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Local Plants Potentially Suitable for Phytoremediation of Soils Polluted by Heavy Metals: The Case of Landfill Sites

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Abstract

Landfills are contaminated sites that need to be cleaned up to prevent human and environmental exposure to pollutants. This article aims to identify local plants capable of restoring soil polluted by heavy metals. To this end, plant species at the Bonoua landfill were inventoried. X-ray fluorescence spectrometry was used to determine the heavy metal content of soil and plants from the landfill. The bioconcentration factor (BCF) of metals in plants was evaluated. The Bonoua landfill is covered with 62 plant species, comprising 28 botanical families and 50 genera. The BCF varied from 0.08 (titanium) to 2.27 (strontium) for *Phyllanthus amarus*; from 0.06 (titanium) to 1.83 (copper) for *Alternanthera sessilis* and from 0.03 (arsenic) to 2.10 (strontium) for Amaranthus spinosus. *Phyllanthus amarus*, *Alternanthera sessilis*, and *Amaranthus spinosus* are strontium-accumulating species (BCF > 1). Similarly, copper BCF values were above 1 for *Phyllanthus amarus*, and *Alternanthera sessilis*. These two plant species are therefore copper accumulators. In short, *Phyllanthus amarus*, *Alternanthera sessilis*, and *Amaranthus spinosus* are candidate species for phytoremediation of heavy metal-polluted soils, given their BCF > 1.

Keywords

Heavy Metals, Phytoremediation, *Phyllanthus amarus*, *Alternanthera sessilis*, *Amaranthus spinosus*

1. Introduction

The management of household waste is a major challenge facing urban centers.

In developing countries, waste is collected from households and transported to landfill sites. Some landfills are equipped with devices that enable waste to be treated by more or less secure burial. Other landfills, on the other hand, are open-air and the waste decomposes slowly, releasing many harmful chemical substances into the soil, including trace metals (Chaer et al., 2016; Hussein et al., 2021; Hölzle et al., 2022). Their presence in the soil represents a potential threat to man and the environment. Trace metals are known to have various harmful effects on humans, including cadmium proteinuria, osteomalacia, hydrargyrism, tubular nephritis and growth disorders in children (Unak et al., 2007; Musa & Abdullahi, 2013). These toxic effects generally result from the disruption of cellular events, including growth, proliferation, differentiation, damage repair processes and apoptosis (Jaishankar et al., 2014; Balali-Mood et al., 2021; Mitra et al., 2022). Furthermore, heavy metals from landfills can seep into the soil and then contaminate groundwater, which is the source of drinking water supplies. These metals can also migrate to surface waters (lakes, rivers, lagoons and sea) under the action of runoff, and contaminate the food chain (Adjiri et al., 2008; Chaer et al., 2016; Bellouard, 2023). To avoid contamination of trophic chains by pollutants, soils must be depolluted when landfills are closed. Traditional methods for depolluting contaminated sites involve excavating contaminated soil layers and confining them in hermetically sealed, oxidation-resistant enclosures to prevent human exposure and the escape of pollutants to new areas (Scullion, 2006). However, these practices are not only costly but also destructive of the land's arable horizons. In addition, these practices intensify air pollution through the carbon dioxide released by the motorized machinery involved in excavation. Given the consequences of traditional methods of soil decontamination, research is increasingly turning towards biological methods of soil decontamination, among which phytoremediation is becoming more and more emerging (Chen et al., 2022). Phytoremediation, a method based on the use of plants that hyperaccumulate pollutants, is a less costly and more environmentally friendly alternative (Petruzzelli et al., 2021; Durante-Yánez et al., 2022; Sharma et al., 2023). Phytoremediation have been used for depollution water and soil, and this led to promising results (Cui et al., 2012; Buscaroli, 2017; Mustafa & Hayder, 2021). The aim of this work was to study the potential of some local plants to decontaminate sites polluted by heavy metals. This requires both a study of species abundance and an assessment of the bioconcentration potential of trace metals in some species, found landfill site of Bonoua (Côte d'Ivoire). This study could help strengthen the list of plants potentially suitable for phytoremediation.

