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ORIGINAL PAPER

Using plants to manage uncontrolled dumpsites: metal phytoremediation by endemic species from subtropical sites

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Abstract
The present research studied the potential of using plant species adapted to areas affected by Municipal Solid Waste disposal to phytoextract or phytostabilize heavy metals. The study area was an old unlined landfill that is regarded as contaminated by heavy metals, organic matter, and salts. Firstly, soil contamination around the waste deposit was assessed, secondly, the ability of local plants to extract metals from the soil was evaluated and thirdly, a greenhouse pot experiment was conducted using *Vetiveria zizanioides* (vetiver) planted in different soil samples collected from the study area. Heavy metal concentrations were below the Brazilian Screening Level in all soil samples but were generally higher at sites directly affected by the waste disposal, especially for Ba, Cu, Fe, Pb, and Zn. *Psidium guajava* (guava tree) and *Pennisetum purpureum* (elephant grass) growing naturally over the landfill surface presented potential applications for phytoextracting Ba, Pb, and Zn. Regarding the pot experiment with vetiver, it was observed that the plants could adapt to all the different treatments, showing their environmental adaptability. Metals were found to accumulate mainly in root tissues, indicating the potential for phytostabilization. Relevant bioaccumulation and translocation factors were found, respectively, for Ba, Cu, and Zn, and Ba, Cr, and Zn. The study concluded that guava tree, elephant grass, and vetiver can contribute to mitigating impacts of waste disposal sites and are able to thrive in such environments under a subtropical climate, phytoextract and/or phytostabilize Ba, Cu, Pb, and Zn, and thus, avoid leaching to the surroundings.

Keywords Municipal solid waste · *Pennisetum purpureum* · Potentially toxic metals · *Psidium guajava* · *Vetiveria zizanioides*

Introduction

Although inadequate solid waste disposal causes soil, air and water contamination and poses a risk to public health (Bjerg Et Al. 2013; Morita et al. 2021), it is still commonly used in developing countries (D-WASTE 2013; Lavagnolo 2019). Moreover, when these areas are closed, they are constantly abandoned, without adopting remediation and mitigation techniques, which causes impacts to persist (Morita et al. 2020a; Zolnikov et al. 2018).

In this regard, it is important to study and urge the adoption of low-cost remediation techniques, which are adapted to socioeconomic contexts found in developing countries and can be used for mitigating the impacts of waste disposal sites. Phytoremediation is a promising technology for such applications due to the low costs involved, easiness of implementation, public acceptance, the possibility of in situ implementation, and non-invasiveness, avoiding the need for digging up and removing the contaminated soil (Pandey and Bajpai 2019).

Additionally, it is especially effective in areas with lower and more distributed contaminant concentrations (Marmiroli and Mccutcheon 2003), which is commonly the case of old dumpsites and unlined landfills receiving mainly domestic waste (Morita et al. 2020a; Ehrig and Stegmann 2018). Phytoremediation can be used to control erosion processes, promote ecological restoration, produce biomass and energy,

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and negotiate carbon credits (Oliveira et al. 2009; Pandey and Souza-Alonso 2019), which are necessary or beneficial for such areas.

When used in waste disposal sites, Morita and Netto (2022) classified phytoremediation techniques into four categories, depending on the site of application and the processes involved: (a) use of phreatophytes around dumpsites and landfills to promote a (phyto)hydraulic barrier; (b) use of aquatic species in drainage or leachate puddles commonly formed around dumpsites, contributing to leachate treatment; (c) use of phytoaccumulation species over landfills and at soil-contaminated sites; (d) adoption of alternative/vegetative covers that can enhance evapotranspiration, and thus prevent the formation of leachate (phytocapping).

Considering this, *Populus spp, Salix spp,* and *Eucalyptus spp* have been reported as phreatophytes with the potential application to promote (phyto)hydraulic containment, enabling the remediation of organic contaminants (McCutcheon et al. 2003) and nitrate (Luiz and Hirata 2018); *Typha latifolia* and *Phragmites australis* are constantly used to design constructed wetlands all around the world (Bakhshoodeh et al. 2020) and could be adopted in drainage commonly formed around uncontrolled dumpsites; finally, several species have potential applications as they are planted over landfills, either to phytoacumulate/phytostabilize metals (*Brassica juncea, Thlaspi spp,* and *Vetiveria zizanioides*) or to enhance evapotranspiration and avoid leachate formation (*Eucalyptus spp, Alphitonia excelsa, Hibiscus tiliaceus*, etc.) (Nagendran et al. 2006; Pandey et al. 2019; Salt et al. 2018). In all cases, it is important to select species adapted to the local conditions, which include climatic adaptation and tolerance to contaminants. Additionally, the selected plants must be able to extract metals so that the remediated soils reach concentrations that are below Screening Levels (S.L.); these standards vary considerably for different countries (see Table 1_{SM} of the *Supplementary Material*).

From those mentioned applications, it is interesting to note that some species can be planted over landfills and function both as alternative covers and as phytoaccumulators, having promising applications in the control and mitigation of impacts. In this regard, grasses are prospective candidates due to their high biomass yields, fast growth, adaptation to infertile soils, suitability for the phytoextraction of mildly polluted soils or phytostabilization of soils with low-to-moderate concentrations of trace elements (Rabelo et al. 2021). Additionally, such high biomass production also makes them promising for bioenergy production (Jha et al. 2017), having potential applications as non-food energy crops over landfills (Shah et al. 2023).

The *Vetiveria zizanioides* (or *Chrysopogon zizanioides,* commonly named vetiver) grass has recently gained attention due to its high tolerance to As, Cd, Cu, Pb, Hg, Ni, Se, and Zn, having accumulated over 10,000 mg Zn/kg dry root and 10,000 mg Pb/kg dry root, and survived in soils of up to 959 mg As/kg and pH values ranging from 3 to 11 (Pandey et al. 2019; Suelee et al. 2017). Additionally, it has a powerful radicular system and is able to penetrate around 2 m deep in 6 months, or about 3 cm per day, and produce about 100 thousand tons of biomass per hectare (Pandey et al. 2019; Suelee et al. 2017). Moreover, it has a wide geographical distribution and enables an economic return (Pandey and Praveen 2020).

