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RESEARCH ARTICLE

# Are anthropogenic soils from dumpsites suitable for arable fields? Evaluation of soil fertility and transfer of potentially toxic elements to plants

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**Abstract**
*Background and purpose* The fertility of anthropogenic soils developed from dumpsites used for arable fields is not well-studied. The study aimed to evaluate the fertility of anthropogenic soils from an abandoned dumpsite in Awotan, Nigeria, by measurable indicators and the bioaccessibility of elements of selected plant species.
*Methods* The study adopted multi-analytical approaches to determine the signatures of the soils and further parameterized the bioaccessibility of elements to plants.
*Results* The comparatively high content of Ca and Na in the anthropogenic soil contributed to the slightly alkaline soil reaction against the slightly acidic control. The high amount of organic matter is well-indicated by the enrichment of organic C and N in the anthropogenic soil. Waste deposition significantly contributed to the high accumulation of macronutrients (P, Ca, K, S) and micronutrients (Mn, Na, Fe) sufficient for maximum plant growth and yields, with an adequate C/N ratio supporting effective mineralization. The high cation exchange capacity of the anthropogenic soil contributed to cations binding. Indiscriminate waste deposition resulted in a high accumulation of potentially toxic elements (PTEs; Cu, Zn, As, Cd, Pb) above permissible limits in agricultural soils following WHO limits. Potential effects on lives are evident in the high PTEs accumulation in roots and leaves of *Chromolaena odorata*, *Saccopetalum tectonum*, *Passiflora foetida,* and *Senna siamea*. These plant species exhibited various PTEs accumulation, especially for Cd and Pb.
*Conclusion* Although anthropogenic soils remained fertile, the bioaccessibility of PTEs by plants indicates potential threats to consumers of crops and herbs produced from such sites.

**Keywords** Anthropogenic soil · Bioaccessibility · Macronutrient · Micronutrient · Potentially toxic elements · Soil fertility

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## Introduction

Anthropogenic soils (human-altered-soils) can develop from diverse activities, including metallurgy, farming, and often deposition of waste in specified locations (Hard et al. 2019). Wastes deposition often occurs at locations created by households or large land sizes for an entire community, especially in rural settings. With time these waste deposition sites, often called dumpsites, are abandoned and often reused as arable fields (Oyakhilome et al. 2019).

The material composition of decomposed waste in dumpsites is a function of elements (macro, micro, or risk elements) released into soils. For example, Sajjad et al. (2022) and Wan et al. (2019) reported that the presence of plastics in soils increases the content of potentially toxic elements (PTEs, e.g., Zn, Cu, As, and Pb) and excessive loss of soil $H_2O$ and may lead to microbial activity limitation. The accumulation of PTEs has toxicological consequences on soil–water/plant-animal interactions (e.g., Taylor et al. 2010; Thomas et al. 2015). For example, up to 4692 mg of Pb $kg^{-1}$ was detected in landfill (Gupta et al. 2011), with subsequent uptake by plants (Amusan et al. 2005). The deposition of waste, including the occasional burning of dumpsites and decomposition of organic matter, can also change the matrix color and other physical properties of the previous natural soil.

Waste, including kitchen leftovers (e.g., bones, wood ash, and food residues), can decompose to release vital plant nutrients (such as P, Ca, K, Mn, and Fe) into soils. Additionally, Bassey et al. (2021) recorded beneficial and pathogenic microbes belonging to *Clostridium, Escherichia, Pseudomonas, Enterococcus, Micrococcus, Shigella, Klebsiella,* and *Bacillus* in dumpsite soil. However, indiscriminate disposal and burning or decay of wastes can result in substances that contain elevated metal / (loid)s, for example, As and Cd, together with excess amounts of some elements needed by plants in small contents (such as Zn and Cu) (Kalina et al. 2019). Therefore, the feasibility of crop and herbage production of former dumpsites is questionable.

Repurposing old dumpsites for green space is not a new thing. Abandoned dumpsites, alternatively, are often converted into arable fields and agricultural grazing lands. Although some authors evaluated the negative impacts of solid wastes disposition on soils from dumpsites, these studies related to risk elements (e.g., Pb and Cd) abundant in industrialized localities (Fakayode and Onianwa 2002; Onipede and Bolaji 2004) and reclamation of areas dumped with mine waste (Novak et al. 2008). Hence, the need for intermittent analyses of anthropogenic soils emanating from dumpsites. So far, what is not well-known in such arable fields is the fertility derived from their chemical, physical, and biological signatures and the level of toxicity of such soils and respective biomass.

For this study, soil quality is assessed based on indicators on the concept of control charts, e.g., regional and global permissible limits. Estimation of the enrichment factor of elements includes a direct comparison between soils from the dumpsite and surrounding control site without waste deposition. The evaluation of indicators of soil fertility includes one of the most pertinent aspects of sustainable agricultural production (Sarhat 2015). The uptake and translocation of elements by plant species in such sites with diverse soil characteristics are required to support the accession of soil fertility. Hence, it is relevant to estimate the level of bioaccessibility of elements in the soil to plants to provide complete proof of the properties of soils in dump sites.

The current study provides comprehensive exploratory research on the fertility of one of the largest abandoned dump sites in Africa, Awotan, Nigeria (Alia et al. 2013; Amuda et al. 2014; Raman and Narayanan 2008), considering physical, chemical, and biological indicators. Many such sites are currently used for agricultural production worldwide, e.g., Mzedi in Malawi (Kalina et al. 2019), Chiang Mai in Thailand (Boonmahathanakorn 2020), Calabar in Nigeria (Bassey et al. 2021), and Tucson, Arizona (USA; Hard et al. 2019). However, studies that provide a detailed evaluation of the fertility of soils from dumpsites and assess their bioavailability of potentially toxic elements are less published.

Therefore, the current study demonstrated the fertility of anthropogenic soils from the dumpsite by 1) Comparing the soil physical properties of the dumpsite to surrounding control without the deposition of waste, 2) Estimating the enrichment of chemical properties (including pH, macro, trace, and risk element contents) of the anthropogenic soils from the dumpsite, and 3) Exploring the bioavailability of risk elements of selected plant species to make conclusive inferences on the suitability of such sites for arable fields.

## Materials and methods

### Study site

The studied abandoned dumpsite (7°27′41'' N 3°50′52'' E; Fig. 1) is in Awotan, Ibadan in Oyo state, approximately 128 km NE of Lagos and 345 km SW of Abuja, the federal capital of Nigeria. The studied dumpsite has been in existence since 1829. The dumpsite covers an area of approximately 22 ha, with the distance of the nearest settlement only 200 m. The study area experiences two local climates; rainy (March to ends in October) and dry/harmattan (November to February) seasons. The average annual precipitation is 1311 mm, and an altitude between 200 and 300 m a. s. l. (MacDonald et al. 2005). The temperature of the study area ranges from 21 and 35 $^{o}$ C in the wet and dry seasons, respectively. The study site is well-characterized by lixisol, located on an igneous and metamorphic rock (Adelana et al. 2008; MacDonald et al. 2005).

### Sampling design and sample collection

The study adopted to judgmental sampling technique after Maul (2018) by considering randomized sampling to cover the variability of soil and plant samples on the site. Four pits (Locus A – D) were excavated approximately 200 m apart on the edges of the dumpsite since the waste extends to 4 – 5 m high in the southwest section. The entire studied site is predominantly occupied by similar indiscriminate deposition of wastes, which provides an overview of the sampling approach adopted. Soil samples representing control additionally were collected from two randomized pits (non-residential area) with no waste deposition, approximately 200 m away from the dumpsite, with the same soil and parent bedrock. The waste exhibit high variability of substances, including plastic bags, and partly decomposed organic, and inorganic materials.

