local forest soil to tailings substrate.

Heavy metal concentrations

The mean concentration of heavy metals differed significantly ($p < 0.01$) among sites except Cd ($p = 0.213$). In comparison to the local forest soil which was being used as baseline or reference samples, the mine soils had elevated levels of potentially toxic heavy metals (Fig. 3). However, the concentrations varied greatly depending on the mine wasteland. The substrates from the tailings dam contained the highest concentrations of As, Pb, Co and Cu compared with substrates from overburden materials and adjacent forest soil. Substrates from overburden material had the highest concentrations of Ba, Cr and V compared with substrates from tailings dam and forest soils. The concentrations of Ni and Zn did not differ between tailings dam and overburden materials, but were significantly higher than the adjacent forest soils. Among the heavy metals analyzed in the present study, the concentration of Cu was the highest in the mine wasteland (12233.3 ± 1746.9 mg kg^{-1} for tailings dam; and 7411.7 ± 1317.5 mg kg^{-1} for the overburden) while the concentration of Cd was the lowest (0.60 ± 0.25 mg kg^{-1} for tailings dam; 0.25 ± 0.13 mg kg^{-1} for overburden); and the later did not differ significantly from the forest soil (0.78 ± 0.13 mg kg^{-1}).

Degree of contamination and pollution

The degree of contamination by each heavy metal was analyzed for tailings dam and overburden; and the results showed a very high degree of contamination of the tailings dam by all heavy metals except cadmium, chromium and vanadium, which had low to moderate degree of contamination (Table 2). For the overburden, the degree of contamination was low for cadmium, moderate for arsenic, lead, chromium, and vanadium and very high for barium, cobalt, copper, nickel and zinc (Table 2). The overall degree of contamination was nearly twice higher for the tailings dam than the overburden materials. Similarly, the pollution load index was 1.5 times higher for the tailings dam than the overburden materials (Table 2).

Discussion

Soil compaction, poor macro-nutrient availability and soil acidity (particularly on overburden sites) are typical features of mine wasteland sediments. With regard to particle size distribution, the mine wasteland substrates are mainly composed of silt and sand particles with very little clay while the local forest soil has more sand and clay (Fig. 2). The high silt and sand contents on the mine wastes imply the substrates have low aggregates and nutrient binding capacity (Brady and Weil 1996), and their capacity to retain water is low. In comparison, the local forest soil has more sand and clay than silt. The high rainfall that the area receivess every year may have leached the clay particles. The textural compositions of the soil have an effect on the ability of the soil to retain the nutrients. Generally, finer soils/sediments that have more clay or silt have high retention ability than coarse soils/sediments (Witheetrirong et al. 2011). This could explain why the total organic carbon and nitrogen contents of tailings and overburden substrates are slightly lower than the local forest soil, which has more clay texture in addition to the vegetation that boosts these nutrients through litter fall. The bulk density of tailings substrate and local forest soil is within the normal range of 1.1–1.6 g cm^{-3} (Aubertin and Kardos 1965) compared with the overburden substrate with wider

Table 1 Physico-chemical characteristics of forest soil and mine wasteland substrates (mean ± SE)

Properties	Bulk density (g cm^{-3})	pH (H_2O)	Total organic carbon (%)	Total nitrogen (%)	Available phosphorus (mg kg^{-1})	Potassium (mg kg^{-1})	Sodium (mg kg^{-1})	Magnesium (mg kg^{-1})	Calcium (mg kg^{-1})	Base saturation (%)
Local forest	1.24 ± 0.06a	5.05 ± 0.09a	2.24 ± 0.16a	0.07 ± 0.01a	4.9 ± 0.0a	37.8 ± 2.6a	49.0 ± 0.00a	81.2 ± 17.8a	99.0 ± 0.00a	7.13 ± 1.59a
Overburden	1.44 ± 0.13b	5.63 ± 0.11b	1.17 ± 0.16b	0.05 ± 0.0b	4.9 ± 2.7a	37 ± 5.2a	49.0 ± 26.8a	103.5 ± 20.4b	142.2 ± 21.9b	35.37 ± 4.15b
Tailings dam	1.49 ± 0.03b	8.04 ± 0.06c	1.41 ± 0.21c	0.05 ± 0.0b	4.9 ± 2.7a	35.4 ± 5.4a	49.0 ± 26.8a	788.3 ± 195.8c	3431.7 ± 855.9c	80.0 ± 0.00c