Pennisetum purpureum (elephant grass) also demonstrated applicability in phytoremediation projects, having accumulated Cu (~6.91 mg/kg), Zn (85.13 mg/kg), and Mn (207.35 mg/kg) in its leaves (de Oliveira Mesquita et al. 2021) and presented more tolerance to Cu than vetiver, when exposed to MSW leachate (Hassan et al. 2020). Additionally, it was able to phytoremediate Cd and produce bioenergy (Zhang et al. 2014) and remove excess soil P (Silveira et al 2013).

Finally, some woody species are widely distributed geographically and might also bring an economical return while working as phytoremediators of waste disposal sites; this is the case of *Psidium guajava* (guava tree). Bandyopadhyay and Maiti (2022) observed its ability to phytostabilize Cu and Ni when planted over an industrial waste dump blanketed with forest soil. Maiti et al. (2015) observed Bioconcentration Factors (BF) > 1 for Fe, Mn, Zn, Cu, Ni, and Cd when such species grew on a reclaimed coal mine overburdened dump. Nevertheless, the application of edible fruit species in phytoremediation projects must be carefully monitored to minimize the accumulation of metals (Maiti et al. 2015) and avoid health risks.

Although there are several studies evaluating the phytoremediation capability of plant species, there is still a lack of research assessing their adoption, adaptation and extraction ability when planted on Municipal Solid Waste (MSW) disposal sites, especially the uncontrolled ones, enabling the mitigation of impacts and the prospect of an economical return. This work aimed to evaluate the feasibility of using plants adapted to subtropical climates and to MSW uncontrolled disposal sites to mitigate heavy metal contamination, enabling their application as alternative covers and avoiding contaminant leaching. The study was conducted in an uncontrolled disposal site in Sao Paulo state, Brazil in 2019. It is expected that plant species, especially grasses, can be effective tools to control and mitigate the impacts generated by dumpsites receiving Municipal Solid Waste (MSW), commonly located in developing countries.

Materials and methods

Study area and considered cases for study

The study area is an old dump (Santa Madalena) located in the municipality of São Carlos, São Paulo State, Brazil

(Fig. 1), in an outcrop zone of the Guarani Aquifer, comprising sandstone from the Botucatu formation (PMSC 2011). The local climatic conditions are classified as a humid subtropical climate (Cfa by Koppen and Geiger) with an annual precipitation of about 1440 mm and an average temperature of 19.7 °C.

Household, industrial, and health service waste, as well as construction and demolition debris, were thrown into a gully without implementing pollution mitigation measures, from 1980 to 1996. Approximately 440,000 m^3 of waste was disposed of in an area of approximately 74,000 m^2. After ceasing the disposal activities (1996), the waste was covered with a soil layer and the site was abandoned.

Several studies were conducted in the area, showing that the waste cannot be considered inert yet (Pelinson et al. 2020) and that the generated pollution is spreading (Morita et al. 2020b) and has persisted over time (Morita et al. 2020a). Thus, the São Paulo Environmental Protection Agency (CETESB) included the site in the list of contaminated areas in the state of São Paulo (CETESB 2020) and the contamination was associated with potentially toxic metals (As, Ba, Co, Pb, and Se above Brazilian Screening Levels in groundwater samples) (PMSC 2011). Organic matter (values of Chemical Oxygen Demand [COD] of up to 90 mg/L in groundwater samples) and salts (Electrical Conductivity of until ~ 600 µS/cm in affected groundwater samples, in which ~ 50µS/cm was a common background value for the area) have also been regarded as relevant pollutants (Morita et al. 2020a).

Soil collection and analysis

Soil samples were collected in four areas, depicted in Fig. 1, which were selected as a function of their level of contamination. Thus, 'M' was considered an upstream area, supposedly not affected by the dump, and characterized by its sandy soils; 'L' is a location over the waste dump, where a mixture of cover soil and waste can be found, and where more contaminants are expected to be identified; 'T' is a flooded area downstream of the dump, visually influenced by leachate flow; and 'G' is a downstream area, whose soils are apparently not affected by leachate and where guava plantation is carried out.

At each of the four selected areas, triplicate samples (~ 1.0 kg each) were collected at about 30 cm deep, using shovels and hoes, and were kept in plastic bags until