Random bulk soil sample collection involves the upper 0 – 30 cm (arable layer) and 30 – 60 cm

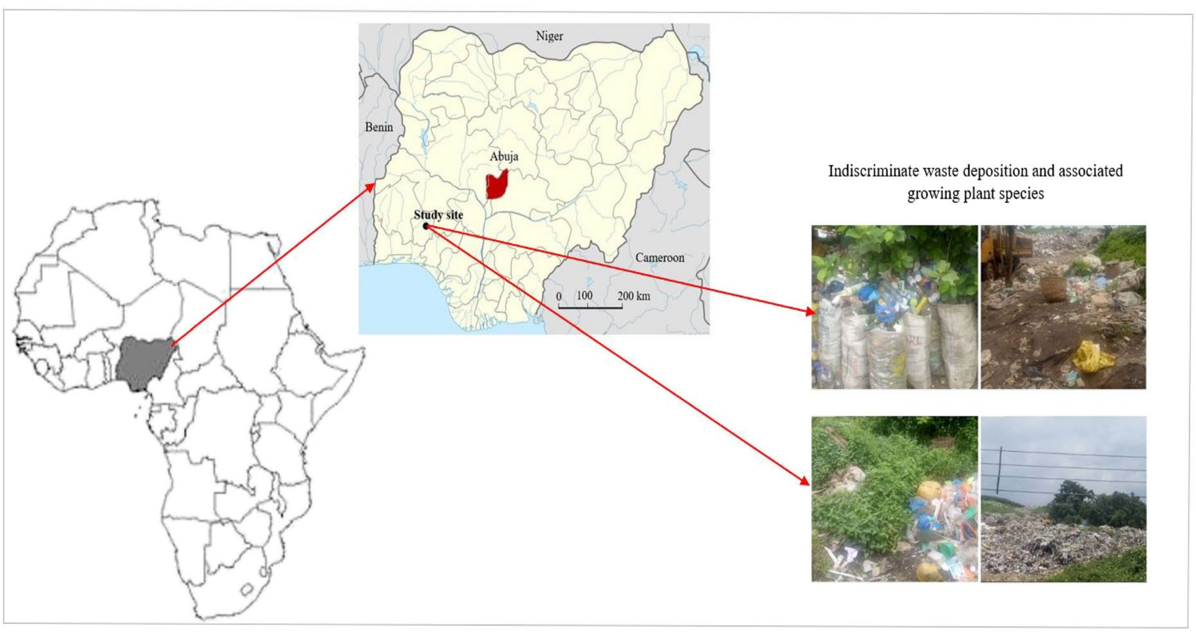


**Fig. 1** Map of Nigeria showing the location of the studied dumpsite in Awutan and associated waste deposition

(subsoil layer) depths from each pit after the removal of surface litter. Sampling involved the collection of three soil samples from each depth, making an overall total sample number of 36. Two duplicates of the most mature dominant plant species, *Chromolaena odorata* L. (Asteraceae), *Saccopetalum tectonum* (Annonaceae), *Passiflora foetida* (Passifloraceae), and *Senna siamea* (Fabaceae) subsequently were collected in proximity to each sampled pit of the dumpsite. The nomenclature of the taxa used followed that adopted in APG IV- Angiosperm Phylogeny Group (https://www.gbif.org/species/3106). Only the leaves of mature *S. siamea* were easily accessible during collection. Both plant and soil samples were collected and put in labeled polyethylene bags in May 2019.

## Sample preparation and analysis

### *Soil*

The collected soil samples were air-dried and sieved. The homogeneous fraction under a 2 mm sieve was then analyzed for the pseudo-total content of elements. Procedure for soil samples digestion:

Approximately 5.0 g of each homogenized soil sample was weighed into a conical flask, with 10 ml of concentrated nitric acid ($HNO_3$) added. The mixture was heated on the hot plate at 120 ºC for approximately 20 min to near dryness and was allowed to cool and then filtered (using Whatman filter papers 125 mm Ø Cat No. 1001125) before being transferred into a standard flask made up to 50 ml of distilled $H_2O$. The digested solutions further were analyzed for the presence of pseudo-total element concentrations using an Atomic Absorption Spectrometer (AAS) Type: S4 AA System, Nc: 942,340,030,042).

Soil reaction ($pH_{[CaCl2]}$) was measured in a 1/2.5 (w/v) suspension of soil and 0.01 M $CaCl_2$. Soil organic C (SOC) and total N were also determined with a Skalar Primacs SNC-100 analyzer produced by Skalar (Netherlands). The cation exchange capacity (CEC) was determined according to the ISO 11260 (ISO 1994) procedure.

### *Plant biomass*

Below (roots) and above-ground (leaves) biomass were detached and washed with deionized ultrapure $H_2O$ to remove ions transported from environmental dust. All the samples were additionally dried in the electric oven (SLW 53 STD, Pol-Eko, Wodzisław Śląski, Poland) at 60 °C for 72 h. Dried plant samples of each species were then ground with an electrical plant tissue pulverizer (particle size of 0—1 mm) and stored in sealable bags. Homogenized powdered samples were analyzed for total Cu, Zn, As, Cd, and Pb contents as follows: The decomposition of the plant samples (dry weight) followed the microwave-assisted acid digestion (USEPA 3052, 1995), and the contents of elements were determined by using inductively coupled plasma atomic emission spectrometry (ICP-AES, Agilent 5900, Technologies Inc., USA). The individual samples were analyzed in triplicates.

## Size distribution of soils

Analysis of the soil grain distribution followed the mechanical sieve approach by FAO (2008) with size fractions of 2 ("very coarse"), 1 (coarse), 0.5 (medium), and 0.25 (fine) mm. For each representative soil sample, 20 g was used for this analysis. Moreover, texture description followed the approach according to FAO (2008).

## Statistical analysis

There was homogeneity of variance among data for all the analyzed samples. Dataset met the assumption of parametric statistics according to the Shapiro–Wilk W normality test. One-way ANOVA model was used to evaluate the differences in soil chemical properties, and content of elements in dry weight of biomass samples followed by the post hoc comparison using the Tukey honest significant difference (HSD) test applied to identify significant differences between chemical properties of soils with depth and content of elements among biomass. To evaluate the relationship between the concentration of elements, soil reaction (pH), and particle size distribution we used Pearson's correlation. STATISTICA 13.4 (www.statistica.io) was used to perform all statistical analyses.

## Metal transport and accumulation indices

To study the behavior of PTEs in the soil–plant system, bioaccumulation (*BF*) and translocation factors (*TF*) were calculated as the ratio of PTE in vegetative aerial structures (leaves) to those in soil and root, with values > 1 indicating enrichment of the plant structures- accumulators (Mesa et al. 2017).

The calculation of *BF* follows the equation after Baker (1981),

$$i)\ BFl = leaf\ content\ of\ element\ (D\ wt) \div element\ content\ in\ soil,\ \text{depth } 0-60 \text{ cm depth}$$

$$ii)\ BFr = root\ content\ of\ element\ (D\ wt) \div element\ content\ in\ soil,\ 0-60 \text{ cm depth} \quad (1)$$

The calculation of *TF* follows the equation according to Klink et al. (2014),

$$iii)\ TF = leaf\ content\ of\ element\ (D\ wt) \div root\ (D\ wt)\ content\ of\ element \quad (2)$$

## Results

The statistical description of soil's physical and chemical properties, the elemental composition of plant organs, and the bioavailability of PTEs are in Figs. 2, 3, 4, 5, 6, 7 and Tables 1, 2, 3, 4.