Means followed by different letter across the row are significantly different ($p < 0.05$)

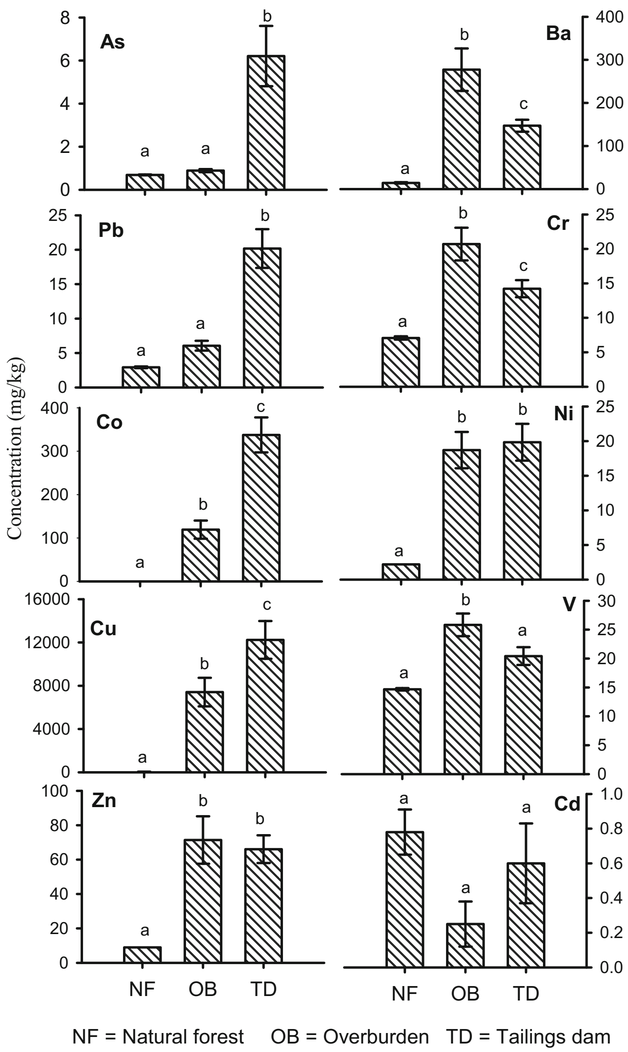

Fig. 3 Concentrations of heavy metals in local forest soil and mine waste sediments (mean ± SE). Bars with different letter are significantly different ($p < 0.05$)

range (Table 1). The high bulk density may most likely have been influenced by the use of machinery during deposition of waste, and also due to the fact that mine soils are young soils that are made up of undifferentiated material. The compacted overburden substrate would be a challenge for establishment and growth of plants as it restricts root penetration especially for deep rooted plants (Thompson and Jansen 1987).

The mine wasteland substrates had low pH, particularly for the overburden (Table 1), which is a characteristic of most sulphide ore mine soils (Wong et al. 1999). The high pH value for the tailings dam compared with the overburden was due to the addition of lime into the effluent prior to discharging by the mining company in an effort to reduce soil acidity and encourage colonization of autochthonous species. Soil pH plays a crucial role in influencing other soil processes; e.g. those connected with nutrient availability and the mobility of potentially toxic elements such as heavy metals (Bussinow et al. 2012). Under acidic conditions, heavy metals easily dissolve to form toxic concentrations, which may hinder plant growth (Donahue et al. 1990; Das and Maiti 2005). The low pH and high rainfall in the area can offer a favorable environment for the heavy metals to easily dissolve; thus making them to occur at high concentrations in the mine waste substrates (Ciftci et al. 2005). The availability of macro-nutrient also varied between the local forest soil and mine wasteland substrates. The potassium and sodium contents were low across all studied sites whilst the calcium and magnesium contents were considerably higher in mine waste substrates than in the forest soil. One possible explanation for this would be the fact that the Zambian soils are generally of low potassium content (Mashuta et al. 2010). The other would be the possibility that monovalent cations (K and Na) might have leached from the system substantially while the divalent cations (Ca and Mg) are strongly adsorbed to soil particles at increasing soil moisture content during the rainy season. Furthermore, the addition of lime into the effluent by the mining company would attribute to high content of Ca in mine waste substrates.