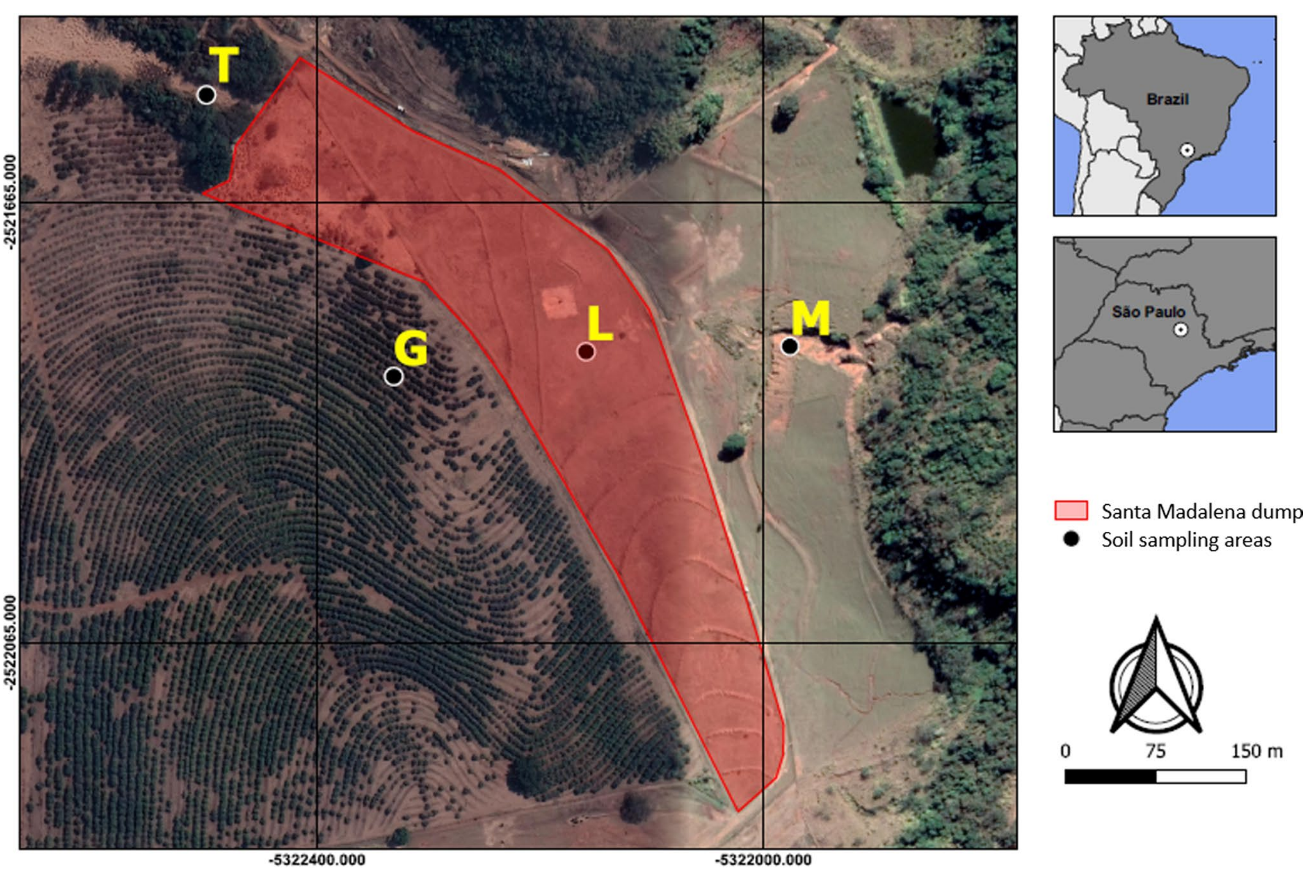

Fig. 1 Study area and location of sampling points

analyzed in the laboratory. For chemical analysis, a 0.25 g sub-sample was taken from each sample, using the quartering method (ABNT 2004), and analyzed according to the procedure described in Sect. "Analysis of metals in plant tissues and soil samples"

For the greenhouse pot experiment (see 4.4), the triplicates were mixed/homogenized to form composite samples (~3.0 kg from each site), which were used as substrates for different treatments ('L','G', 'M', and 'T').

All the soils collected for this study were previously evaluated by Velozo (2006), having similar characteristics in terms of hydraulic conductivity (~10^{-5} m/s), density (~1,5 g/cm^3), humidity (from 3 to 22%), porosity (~40%), granulometry (sandy), and Cation Exchange Capacity (from 0.5 to 2.0 meq/100 g for 'M' and 'G' and 1.5 to 3.5 meq/100 g for 'L' and 'T'). Additionally, physicochemical analyses have been conducted by Morita et al. (2020c): the pH was found to be close to neutrality (~7) for all samples and the Electrical Conductivity differed for each sample (~20—50 µS/cm for 'M' and 'G', ~300 µS/cm for 'T' and ~200 µS/cm for 'L').

Sampling of local plant tissues

In order to assess the metal concentrations in aerial tissues of plants that naturally developed in the study area and determine the phytoextraction capacity of these species, their aerial plant tissues were sampled. Plant tissues were collected at the same sampling points depicted in Fig. 1: *Pennisetum purpureum* at 'L' (elephant grass, called sample L_pp), *Psidium guajava* at 'L' and 'G' (guava tree, called samples L_pg and G_pg, respectively), *Brachiaria decumbens* at 'M' and 'L' (brachiaria grass, called samples M_bd and L_bd, respectively), and *Typha domingensis* at 'T' (cattail, called sample T_td). These species were selected due to their natural occurrence in the studied area, showing environmental adaptability; therefore, not all species were collected at the different sampling locations.

Aerial tissues were collected from different individuals of the same species and sampling area and were mixed to make up composite samples. The tissues were washed in running water, prepared and analyzed according to the procedure described in item 4.5.

Root tissues were not sampled because of the plants' significant root development and the associated difficulty in extracting them individually from the compacted soils.

Greenhouse pot experiment

A pot experiment using the soils collected from the areas depicted in Fig. 1 and saplings of the species *Vetiveria zizanioides* (vetiver) was performed. Although such species do not occur naturally in the studied area, its high reported adaptability and potential application at waste disposal sites (Pandey et al. 2019) made it interesting to assess in terms of the objectives proposed in the present research. Four different treatments were established by planting vetiver individuals in 2L-pots containing soils collected from 'L', 'M', 'T', and 'G', and watering the plants daily with 100 mL of clean water for 120 days. One additional treatment (CH) was conducted using the soil collected in M and watering the plants daily with leachate collected from the studied dump, which was sampled using the leachate monitoring station described by Pelinson et al. (2020). The characteristics of the leachate used to water the plants are presented in Table 2_{SM} of the *Supplementary Material*.

Therefore, five treatments were studied, called 'L', 'M', 'T', 'G', and 'CH', each composed of triplicates. The experiments were conducted in a greenhouse at the University of São Paulo (USP), São Carlos city, Brazil, allowing the maintenance of controlled climatic conditions. The plants' height was measured and the leaves were counted monthly.

After 120 days of conducting the experiments, the plants were harvested; roots and shoots were separated and washed in running water. The triplicates evaluated for each treatment ('L', 'M', 'T', 'G', and 'CH') were mixed to make up composite samples. Thus, for each treatment two composite samples were analyzed, comprehending the shoot ('S') and root ('R') tissues ('LS' and 'LR', 'MS' and 'MR', 'TS' and 'TR', 'GS' and 'GR', and 'CHS' and 'CHR'). Sample preparation and analysis were conducted as described in Sect. 4.5.