### Bulk soil chemical properties

There were significant differences in the pH levels and the contents of macro, micronutrients, and potentially toxic elements at individual loci (Figs. 2, 3, 4, 5, 6). Background values of pH and plant nutrients (SOC, N, P, Ca, K, Na, Fe, Mn, Cu, and Zn) were

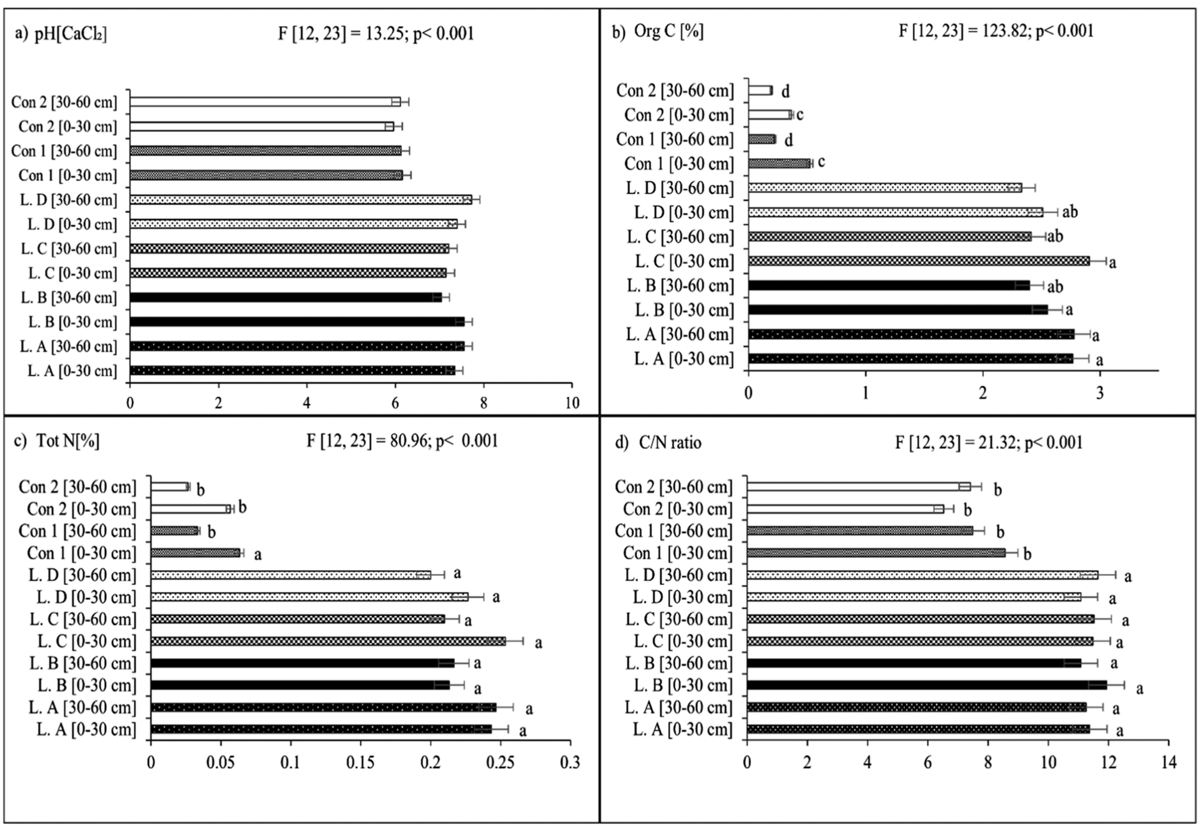


**Fig. 2** Effect of waste deposition on (**a**) pH and mean content of (**b**) organic (org) C, (**c**) total (Tot) N, and (**d**) C/N ratio from different sampled locations. The F-and p-values were obtained by One-way ANOVA. Using Tukey *posthoc* HSD test, mean values with the same letters were significantly not different. The error bars indicate the standard error of the mean

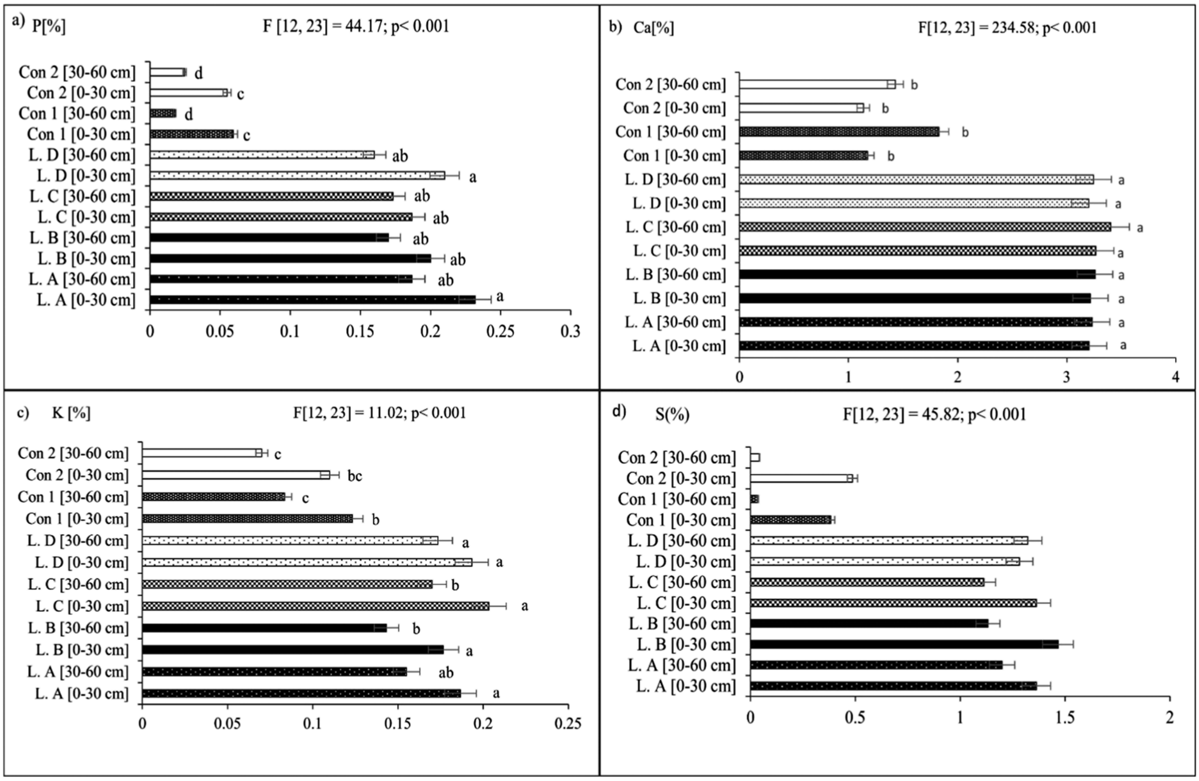


**Fig. 3** Effect of waste deposition on the mean content of total (**a**) P, (**b**) Ca, (**c**) K, and (**d**) S from different sampled locations. The F-and p-values were obtained by One-way ANOVA. Using Tukey *posthoc* HSD test, mean values with the same letters were significantly not different. The error bars indicate the standard error of the mean

predominantly lesser compared to soils from the dumpsites (Figs. 2a–c, 3, 4a–c, and 5a–b) and vice versa in the case of S (Fig. 4d). Additionally, there was no increasing or decreasing pattern of elements with depth in Loci A – D. However, decreasing trends of SOC, N, P, Ca, K, S, Fe, and Na were detected only with depths in control.