The Copperbelt Province of Zambia is generally rich in copper and therefore the soils are generally expected to have high concentration of copper. The results show the occurrence of high concentrations of heavy metals in mine wasteland substrates compared to the local forest soil (Fig. 3). High concentrations of heavy metals in mining generated wasteland soils have been observed in many parts of the world; e.g. Iran (Khorasanipour et al. 2011; Ghaderian and Ravandi 2013), China (Li et al. 2007), Hong Kong (Wong 2003) and France (Remon et al. 2005). This is typical of most mine wasteland sediments and areas rich in minerals (Khorasanipour et al. 2011). According to Adriano (2001), an average global value for total Cu in uncontaminated soils is about 30 μg g^{-1}, while for Zn 80–120 μg g^{-1}. Similarly, the global baseline for other metals in uncontaminated soils is 20 μg g^{-1} for Pb (Kabata-Pendias and Pendias 1992), 100 μg g^{-1} for Ni (Ross 1994), 2–50 mg g^{-1} for Cr (Addo et al. 2012) and 0.01 mg kg^{-1} for Cd (World Health Organization 2006). Thus, all the heavy metals in the studied mine wasteland can be considered as contamination, except for cadmium, which is generally believed to occur in low concentrations in nature (Wild 1993; James and Brown 2009). It has been shown that heavy metal pollution in either soils or sediments is strongly associated with geological differences (Ikenaka et al. 2010).

In the present study, the concentration of Cu was substantially higher in the mine wasteland substrates than in the forest soil (Fig. 3). And in comparison to other areas,

Table 2 Contaminant factor, overall degree of contamination and pollution load index for different heavy metals on tailings dam and overburden sites

Metals	Contamination factor		Contamination degree (in tailings/overburden)
	Tailings dam	Overburden	
Arsenic	8.95	1.28	Very high/moderate
Barium	10.26	19.34	Very high/very high
Lead	6.88	2.07	Very high/moderate
Cadmium	0.77	0.32	Low/low
Cobalt	153.41	54.2	Very high/very high
Copper	242.24	146.76	Very high/very high
Chromium	2.01	2.93	Moderate/moderate
Nickel	9.02	8.5	Very high/very high
Vanadium	1.39	1.76	Moderate/moderate
Zinc	7.34	7.93	Very high/very high
Overall degree of contamination	442.3	245.1	
Pollution load index	8.97	5.84	

Note that the concentrations of heavy metals in the forest soil are baseline value for computing contamination factor

the concentration of Cu in the mine wastelands is slightly higher than values reported from the Monarch south tailings in Botswana with copper concentration ranging from 865 to 2125 mg kg^{-1} (Vogel and Kasper 2002), soils around an abandoned mine site in south west Spain with 2874 mg kg^{-1} Cu (Fernández-Cadena et al. 2014), in an abandoned Cu mine site in northeastern Brazil with concentration ranging from 3601 to 9601 mg kg^{-1} in the bulk soils (Perlatti et al. 2015). The high Cu concentration in the present study may be attributed to the mineralogy of the studied sites and the processing efficiency. The current mining technology used in Zambia allows for extraction of copper to maximum of 40% from the ore materials. Furthermore, processing of ore concentration in the past was only applicable to copper sulphide although copper ore is a mixture of copper sulphide and copper oxide (pers.com, Environmental coordinator for Konkola Copper Mines). Thus, copper oxide was being lost to the tailings and therefore became part of the heavy metals in the tailings. This also applies to other non-target metals (iron, manganese, lead etc.) that could be present in the ore and disposed as waste to the tailings dams.