Analysis of metals in plant tissues and soil samples

The soil and plant tissue samples were dried in an oven with circulation and air renewal at 65 °C for 48 h and were then crushed. Sub-samples of 0.25 g were weighed, digested with nitric acid and hydrogen peroxide in a microwave digestion system, diluted with deionized water to make up a 50 mL-solution and analyzed in an ICP-MS analyser. The parameters analyzed were aluminum (Al), antimony (Sb), arsenic (As), barium (Ba), beryllium (Be), bismuth (Bi), boron (B), cadmium (Cd), calcium (Ca), lead (Pb), cobalt (Co), copper (Cu), chromium (Cr), tin (Sn), strontium (Sr), iron (Fe), phosphorus (P), lithium (Li), magnesium (Mg), manganese (Mn), mercury (Hg), molybdenum (Mo), nickel (Ni), potassium (K), silver (Ag), selenium (Se), sodium (Na), thallium (Tl), titanium (Ti), uranium (U), vanadium (V), and zinc (Zn).

Concentrations in mg/kg were obtained by using Eq. 1:

$$[Element]\left(\frac{mg}{kg}\right) = \frac{[Element]\left(\frac{mg}{L}\right) * Sample\ volume}{Sample\ mass} \quad (1)$$

where sample volume and sample mass were 50 mL and 0.25 g, as described above.

Results and discussion

Soil sample analysis

Table 1 shows the metal concentrations in the evaluated soil samples (mean and standard deviation). Elements whose concentrations were below the detection limit (DL) or blank sample concentration (Bl) for all samples ('T', 'M', 'G', and 'L') were not shown. Brazilian Screening Values ('BSV') for soils considering agricultural use are also shown.

It can be observed that no sample presented metal concentrations above the 'BSV'; therefore, the evaluated soils cannot be regarded as contaminated, based on the collected samples. Nevertheless, it can be noted that sample 'L' generally presented results higher than 'G', 'T' and 'M', especially for Ba, Cu, Fe, Ni, Pb, and Zn; this is because this soil directly covers the waste. Therefore, implementing phytoremediation over such soil ('L') would possibly help control the transport/leaching of metals to the surroundings.

It is important to mention that although soil analysis did not indicate contamination, it showed the existence of a mixture of different heavy metal concentrations ('L') that is not naturally found in the environment ('M'); thus, it is important to evaluate the plant adaptation to such a condition.

Moreover, Morita et al. (2020a) observed that the impacts are persistent in surface waters collected in 'T' and in groundwater collected in 'G', especially for COD and salts, and Morita et al. (2020b) found Pb and Co concentrations above the 'BSV' for groundwaters collected in 'G', showing that those areas are indeed impacted by the landfill, but might not have their soils intensely affected. Therefore, the adoption of mitigation measures in the area and the study of plant adaptation is still needed.

Local plant tissue analysis

Although many elements were analyzed in species collected in loco (see item 4.5.), only the parameters with significant concentration or variability are shown here (Fig. 2).

The samples which presented the highest concentrations of Ba, Pb, and Zn referred to species growing over the landfill, especially L_pp (elephant grass) and L_pg (guava tree), which agrees with the results of metal concentrations in soil samples (Table 1). This shows that the plants act on the phytoextraction of such metals, but the concentrations found are still low and do not seem to pose a risk to the biota (Mota and Santana 2016; Nogueira et al. 2010), which is beneficial to the phytoremediation proper management. This can be attributed both to the species' low capability of extracting metals and the low metal concentrations found in the studied area, a combination that is promising for using phytoremediation techniques in old landfills and dumps.

It is also interesting to note that guava trees sampled in 'G' (G_pg) did not present considerable concentrations of heavy metals, which shows that the development of commercial guava plantations in the area does not seem to pose risks to the biota and public health. This can be associated with the low concentrations of heavy metals in the soils collected in 'G' (Table 1); thus, although groundwater was found to be contaminated in the area (Morita et al. 2020b; PMSC, 2011), it is suggested that such contamination originates from horizontal groundwater flow, and not from vertical infiltrations and that the plants' roots do not reach these contaminated waters.

Finally, it is important to mention that only the phytoextraction capacity was evaluated in local plants, by analyzing metal concentrations in aerial tissues; phytofiltration or phytostabilization were not evaluated and could also be potential mechanisms for remediating the area.

Table 1 Mean concentration (mg/kg) and respective standard deviation of metals in the different analyzed soil samples

Samples	'T' (mg/kg)	'M' (mg/kg)	'G' (mg/kg)	'L' (mg/kg)	'BSV' (mg/kg)
Al	5330 ± 1730	2082 ± 443	9564 ± 1035	7202 ± 999	
Ba	< Bl	< Bl	4 ± 3	20 ± 9	300
Ca	601 ± 98	75 ± 8	455 ± 118	792 ± 161	
Cu	< Bl	< Bl	0.3 ± 0.4	14.1 ± 10.5	200
Fe	11,373 ± 3966	3991 ± 270	13,086 ± 379	12,837 ± 698	–
K	240 ± 156	240 ± 105	46 ± 30	180 ± 20	
Mg	230 ± 51	229 ± 3	150 ± 27	203 ± 21	–
Mn	77 ± 21	28 ± 4	174 ± 11	86 ± 27	–
Na	200 ± 0	113 ± 30	120 ± 0	160 ± 40	
Ni	< Bl	< Bl	< Bl	0.3 ± 0.6	70
Pb	< Bl	< Bl	3 ± 1	18 ± 2	180
Zn	< Bl	< Bl	9 ± 7	76 ± 10	450