The soil reaction of the anthropogenic soil was slightly alkaline (Fig. 2a) under the influence of Ca and Na (Figures S2a and b) compared to slight acidity in control. The results further show suitable conditions for the mineralization of nutrients, according to the C/N ratio of approximately 12 in the soil from the dumpsite, due to the comparatively increased contents of SOC and total N (Figs. 2b and c). Increased SOC, N, and C/N ratio support higher content of organic matter in the anthropogenic soil than control of this study.

The soil composition was evaluated principally against the limits of metallic elements, according to WHO's permissible limits for agricultural soils (Chiroma et al. 2014). Waste deposition significantly increased the content of Cu, Zn, As, Cd, and Pb in the soil from the dumpsite above the regulatory levels for agricultural soils and background values in control (Figs. 5 and 6). The Ni contents in both the dumpsite and control were below limits in arable soils (Fig. 6b). The results of waste deposition cause increases in CEC (126—142 $mmol_{+}\ kg^{-1}$) in all the locus of the dumpsite in comparison with control-9.2 – 15.7 $mmol_{+}\ kg^{-1}$ (Fig. 7).

## Physicochemical characteristics of soil

Soils from the study site and control are primarily similar, exhibiting sandy loam characteristics (72.1 sand: 7.8 silt: 19.3 clay) according to FAO (2008) (Table 1). Sub-soil layers across the loci predominantly characterize coarse particles inter-grained by fine soils (clay and silt) serving as adhesives, which may prevent a high rate of leaching of elements. Meanwhile, a comparatively high percentage of coarse particles may

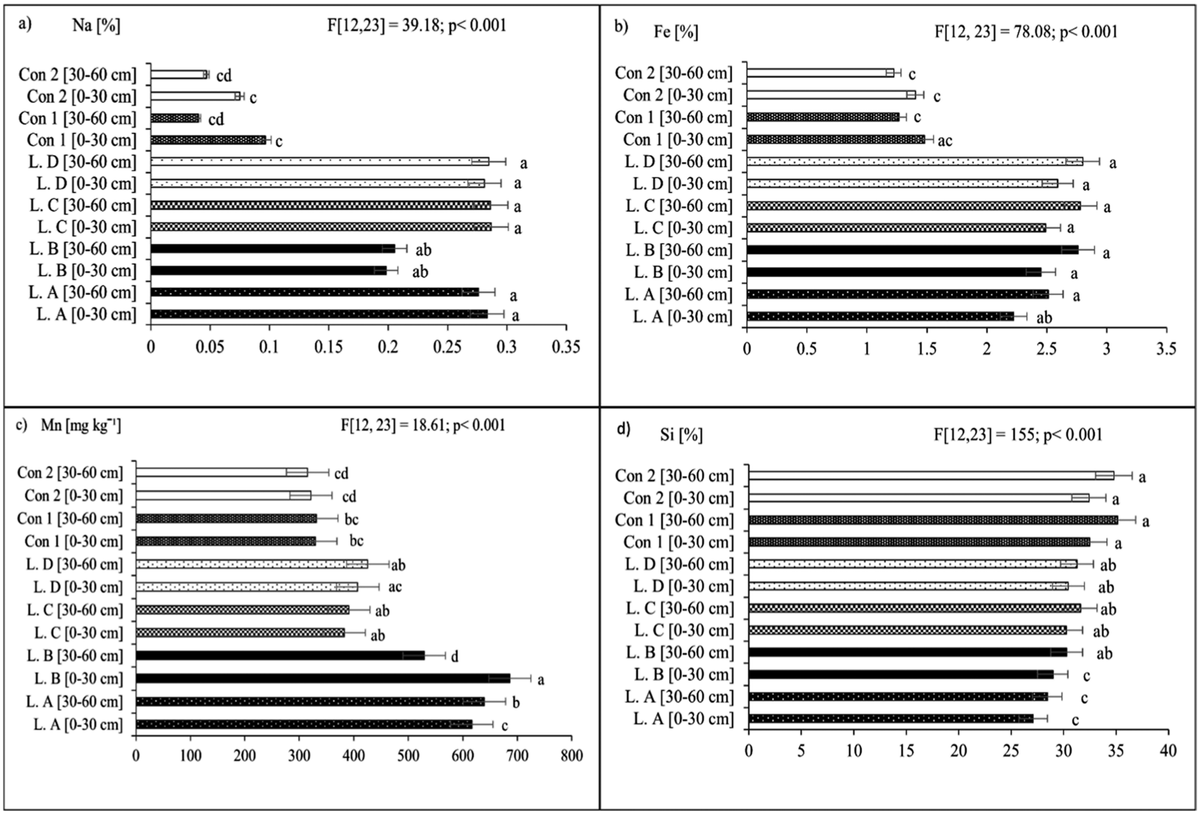


**Fig. 4** Effect of waste deposition on the mean content of total (**a**) Na, (**b**) Fe, (**c**) Mn, and (**d**) Si from different sampled locations. The F-and p-values were obtained by One-way ANOVA. Using Tukey *posthoc* HSD test, mean values with the same letters were significantly not different. The error bars indicate the standard error of the mean

support the preferential gravitational flow of elements in solution form during precipitation.

## Relationship between soil chemical properties and particle size distribution

Gravels (>2 mm), coarse (<2—1 mm) mm), and medium (>1—0.5 mm) soil particles exhibited no significant positive correlation with the studied elements (Table S1). Except for Cu (r=0.60; p<0.05), there was no significant positive correlation between silt (<0.5 – 0.25) and the remaining studied elements. The correlation model indicates no adsorption of elements on clay particles (<0.25 mm). There was no correlation between soil reaction (pH) and the content of S, an indication of no or minimal leaching of elements ($r$=-0.08, p=0.722; y=1.5484—0.0363*x). Soil reaction has a significant positive relationship with Ca (r=0.53; p=0.001) and Na (r=0.55; p=0.005; Figure S1a and b). The contents of Cu, Zn, As, Cd, and Pb have no significant positive correlation with organic C and total N, an indication of less sorption potential (Table S2).

## Potentially toxic elements in plant organs

Individual plant species display different contents of Cu, Zn, As, Cd, and Pb accumulation in their above- and below-ground biomass (Table 2). Out of the overall content of 966 mg Cu $kg^{-1}$ in the soil from the dumpsite, *S. siamea* accumulated 55.4% in the leaf (d wt., dry weight), 15.3% by *C. odorata* L, and approximately 10% for the remaining species. Copper root accumulation was 33.4% in *P. foetida*, 24.4% in *S. tectonum* (24.4%), and 9.1% in *C. odorata L.*

Accumulation percentage according to the mean content of Zn in the soils was 64.5% in *S. siamea,* followed by 55.1% in *P. foetida,* 23.6% in *S. tectonum,* with 21.6% in *C. odorata L.* Root accumulation of Zn was 86.7, 48.4,