The concentrations of heavy metals also show great variations among sites, for example the mean concentration of copper was 12 237.3 $\pm$ 1746.9 mg kg^{-1} on the tailing, 7411.7 $\pm$ 1317.5 mg kg^{-1} on the overburden and 50.5 $\pm$ 3.8 mg kg^{-1} on the local forests. For lead, the concentration was 20.2 $\pm$ 2.8 mg kg^{-1}, 6.1 $\pm$ 0.7 mg kg^{-1} and 2.9 $\pm$ 0.1 mg kg^{-1} on the tailing, overburden and forest soil, respectively. These concentrations on the studied mine waste substrates are several times higher than in the local forest. This scenario is common for all the heavy metals studied except cadmium. The differences may be attributed to the fact that tailings and waste rock are processed differently, while soils in the local forest are undisturbed. Our findings in terms of heavy metal concentrations are within the levels reported by other scientists (Kříbek et al. 2010; Ettler et al. 2012; Sracek 2015).

The total concentrations of the studied heavy metals provide insight to the extent of their contamination and pollution levels. To highlight the degree and extent of contamination, single and integrated indices were used. The indices used in this study showed that the tailing and overburden substrates are highly polluted with pollution load index of 8.97 and 5.84, respectively (Table 2). While the contaminant factors for all metals with an exception of Cd indicated moderate to very high contamination degree for both the tailings and the overburdens (Table 2). The overall contamination of the sites studied based on the contamination factor indicates a difference in the contamination levels for some metals (Table 2). The contamination on the tailing follows the order from the highest to the lowest; $Cu > Co > Ba > Ni > As > Zn > Pb > Cr > V > Cd$; whereas the contamination of heavy metals on the overburdens from the highest to the lowest follows the order; $Cu > Co > Ba > Ni > Zn > Cr > Pb > V > As > Cd$. Arsenic and Lead show high contamination on the substrates of the tailings dams and moderate contamination on the overburden materials. In studies done elsewhere, similar indices have been used in the assessment of heavy metal contamination of either soil or water (Nikolaidis et al. 2010; Nweke and UKpai 2016). As a whole the pollution load index exceeds 1 by a great margin on both the tailings dams and the overburden materials, which is an indication of the loss of the quality of young developing soil (Seshan et al. 2010). Thus, metalliferous mine tailings and overburden materials restrict growth for all but the most metal-tolerant plants (Wong 2003); leaving mine wastelands devoid of vegetation for extended period of time.

Conclusion and implications

Insights into the total content of heavy metals in the soil is an important step in estimating the hazards that the metals may pose to the vital roles of soil in the ecosystem and also in comparison with the quality of set standards. The findings from the present study reveal that the copper mine wastes (the tailings dams and overburden waste rock sites) are highly contaminated by heavy metals. This, in turn, might pose serious hazards to human health and agricultural productivity through surface or groundwater pollution, offsite contamination via aeolian dispersion and water erosion, and uptake by vegetation and bioaccumulation in food chains. For instance, a study made to discriminate between lithogenic and anthropogenic sources of metals and sulphur in soils of central and northern Zambia (Kříbek et al. 2010) reported very high concentrations of heavy metals in dust samples from areas surrounding mining operations including slag and tailing deposits. The high level of heavy metal pollution calls for immediate attention, such as metal attenuation measures, to reduce contamination of the surrounding environment and the health risk to which the nearby community will be exposed.

Soil characterization is a vital activity to develop appropriate and effective restoration protocols for mine wastelands. Developing re-vegetation protocols based on information obtained from ecosystem characterization of the sites earmarked for restoration can make the effort successful. In the present study, soil compaction, poor macro-nutrient availability and soil acidity (particularly on overburden sites) coupled with toxic level of heavy metals would be the main challenges for successful phytostabilization of copper mine wastelands. Thus, site amendment measures, such soil scarification, application of biochar and manure, should be considered to modify the mobility and uptake of heavy metals and to enhance growth performance of species prior to planting on these sites. Emerging evidence showed that addition of biochar and biosolid to soils contaminated by heavy metal is effective in immobilization of the metals (Ahmad et al. 2017) and ameliorate the nitrogen and phosphorus deficiencies of mine spoil to support better survival and growth of reintroduced native species (Nussbaumer et al. 2016). As a whole, the knowledge gained from this study provides a baseline for developing environmental guidelines, suggestions for concomitantly modifying the mobility and uptake of heavy metals from copper mine wastelands and ensure the success of phytostabilization efforts.

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