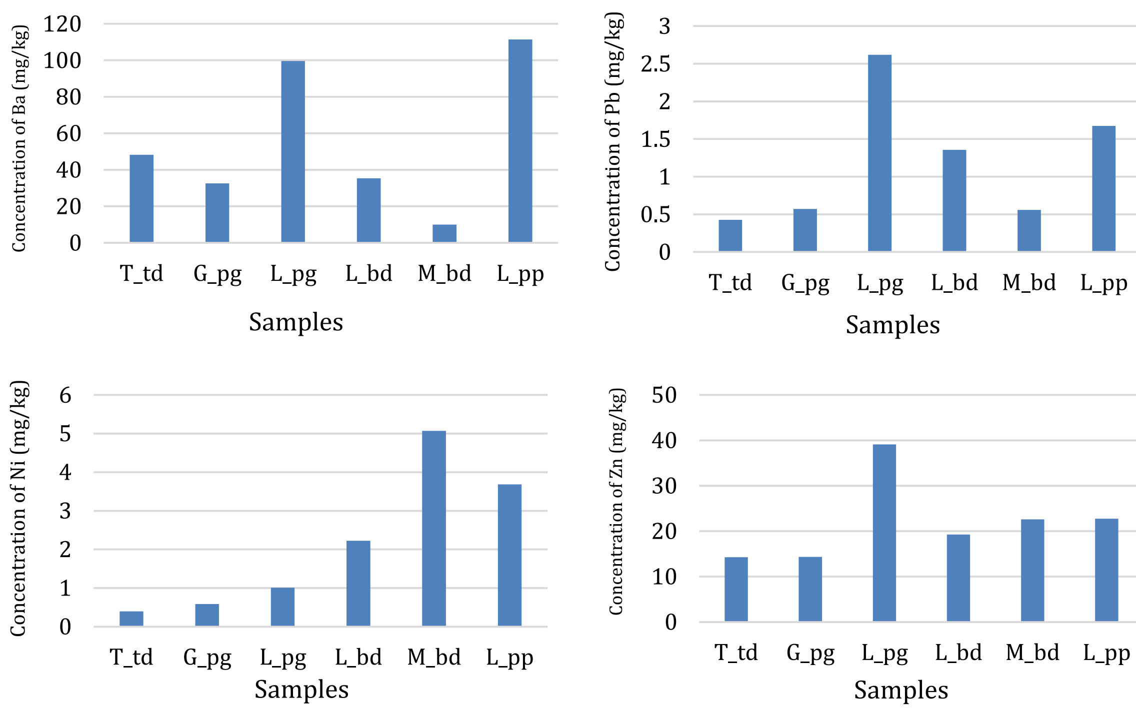

Fig. 2 Ba, Pb, Ni, Zn concentrations for aerial tissues collected from plants in the study area

Greenhouse pot experiment

Growth parameters

Figure 3 shows the variation in height and the number of leaves for the different treatments, considering the means of the triplicates.

Firstly, it is important to mention that plants from all treatments were able to thrive and did not show signs of phytotoxicity, which shows their suitability for application in the study area, not only for remediation but also for drainage and erosion control. Nevertheless, it can be noted that some soils led to a more considerable development of the plants, which is discussed as follows.

Generally speaking, the plants' growth and development of leaves followed the same trend: two groups presented less development ('CH' and 'M') and two groups presented greater development ('T' and 'G'), while 'L' developed many leaves but presented low heights. The result revealed that the vetiver species reacted negatively to sandy soils

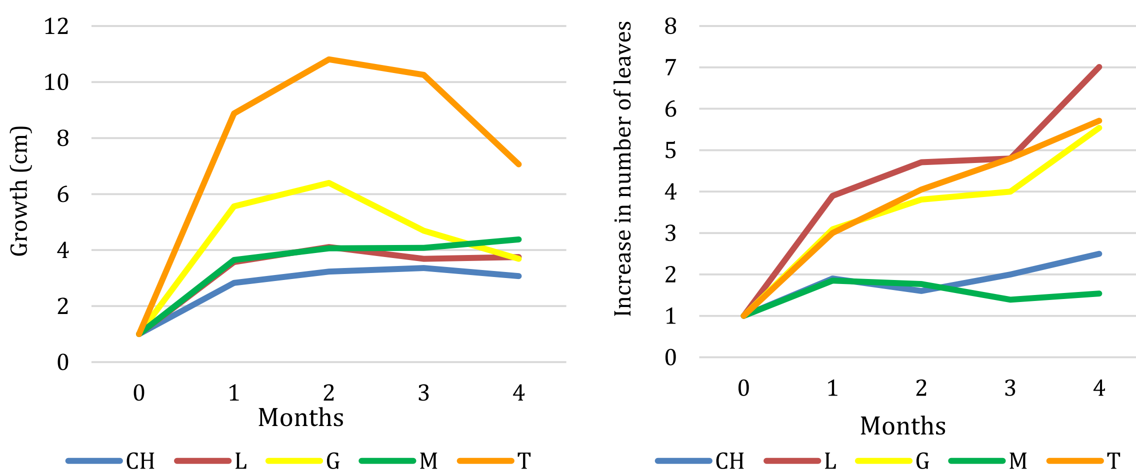

Fig. 3 Growth (left) and increase in number of leaves (right) for the different treatments

('M'), as well as to direct contact with leachate ('CH'). On one hand, this can be associated with these soils' low nutrient content and low capability to retain moisture. On the other hand, considering that the treatment 'CH' presented a slightly worse performance when compared to 'M', it can be affirmed that direct contact with leachate may have impaired the plants' development. Nonetheless, it is important to note that the plants could survive and present resistance to contamination; therefore, their application in the remediation of dumpsites, even in sandy soils receiving leachate, could still be promoted.