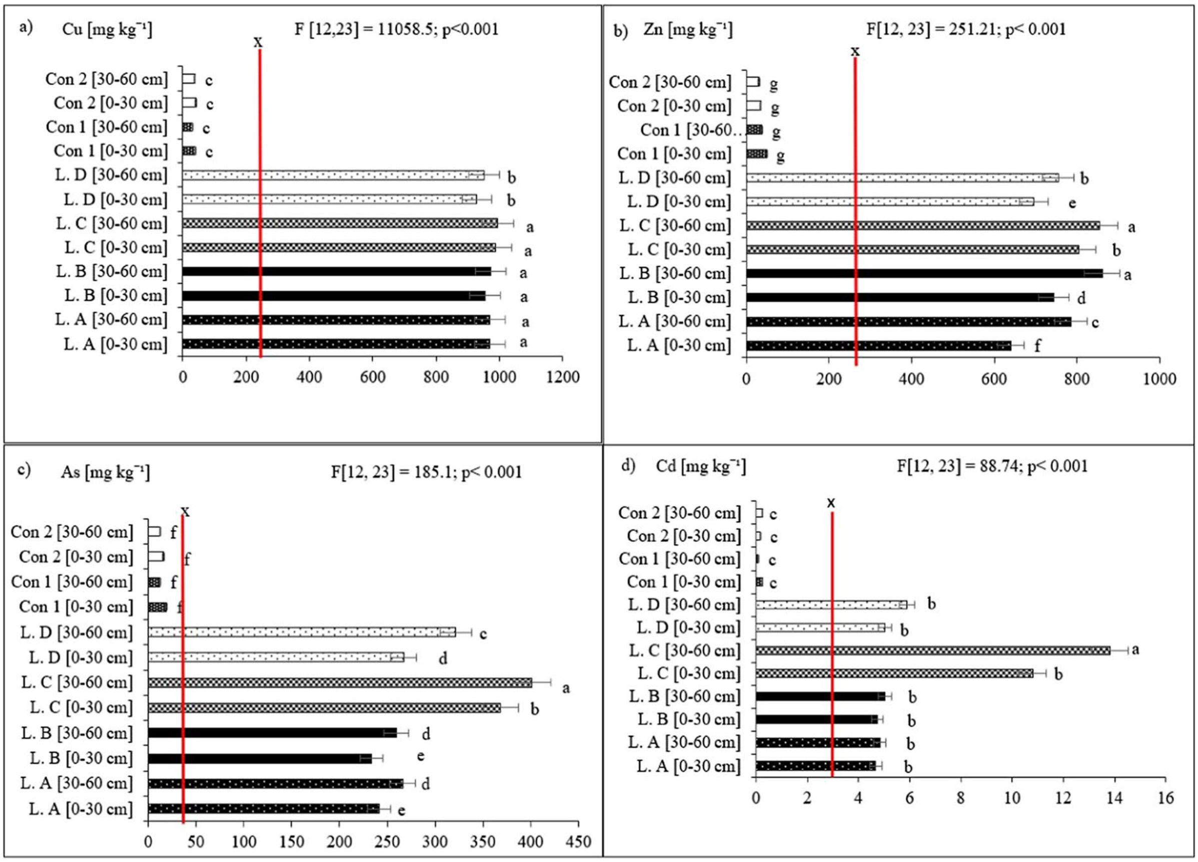


**Fig. 5** Effect of waste deposition on the content of (**a**) Cu, (**b**) Zn, (**c**) As, and Cd from different sampled locations. The F-and p-values were obtained by One-way ANOVA. Using Tukey *posthoc* HSD test, mean values with the same letters were significantly not different. The error bars indicate the standard error of the mean. Abbreviation: x- permissible limit in agricultural soils according to WHO (Chiroma et al. 2014)

and 17.1% in *C. odorata L, S. tectonum,* and *P. foetida,* respectively. Except for *Saccopetalum tectonum* (22.9%), both leaf and root accumulation of As were ≤ 10% in all remaining plant species. Additionally, Cd accumulation in leaves was 201.5, 83.2, 38.2, and 27.7% in *S. siamea, S. tectonum, C. odorata L,* and *P. foetida*, respectively. Root Cd accumulation, except for *C. odorata* L (101.2%), was over 200% for all the species. The accumulation efficiency of Pb was > 100% for all organs of the studied species except for *S. tectonum* (82.8%) in leaves.

### Bioaccumulation indicators

The selected plant species exhibit diverse transport systems of PTEs in different organs (Table 3). *C. odorata L* has a high uptake ability for Cd and Pb (BFr > 1) and an efficient translocation of Pb (BFl > 1) and Cu (TF > 1) to the leaf. Meanwhile, *S. tectonum* has a high soil-root quotient (BFr > 1) for both Cd and Pb, together with effective leave transport (TF < 1). Similarly, *P. foetida* shows high Cd and Pb root uptake, leaf translocation of Pb, and TF > 1 for Zn, while *S. siamea* has high leaf uptake for both Cd and Pb (BF > 1).

## Discussion

One of the misconceptions, especially in rural settings, is that the degradation/decomposition of waste can eventually fertilize soils for crop production. Recent studies have shown the adverse effects of different waste deposition on soils (e.g., Chernykh et al.

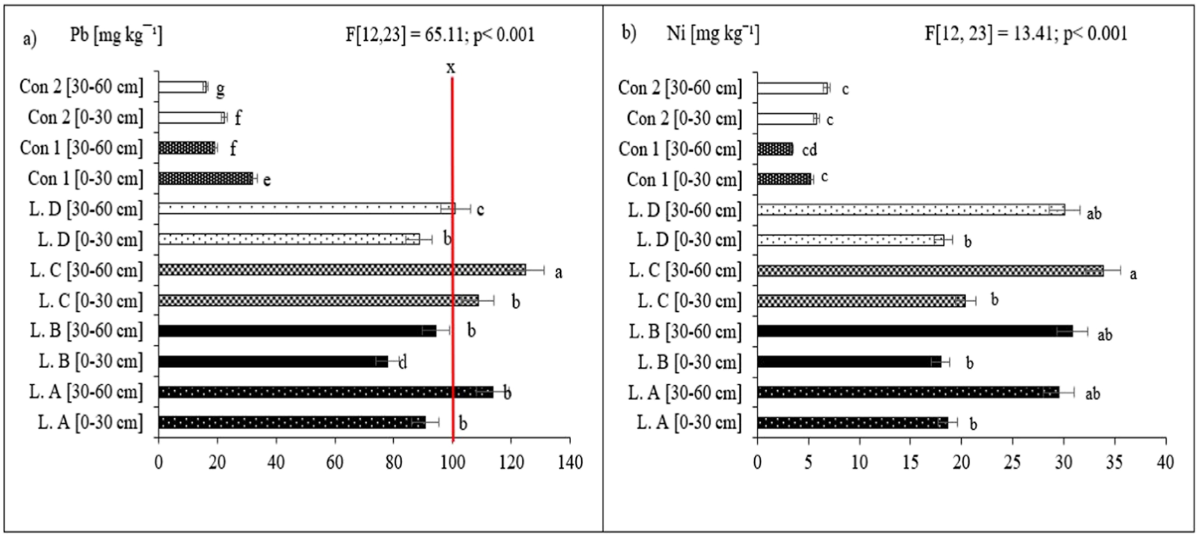


**Fig. 6** Effect of waste deposition on the content of (**a**) Pb and (**b**) Ni from different sampled locations. The F-and p-values were obtained by One-way ANOVA. Using Tukey *posthoc* HSD test, mean values with the same letters were significantly not different. The error bars indicate the standard error of the mean. Abbreviation: x- permissible limit in agricultural soils according to WHO (Chiroma et al. 2014)

2021; Giao and Minh 2022; Yeilagi et al. 2021). The current study offers valuable practical insight into the effects of indiscriminate deposition of waste to soils and the trophic levels, suggesting the critical assessment of several fertility indicators to make conclusive inferences on the use of dumpsites for agricultural fields.