Regarding the groups with greater development, it can be observed that 'T' presented the highest average height most of the time, in addition to greater growth in relation to the initial height and a significant number of leaves. The soils used for this treatment were collected in a flooded region downstream of the landfill, where leachate commonly flows; thus, several nutrients accumulated in the region (K, Ca, and Mg, see Table 1) may have contributed to the plants' growth. Additionally, Morita et al. (2020c) found high concentrations of ammonium (~ 40 mg/L), Total Kjeldahl Nitrogen (~ 100 mg/L), and COD (~ 100 mg/L) in surface water collected in the area. On one hand, this indicates that the site is highly polluted. On the other hand, it shows characteristics that can be beneficial to the plants' development. Moreover, considering that Morita et al. (2020a) found much lower values downstream of T, it is suggested that natural processes—possibly plant-mediated—contribute to the natural attenuation of contaminants. In this regard, the application of plant species in the zone—such as vetiver, which proved to adapt to the local conditions—can promote several phytoremediation mechanisms, such as phytoextraction, phytostabilization, rhizofiltration, and rhizodegradation, which are promising in restricting the transport of nutrients, organic matter and metal to water resources existing downstream of the landfill (Danh et al. 2009; Davamani et al. 2021; Pandey and Praveen 2020; Suelee et al. 2017).

Figure 3 also shows that treatment 'G' presented the second-highest growth and number of leaves. The soil used for the specimens in group 'G' was taken from a guava plantation adjacent to the landfill, in which some soil enrichment was possibly adopted, contributing to the plants' growth. Thus, considering that no restriction in vetiver growth or toxicity was verified in the pot experiment and that the guava plantation is already installed in the area and does not seem to pose a risk to the biota and public health (see Sect. 5.2), it is suggested that such commercial plantation can be continued.

Attention should be paid to a trend towards a reduction in the mean height of treatments 'T' and 'G' at the end of the study. This propensity is perhaps linked to the natural cycle of the plants' renewal, in which the leaves are periodically renewed. Furthermore, in a natural environment, the vetiver species can have roots that are more than 2 m long (Pandey et al. 2019); thus, the environment in which the specimens were planted (pots) must interfere with their growth and life cycle. Therefore, considering that those treatments were the ones with the greatest growth, it is feasible that the plants achieved the peak of development earlier, undergoing restrictions due to the pot's size. Additionally, as the number of leaves did not undergo the same tendency, it is supposed that the mass of the leaves affected the height development. Consequently, it is suggested that the decrease in the plants' height for treatments 'T' and 'G' at the end of the experiments is not associated with negative or toxic effects of the sampled soils.

Finally, treatment 'L' presented one of the lowest height developments, but the highest number of leaves. Similar to what has been discussed for 'T' and 'G', it is supposed that the higher number of leaves in the plants from such treatment restricted their growth in terms of height, but such a phenomenon was not associated with negative or toxic effects on the soils.

Although the visual analysis indicated the existence of a difference between the studied treatments, it was necessary to perform the analysis of variance (ANOVA) to verify if this difference was statistically relevant. The data used for this analysis was the difference between the first and last measurement, considering the height and number of leaves of each individual of the different treatments.

Considering the plant height, $\rho = 0.1535 > 0.05$ (significance level), there was no significant difference for the different vetiver treatments. On the other hand, for the number of leaves, $\rho = 0.03011 < 0.05$, there was inequality between the variances. The Tukey test was applied and revealed a statistical difference in the number of leaves between treatments 'M' and 'L'.

Thus, it is suggested that the plants could adapt to all soils sampled in this study but presented the greatest development for soil 'L' (regarded as the most affected by the landfill impacts), and the lowest adaptation for 'M' (sandy upstream soils). Soils from 'T', which were also significantly affected by leachate, also adapted well to the site's conditions (Figs. 3 and 4).

In this regard, considering that the first requirement for phytoremediation application of plant species is their adaptation to the local conditions, it is suggested that vetiver can be feasibly used at the different sampling areas from the studied site, under subtropical conditions.

Additionally, it is suggested that adopting vetiver species over the landfill ('L') can contribute to an increase in evapotranspiration rates, leading to a reduction in the leachate production and functioning as an alternative cover (also known as evapotranspiration covers or phytocappings) (Salt et al. 2018).

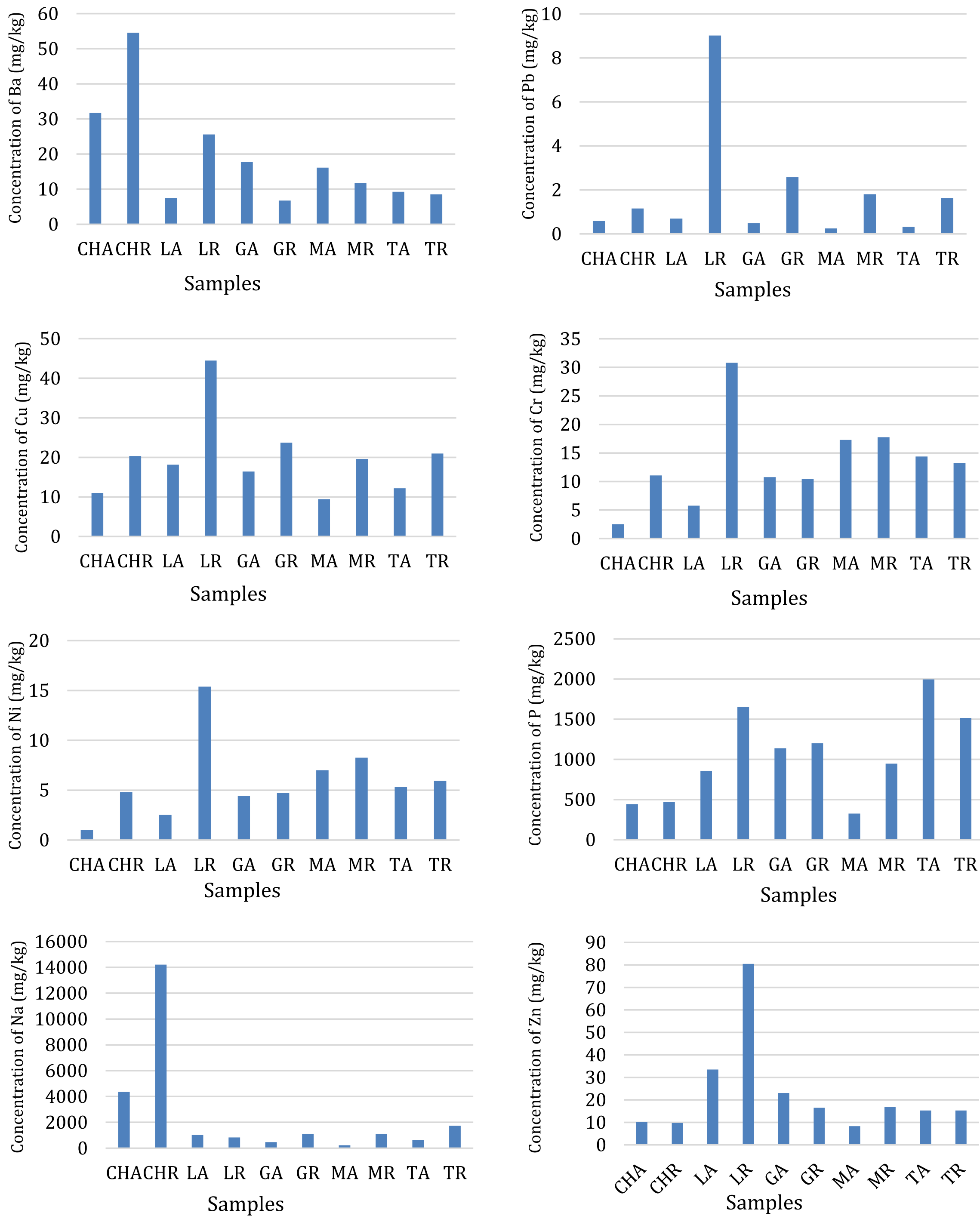

Fig. 4 Ba, Pb, Cu, Cr, Ni, P, Na, and Zn concentrations of vetiver aerial and root tissues

Thus, Feng et al. (2022) concluded that vetiver grass presented the best results, among other studied grasses, to reduce percolation through a landfill cover, having the largest suction for the drying period and the lowest infiltration rates for the wetting period, and presenting a transpiration rate of about 2.4 mm day^{-1}. This result is compatible with values presented by Lamb et al. (2014) for other species used for phytocappings, such as *Eucalyptus spp*. and *Acacia spp.* (~0.28–4.0 mm.day^{-1}).

Vetiver tissue analysis

Figure 4 presents the results of metal concentrations in aerial and root tissues of the different treatments. Only the parameters with significant concentration or variability are shown here.

Firstly, it is important to note that the highest metal concentrations were found in root tissues, showing that the elements were absorbed by the plants but not totally translocated to aerial tissues. This is beneficial considering the security of the biota, which may be more easily exposed to the aerial tissues, and indicates that the results presented in Sect. 5.2. only show the partial absorption of the local plants, as only aerial tissues were analyzed in such cases.

Furthermore, it is important to note that the tissues which presented the highest accumulation of most parameters were 'LR' and 'CHR', respectively, indicating that vetiver does extract metals from the landfill cover and leachate, and is effective for their remediation.

For element P, the greatest absorption occurred for treatment 'T' can be observed, which agrees with the significant development of plants growing in such soil (Fig. 3) and with the greatest level of organic content found in such a location (Morita et al. 2020a). Thus, as was previously discussed, in the region where 'T' samples were collected, several phytoremediation techniques are prone to occur, and the adoption of wetlands is promising for attenuating the impacts downstream of the landfill. In this regard, wetlands are effective in nutrient and organic matter removal from wastewaters, having been applied to treat leachates, also removing ammonium and heavy metals (Dotro et al. 2017).

It is important to note that the metal concentrations found in aerial tissues of local plants were higher than the ones found for the pot experiment, indicating that the local plants (mainly elephant grass and guava tree) have a greater capacity to phytoextract and translocate Ba, Pb, Ni, and Zn than vetiver. Alternatively, the longer period of exposure and the higher mass of metals found in more significant amounts of soils (pots support a restricted mass of soils) may have influenced the plants' absorption, so that planting vetiver in situ may lead to similar or better results (Pandey et al. 2019; Suelee et al. 2017).

Finally, it is important to observe that vetiver was also able to accumulate Cu, Cr, and Na, which was not observed in local plants. This can be associated with evaluating root tissues in this case, where those elements seemed to accumulate more intensely. The accumulation of Na is especially relevant for 'CHR' and 'CHA', indicating tolerance to salinity—also indicated elsewhere (Liu et al. 2016; Noshadi and Valizadeh 2016)—and applicability to leachate treatment, which is commonly rich in salts (Ehrig and Stegmann 2018).

Translocation factor (TF) and bioaccumulation factor (BF) Table 2 shows the TF for vetiver plants, considering the different treatments evaluated in the pot experiment. The TF represents the potential of the plant to transfer metal from the root to the shoot and is calculated according to Eq. 2; plants with TF > 1 are considered competent in this process.

$$TF = \frac{Metal\ concentration\ in\ shoot\ tissues}{Metal\ concentration\ in\ roots} \quad (2)$$

It can be observed that Ba, Cr, and Zn could be translocated to aerial tissues, especially considering treatments 'G' and 'T'. Soils from guava plantations seemed to promote the highest accumulation of metals in aerial tissues.

In this regard, it is noteworthy that there is a certain risk of accumulating metals in the aerial portion of the plant, because, through herbivory, these metals have the possibility of entering the food chain in a bioaccumulation process. On the other hand, the fact that vetiver is classified as aromatic reduces the risks of contamination to the environment as herbivory occurs less frequently in species of this type (Pandey et al. 2019).

Table 3 shows the BF for the evaluated vetiver plants; the BF quantifies the plant's ability to absorb metal from the soil and displaces it to its plant tissue, either the shoot or the root; plants with BF > 1 are considered competent in this regard. Here, BF was calculated either with root or shoot concentrations, using the highest between them.