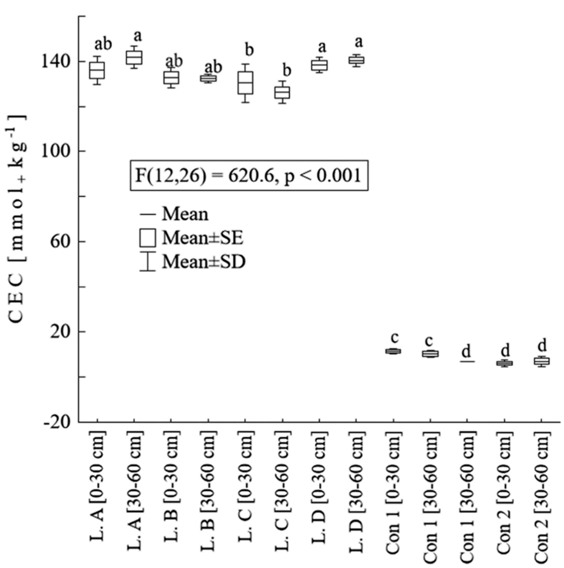


**Fig. 7** Effect of waste deposition on the content of Cation exchange capacity (CEC) from different sampled locations. The F-and p-values were obtained by One-way ANOVA. Using Tukey *posthoc* HSD test, mean values with the same letters were significantly not different

## Implications of soil physicochemical properties on soil fertility

Although the grain distributions of the soils from the dumpsite and control show relatively high similarity with depth, the deposition of domestic waste (e.g., food remains, furniture, and polyethylene materials) and occasional municipal loadings (e.g., plastic materials and by-products of paints from industries) can further affect many soil physical properties. The pore size of the soils with a high fraction of coarse particles ($\geq 2 - 0.5$ mm) supports aeration, which contributes to microorganisms' mobility and hydraulic properties (Hallam 2018; Mangalassery et al. 2013). The relatively high fraction of silt and clay can provide a condition of element retention, while clay particles usually offer a surface area for elements sorption. However, the pH (alkaline) of the anthropogenic soil affects clay dispersion by changing the net charge.

The soil reaction as a "master soil variable" in the anthropogenic soil was slightly alkaline, primarily due to the comparatively high presence of

**Table 1** Physical characteristics, including particle size distribution of soils from the dumpsite and neighboring control (cont.) soils

| Sampled location | Depth [cm] | Texture [a] | Consistency | Grain size distribution [%] | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | ≥ 2 mm | < 2 – 1 mm | < 1 – 0.5 | < 0.5 – 0.25 | < 0.25 |
| | | | | Gravel | Coarse sand | Medium sand | Fine sand | Fines |
| L. A | 0 – 30 | Sandy loam | Coarse slightly sticky + slightly. plastic | 19.4 ± 0.9[a] | 11.5 ± 0.6[ab] | 41.9 ± 2.3[a] | 8.1 ± 0.4[a] | 18.2 ± 1.1[a] |
| | 30 – 60 | Sandy loam | Slightly coarse, sticky + slightly plastic | 17.6 ± 0.3[a] | 11 ± 0.2[ab] | 45 ± 1.9[ab] | 6 ± 0.1[a] | 19.9 ± 0.7[a] |
| L. B | 0 – 30 | Sandy loam | Coarse slightly sticky + slightly plastic | 21.1 ± 1.1[ab] | 12.1 ± 2.2[ab] | 43.8 ± 2.6[ab] | 5.6 ± 0.2[b] | 16.9 ± 1[ab] |
| | 30 – 60 | Sandy clay loam | Coarse, sticky + plastic | 18.7 ± 0.7[a] | 10 ± 0.4[a] | 40.9 ± 1.7[a] | 10 ± 0.09[b] | 20 ± 0.7[a] |
| L. C | 0 – 30 | Sandy loam | Coarse slightly sticky + slightly plastic | 21.4 ± 1.5[ab] | 10.9 ± 0.1[a] | 41.6 ± 3.2[a] | 6 ± 0.3[b] | 19.9 ± 0.3[a] |
| | 30 – 60 | Sandy loam | Slightly coarse, sticky + slightly plastic | 20.7 ± 0.9[ab] | 10.9 ± 0.6[a] | 40.6 ± 2.4[ab] | 8.1 ± 0.5[c] | 19 ± 0.6[a] |
| L. D | 0 – 30 | Sandy loam | Coarse slightly sticky + slightly plastic | 19.7 ± 0.8[a] | 12.5 ± 2[b] | 44.3 ± 2.8[ab] | 5.2 ± 0.02[b] | 18 ± 0.3[a] |
| | 30 – 60 | Sandy clay loam | Coarse, sticky + plastic | 18.1 ± 1.3[a] | 12 ± 2.3[ab] | 40.2 ± 3[a] | 12.3 ± 0.6[d] | 17.2 ± 0.9[ab] |
| Cont. 1 | 0 – 30 | Sandy loam | Coarse, sticky + plastic | 18.1 ± 0.7[a] | 10.3 ± 0.04[a] | 43 ± 0.8[ab] | 8.6 ± 0.8[a] | 20 ± 2[a] |
| | 30 – 60 | Sandy loam | Coarse, sticky + plastic | 18 ± 0.2[a] | 10 ± 0.2[a] | 42.6 ± 1.4[ab] | 9.1 ± 0.2[c] | 19.7 ± 0.9[a] |
| Cont. 2 | 0 – 30 | Sandy loam | Coarse, sticky + plastic | 18.7 ± 0.1[a] | 11 ± 0.6[ab] | 41.4 ± 1[a] | 9.7 ± 0.2[c] | 19.9 ± 1.3[a] |
| | 30 – 60 | Sandy loam | Slightly coarse, sticky + slightly plastic | 16.8 ± 0.4b[b] | 10.9 ± 0.2[a] | 43.7 ± 2.8[ab] | 5.3 ± 0.01[b] | 23 ± 1.5[b] |
| *p*-value | | | | 0.0271 | 0.001 | 0.001 | 0.001 | 0.001 |

[a] represents texture according toFAO (2008)

base-forming cations associated with carbonates and bicarbonates (Ca, K, and Na). Conversely, the acidic conditions occur in control soil with parent material high in elements, such as silica, and high levels of sand with low buffering capacities- the ability to resist pH change (Jiang et al. 2018). Organic matter content evident by the comparatively high contents of SOC and N in the anthropogenic soil is often acidic, and the slightly alkaline condition produces a circum-neutral soil reaction that supports relative mineralization of nutrients for plant uptake. High organic matter and quality, often indicated by C/N values, contribute to optimal mineralization, as in the case of the anthropogenic soil of this study. The soil's ability to hold and supply nutrients is partly related to its CEC, the number of parking spaces for nutrients on soil particles. Cation exchange capacities can also be well-influenced by soil pH. However, in this study, the slightly alkaline pH may produce little or no positive ions. Soils with high amounts of silt/clay and organic matter often show high CEC, which can bind more cations, e.g., Ca, K, and Na. They also have greater buffering capacity.

The decomposition of organic materials indicated by kitchen waste (e.g., animal and fish bones and food remains) contributed to high macro and micronutrients in the anthropogenic soil compared to the control. For instance, the P in the anthropogenic soil (0.16 – 0.23%) was higher than the level for crops and vegetables with high P (0.01 – 0.02%) requirements (Šrek et al. 2010). Besides the comparatively high nutrient (P, Ca, K, S, Fe, Na, and Mn) concentrations

**Table 2** The content of risk elements accumulated in plant organs [leaf and root] and in the soils [mean values of 0—60 cm depths] from the dumpsite

| Location | Species | Cu [mg kg$^{-1}$] | | | Zn [mg kg$^{-1}$] | | | As [mg kg$^{-1}$] | | | Cd [mg kg$^{-1}$] | | | Pb [mg kg$^{-1}$] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Soil | leaf | root | Soil | leaf | root | Soil | leaf | root | Soil | Leaf | root | Soil | leaf | root |
| L. A | *Chromolaena odorata L* | 969 | 171 | 94.5 | 713 | 140 | 807 | 254 | 21 | 4.4 | 4.8 | 3.1 | 6.5 | 102 | 103 | 170 |
| L. B | *Chromolaena odorata L* | 964 | 135 | 81.9 | 802 | 141 | 467 | 247 | 18 | 6.8 | 4.9 | 2.6 | 6.8 | 86.2 | 122 | 146 |
| L. C | *Chromolaena odorata L* | 991 | 147 | 81.5 | 830 | 194 | 471 | 385 | 22.4 | 8.1 | 12 | 2.5 | 7.7 | 117 | 119 | 187 |
| L. D | *Chromolaena odorata L* | 940 | 139 | 91.9 | 725 | 188 | 917 | 294 | 20 | 7.5 | 5.5 | 2.4 | 6.8 | 95 | 149 | 227 |
| | **Mean** | **966** | **148** | **87.4** | **768** | **166** | **665** | **295** | **20.2** | **6.7** | **6.9** | **2.6** | **7** | **100** | **123** | **182** |
| L. A | *Saccopetalum tectonum* | 969 | 74 | 220 | 713 | 213 | 323 | 254 | 51 | 32 | 4.8 | 7.3 | 102 | 102 | 86 | 194 |
| L. B | *Saccopetalum tectonum* | 964 | 78 | 254 | 802 | 168 | 370 | 247 | 41.5 | 27.8 | 4.9 | 1.1 | 114 | 86.2 | 70 | 194 |
| L. C | *Saccopetalum tectonum* | 991 | 94 | 243 | 830 | 144 | 421 | 385 | 71.4 | 33 | 12 | 3.6 | 112 | 117 | 81 | 166 |
| L. D | *Saccopetalum tectonum* | 940 | 119 | 230 | 725 | 199 | 373 | 294 | 106 | 29.5 | 5.5 | 10.7 | 104 | 94.8 | 95 | 178 |
| | **Mean** | **966** | **91** | **237** | **768** | **181** | **372** | **295** | **68** | **31** | **6.9** | **5.7** | **108** | **100** | **83** | **183** |
| L. A | *Passiflora foetida* | 969 | 103 | 309 | 713 | 475 | 129 | 254 | 21.9 | 23 | 4.8 | 1.6 | 67 | 102 | 126 | 577 |
| L. B | *Passiflora foetida* | 964 | 107 | 331 | 802 | 403 | 116 | 247 | 12.3 | 27.6 | 4.9 | 2.2 | 69 | 86 | 145 | 436 |
| L. C | *Passiflora foetida* | 991 | 93 | 338 | 830 | 372 | 145 | 385 | 12.6 | 24.1 | 12 | 2 | 75 | 117 | 125 | 451 |
| L. D | *Passiflora foetida* | 940 | 122 | 312 | 725 | 442 | 136 | 294 | 10.5 | 21.2 | 5.5 | 1.7 | 91 | 95 | 161 | 448 |
| | **Mean** | **966** | **106** | **322** | **768** | **423** | **131** | **295** | **14.3** | **24** | **6.9** | **1.9** | **76** | **100** | **139** | **478** |
| L. A | *Senna siamea* | 969 | 530 | - | 713 | 464 | - | 253.9 | 10 | - | 4.8 | 10.8 | - | 102 | 169 | - |
| L. B | *Senna siamea* | 964 | 518 | - | 802 | 483 | - | 246.7 | 14.6 | - | 4.9 | 17.2 | - | 86.2 | 119 | - |
| L. C | *Senna siamea* | 991 | 505 | - | 830 | 515 | - | 384.9 | 23.8 | - | 12 | 11.8 | - | 117 | 161 | - |
| L. D | *Senna siamea* | 940 | 588 | - | 725 | 520 | - | 294.4 | 24.9 | - | 5.5 | 15.7 | - | 94.8 | 138 | - |
| | **Mean** | **966** | **535** | | **768** | **495** | | **295** | **18.3** | | **6.9** | **13.8** | | **100** | **147** | |

Bold values indicate mean contents of PTEs in soils and plants

**Table 3** Bioavailability indices, including bioaccumulation [BF] and translocation [TF] factors of potentially toxic elements [PTEs] of selected plant species

| PTEs | *Chromolaena odorata L* | | | *Saccopetalum tectonum* | | | *Passiflora foetida* | | | *Senna siamea* |
|---|---|---|---|---|---|---|---|---|---|---|
| | BFl [l/s] | BFr [r/s] | TF | BFl [l/s] | BFr [r/s] | TF | BFl [l/s] | BFr [r/s] | TF | BFl [l/s] |
| Cu | 0.15 | 0.09 | **1.68** | 0.09 | 0.24 | 0.39 | 0.11 | 0.33 | 0.33 | 0.55 |
| Zn | 0.22 | 0.87 | 0.25 | 0.24 | 0.48 | 0.49 | 0.55 | 0.17 | **3.22** | 0.51 |
| As | 0.07 | 0.02 | **3.03** | 0.23 | 0.1 | **2.21** | 0.05 | 0.08 | 0.6 | 0.06 |
| Cd | 0.38 | **1.02** | 0.38 | 0.83 | **15.7** | 0.05 | 0.28 | **11.02** | 0.03 | **2.01** |
| Pb | **1.23** | **1.82** | 0.68 | 0.83 | **1.83** | 0.45 | **1.39** | **4.78** | 0.29 | **1.47** |

Bioavailability indices were estimated from the mean contents of elements in soil (0—60 cm) and plant organs. Abbreviation: l = leaf; s = soil; r = root. BF; TF > 1 indicates the plant could potentially be a hyperaccumulator [Baker (1981) and Mesa et al. (2017)]

Bold values indicate mean contents of PTEs in soils and plants

in the anthropogenic soils, these were within the values in agricultural soils without the application of mineral fertilizers (Marschner 1995; Šrek et al. 2010), which can promote maximum crop growth. Considering the withered nutrient-poor soils of the control in this study, often from the tropics, many farmers may resort to anthropogenic soil from the dumpsite for crop and herbage production.