Once again, the absorption of Ba was relevant, especially for 'G' and 'L'; Cu and Ni also presented significant BF for treatments 'G' and 'L', respectively. It is important to note that the BF could not be calculated for metals whose concentrations in soils (Table 1) were below the blank value; nevertheless, considering that Fig. 4 shows concentrations

Table 2 TF for vetiver plants evaluated in the pot experiment

Element	LA/LR	GA/GR	TA/TR	CHA/CHR	MA/MR
Ba	0.292	2.630	1.089	0.581	1.364
Pb	0.077	0.187	0.197	0.506	0.139
Co	0.160	0.354	0.261	0.093	0.139
Cu	0.408	0.692	0.581	0.542	0.481
Cr	0.188	1.032	1.091	0.226	0.974
Ni	0.164	0.938	0.900	0.208	0.848
Zn	0.416	1.399	1.000	1.039	0.493

Table 3 BF for vetiver plants evaluated in the pot experiment

Element	L	G	T	CH	M
Ba	1.7	6.7	n.a	n.a	n.a
Pb	0.5	0.7	n.a	n.a	n.a
Cu	3.2	83.3	n.a	n.a	n.a
Ni	50.0		n.a	n.a	n.a
Zn	1	2.7	n.a	n.a	n.a

n.a. not applicable, considering that metal concentrations in soil samples were below the blank sample of metals in such tissues different from the blank sample, it can be affirmed that BF > 1 could also be observed for them, which is the case of the element Cr.

The results are compatible with other studies evaluating phytoextraction of heavy metals by vetiver (Chintani et al. 2021; Zhuang et al. 2007) and suggest that vetiver can be used for phytoremediation of old waste disposal sites and mainly acts on phytostabilization, considering the higher accumulation of metals in root tissues (Fig. 4, Table 2). This can be regarded as beneficial to phytoremediation management, considering the risks that translocation could bring to biota and public health.

Additionally, considering that the metal concentrations normally found at old waste disposal sites or leachates are low (Ehrig and Stegmann 2018; Pelinson et al. 2020), it is suggested that phytoremediation using vetiver is a feasible alternative for mitigating impacts of such areas.

The results showed that vetiver, elephant grass and guava could be effectively planted over uncontrolled landfills and dumpsites to phytoextract and phytostabilize heavy metals and are also promising to reduce leachate production (evapotranspiration covers) and enable an economical return for these sites. The mentioned species could adapt well to all conditions found around the reclaimed landfill and could remediate mainly Ba, Cu, Pb, and Zn.

Conclusion

This study aimed to assess the phytoremediation ability of plants adapted to MSW disposal sites, specifically *Vetiveria zizanioides* (vetiver), *Pennisetum purpureum* (elephant grass), and *Psidium guajava* (guava tree). The selected study area was an old unlined landfill situated in the southeast region of Brazil, under a subtropical climate, around which contamination associated with heavy metals, organic matter, and salts has been previously detected, especially in water resources.

Soil analysis indicated that all heavy metal concentrations were below the Brazilian Screening Values. Nonetheless, samples collected from the landfill surface presented higher concentrations of Ba (20 ± 9 mg/kg), Cu (14.1 ± 10.5 mg/kg), Pb (18 ± 2 mg/kg), and Zn (76 ± 10 mg/kg), when compared to other surrounding areas.

Plants naturally growing in the study area, especially elephant grass and guava, presented potential applications for phytoextracting Ba (111 and 100 mg Ba/kg shoot tissues, respectively), Pb (1.7 and 2.6 mg Pb/kg shoot tissues, respectively), and Zn (23 and 39 mg Zn/kg shoot tissues, respectively). As species of natural occurrence in the study area, their application is promising because the adaptation to local conditions (climate, geology, concentration of contaminants) is already observed. Thus, the maintenance and expansion of planting these species would possibly contribute to reducing contamination by heavy metals, organic matter, and nutrients.

Regarding the greenhouse pot experiment, it indicated that vetiver reacted significantly to contamination and soil type. Thus, plants irrigated with leachate and those planted in soils from the upstream region of the dump, which are sandier and have fewer nutrients, showed reduced development. However, the specimens planted in soil from the downstream region, from the landfill surface and from the guava tree plantation showed good adaptability and growth and did not present symptoms of toxicity. Regarding metal accumulation, the species accumulated mainly Ba, Cu, Ni, Pb, and Zn, especially in its root tissues (acting on phytostabilization processes), achieving values of 55, 45, 16, 9, and 78 mg/kg, respectively.

The calculated translocation factors indicated that Ba (TF = 2.6), Cr (TF = 1.091), and Zn (TF = 1.399) also translocated to aerial tissues, even considering the short period of time evaluated (120 days), showing its ability to phytoextract heavy metals. The concentrations found in plant tissues, as well as in soil samples, did not indicate a risk to biota, showing that the application of phytoremediation in such an area would be beneficial to controlling contamination and would not necessarily incur exaggerated costs for the plants' maintenance.

Additionally, considering that vetiver could adapt to the conditions found in the landfill surface, its application as phytocapping of old landfills is promising, as it would contribute not only to metals extraction or stabilization, but also to a reduction in leachate production. In this regard, it is important to mention that roots of the studied species would probably not reach groundwater, and thus would not be applicable to their remediation. Nevertheless, they could be effectively planted over landfills and dumpsites to avoid contaminants leaching into groundwater. This application over uncontrolled landfills and dumpsites has not yet been reported.

Thus, it is recommended that vetiver, as well as local species such as elephant grass and guava tree, are widely used to mitigate impacts of the studied dump, as well as similarly abandoned dumpsites and unlined landfills, allowing the phytostabilization and phytoextraction of heavy metals such as Ba, Cu, Ni, Pb, and Zn.

Finally, taking into account the economic, environmental and social aspects of developing countries, it is extremely important that accessible and effective technologies can be used to manage areas contaminated by MSW disposal. In this context, the results showed a selection of plants adapted to MSW disposal sites and subtropical conditions that, acting in phytoremediation processes, should be used by environmental managers in successful phytoremediation and dumpsite recovery projects. Therefore, this research contributed to the expansion of understanding phytoremediation applied to deactivated and uncontrolled dumps, providing relevant data to the development of techniques for their recovery and bringing about the prospect of economical and energetic return of such abandoned areas.

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Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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