As plant nutrients needed in small quantities (5 – 20 mg kg$^{-1}$ for most recorded values; Marschner

**Table 4** Mean content of potentially toxic elements in organs of selected plants species and their respective permissible limits

| PTE | *Chromolaena odorata* | | *Saccopetalum tectonum* | | *Passiflora foetida* [mg kg$^{-1}$] | | *Senna siamea* | *WHO permissible limit in plants [mg kg$^{-1}$] | **EU leaf vegetables/ fresh herbs [mg kg$^{-1}$] | ***EU root vegetables [mg kg$^{-1}$] |
|---|---|---|---|---|---|---|---|---|---|---|
| | leaf | root | leaf | root | leaf | root | leaf | | | |
| Cu | 148 | 87 | 91 | 237 | 106 | 322 | 535 | 10 | 0.3 | |
| Zn | 166 | 665 | 181 | 372 | 423 | 131 | 495 | 0.6 | < 0.5 | |
| As | 20.2 | 6.7 | 68 | 31 | 14.3 | 24 | 18.3 | 0.5 | - | |
| Cd | 2.6 | 7 | 5.7 | 108 | 1.9 | 76 | 14 | 0.02 | 0.2 | 0.1 |
| Pb | 123 | 182 | 83 | 183 | 139 | 478 | 147 | 2 | 0.3 | |

*WHO (1996)

**Commission Regulation (EC) No 1881/2006 of 19 December 2006 set maximum levels for certain contaminants in foodstuffs (Text with EEA relevance)

***https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32006R1881

1995), the contents of Cu and Zn as plant nutrients were above the permissible limit in agricultural soils, according to FAO/WHO (100 mg kg$^{-1}$ Cu) and EU (140 mg kg$^{-1}$ Cu) guidelines, and 300 mg kg$^{-1}$ for Zn, rendering them toxic for plant (Chiroma et al. 2014; European guidelines 2002). The higher content of PTEs in the soil from the dumpsite is partly the result of the deposition of recycled plastic waste. In this case, PTEs can be used in plasticizers, pigments, stabilizers, and reinforcement components (Luo et al. 2011; Nakashima et al. 2011; Rochman et al. 2013, Hopewell et al. 2009). Morf et al. (2007) reported the upper content range of Pb at 100 – 2000 mg kg$^{-1}$ in the plastic fraction of waste electrical and electronic equipment, which eventually deposited as municipal waste.

## Potentially toxic elements uptake and accumulation by plants

Plants can break the core rules governing the uptake and accumulation of PTEs. For example, some plants produce root exudates and attract specific microbes for PTEs dissolution for effective uptake and nutrient fixation (Visioli et al. 2015), while others (e.g., *Arabidopsis thaliana*) possess active protein transporters (Balafrej et al. 2020). *Acinetobacter, Bacillus, Gluconacetobacter*, and *Pseudomonas* are well-characterized by Zn solubilization (Costerousse et al. 2017), which involves the reduction of soil pH, Zn chelation, or improvement of root growth. However, these mechanisms differ from one microorganism to another. Studies by Vogel-Mikuš et al. (2006) concluded that colonization by arbuscular mycorrhizal in *Nocceae praecox* increased the Zn shoot-to-root ratio, indicating better Zn uptake.

Several plants have different strategies for accumulating excess PTEs in their organs, including the most edible parts, e.g., root/tuber/rhizomes and leaves. In an attempt to exclude high Cu, *P. foetida* retains 40% Cu in the root. Meanwhile, 40% of 966 mg Cu kg$^{-1}$ in the soil represents 386 mg Cu kg$^{-1}$, still above the permissible limit for edible crops (FAO/WHO; Table 4). Similarly, *S. tectonum* had a root accumulation of 24.5% Cu content. It is worth noting that plants, such as *S. siamea,* are used locally in treating malaria fever, especially the leaves (Nas et al. 2018). Meanwhile, this study shows that the leaves of *S. siamea* can accumulate Cu, Zn, As, Cd, and Pb above permissible limits when compared to FAO/WHO and EU (Commission Regulation (EC) No 1881/2006) standards.

The persistence of the selected plant species in the contaminated soil resulted from the adaptation by tolerance or by accumulation and detoxification. All the studied plant species exhibited high tolerance and accumulation, especially for Cd and Pb (BF > 1), which provide a basis for their inclusion in phytoremediation schemes of contaminated sites. Notably, many food crops and vegetables have the high ability to uptake and distribute PTEs in their organs in urban, peri-urban, and rural areas, e.g., *Rumex alpinus*, *Brassica oleracea var. capitata*, and *Daucus carota* (Jungová et al. 2022; Mensah et al. 2009). Selection of the studied plant species in extracting PTES in soils depends on the level of contamination, while critical attention is needed, especially in toxicology, due to the medicinal values of some of these plant species.

Even though many plants exhibit restrictive transport of Pb to shoot due to apoplastic blockage in the root (Asare et al. 2022; Dogan et al. 2018), the leaf content was higher than the allowable limit. Meanwhile, the upward accumulation of Pb by different plants is associated with the content of bioavailable fraction taken by the root (Ashraf et al. 2020). Factors such as enzymatic activities and root exudates (e.g., organic acids) support the desorption of PTEs for subsequent bioavailability (Sun et al. 2020). For example, although total Pb accumulation in *Tetraena qataranse*, in the root, was higher (2784 mg $kg^{-1}$) than that of the shoot (1142 mg $kg^{-1}$), enzymatic activities of superoxide dismutase, catalase, ascorbate peroxidase, guaiacol peroxidase, and glutathione reductase showed a progressive increase in enzymatic activities due to Pb treatment, which enabled easy plant absorption of Pb (Usman et al. 2020). The root architecture of some plants controls soil exploration by regulating plant ability for element uptake (Galindo-Castañeda et al. 2022), thus, the high accumulation of Pb in the leaf of *S. siamea* supports its vital characteristics for phytoextraction of Pb (Gajbhiye et al. 2016). Minimal or no adsorption of cationic elements, e.g., Pb, is implicated by insignificant correlations between organic matter fraction (C and N) and the PTEs.

The redevelopment of waste landfills for agricultural purposes remained sufficiently researched in other parts of the world with mixed results. Green et al. (2014) concluded that places with historic landfills repurposed for grazing are generally safe for grazers, while animals remain exposed to high metal ingestion rates. A study in Eritrea focused on crops grown in landfill soil and observed that although the landfill soil improved the fertility of farmers' fields, it had alarming contents of metals (Tesfai and Dresher 2009). It is now evident that plants can grow well on soils from dumpsites due to nutrient availability. However, these plants may still support the uptake and accumulation of PTEs in different compartments and can adversely affect potential consumers. Unfortunately, food security and quality are less assessed at many local government levels. Although several studies have reported high contents of PTEs, including Pb and Cd, in soil dumpsites (e.g., Giao and Minh 2022; Musa et al. 2019), a direct relationship with plants will indicate the level of impact on the food chain.

## Conclusions

The study revealed the characteristics of anthropogenic soils developed from the indiscriminate deposition of wastes, as these soils are often transformed into arable lands. Physical properties, including the porosity of the studied anthropogenic soils, remained relatively similar compared to the surrounding control without the mark of waste deposition. The anthropogenic soils were well-characterized by slightly neutral soil reactions and high CEC, resulting in the presence of high cationic nutrients (Ca, K, and Na). The high content of SOC and N contributed to the optimal C-N ratio of the anthropogenic soils, which provides a basis for the mineralization of nutrients. The fertility of the soils from the dumpsite was coupled with a substantially high accumulation of macro (P, Ca, K, and S) and micro (Mn, Na, and Fe) nutrients, with no or minimal indication of leaching to groundwater, according to the content of elements at different depths of the soil.

Although the results of the fertility indicators of the anthropogenic soil permit cultivation, the contents of PTEs (Cu, Zn, As, Cd, and Pb) were above regulatory limits in agricultural soils, according to WHO. Availability of Cu, Zn, As, Cd, and Pb in the organs of tolerant plant species (*Chromolaena odorata*, *Saccopetalum tectonum*, *Passiflora foetida,* and *Senna siamea)* in the dumpsite indicate that these crops and herbages produced from this sites can be detrimental to the health of consumers. As many waste disposal sites are not well-streamlined to strategically address their agricultural use, critical analysis of soils and existing plants are required before their use for crop and herbage production.

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**Data availability statement** The datasets generated during and/or analyzed during the current study are available from the corresponding author.

**Declarations**

**Competing interests** The authors declare no conflict of interest.

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