2. Materials and Methods

2.1. Study Area

Bonoua, a locality of over 4300 hectares which includes the villages of Yaou, Adiaho, Tchentcevé, and Samo, is located in the Sud-Comoé region, with Aboisso as its capital (Ake, 2010). It is located at latitudes 5˚07'N to 5˚33'N and longitudes 3˚12'W to 3˚45'W, at an altitude of 30 m above sea level. It is around 60 kilometers from Abidjan, the economic capital of Côte d'Ivoire. It is bordered to the south by the Atlantic Ocean, to the southeast by Adiaké, to the northeast by Aboisso, to the southwest by the Department of Grand-Bassam, and the northwest by Alépé. According to the 2021 General Population and Housing Census (RGPH), the population of Bonoua is estimated at 118,388 (RGPH, 2021). The study area is shown on **Figure 1**.

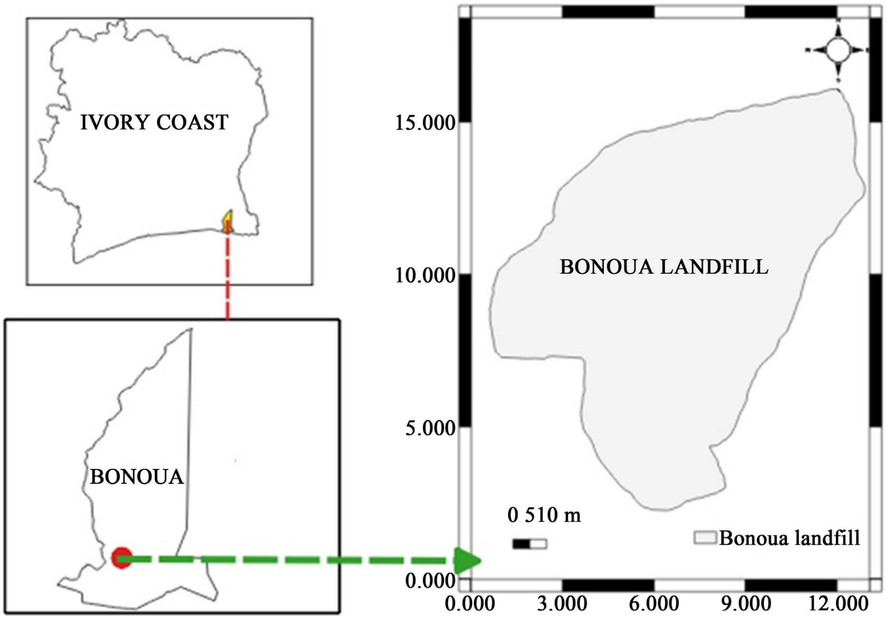

Figure 1. Location of study area.

2.2. Floristic Inventory

Floristic data were collected using itinerant and surface surveys. The itinerant survey is an inventory carried out during walks or hikes (Malan et al., 2007), across the landfill to collect all plant species present. This inventory was used to draw up a preliminary floristic list to facilitate identification for abundance studies. The surface inventory consists of plots of variable geometry (square, rectangular, or circular), depending on the study objective and the relief of the site studied, in which the data sought are taken (Adjakpa et al., 2013). In the present study, ten (10) square plots measuring 4 meters on each side (16 m^2) were laid out at regular intervals on the landfill site. Each plot was visited twice a month over 5 months from April to August 2022. All plants encountered in a plot were recorded, along with the number of individuals, to assess abundance. Herbarium samples were collected and deposited at the herbarium of the Centre Suisse de Recherches Scientifiques en Côte d'Ivoire (CSRS). The plants encountered were identified by specific rank either in the field or at the herbarium of the Centre Suisse de Recherches Scientifiques en Côte d'Ivoire (CSRS). Herbarium determinations were made possible by comparing collected samples with older specimens and using specialist literature (Aké-Assi, 2001) and an online database http://www.ville-ge.ch/musinfo/bd/cjb/africa/. The nomenclature adopted is that of the phylogenetic classification (Chase et al., 2016).

2.3. Soil Sample Collection

Soil samples were taken at the four cardinal points and the center of the landfill. Two (02) samples were taken at the center of the landfill site. At each cardinal point, six (06) samples were collected. The sampling system is shown in **Figure 2**.

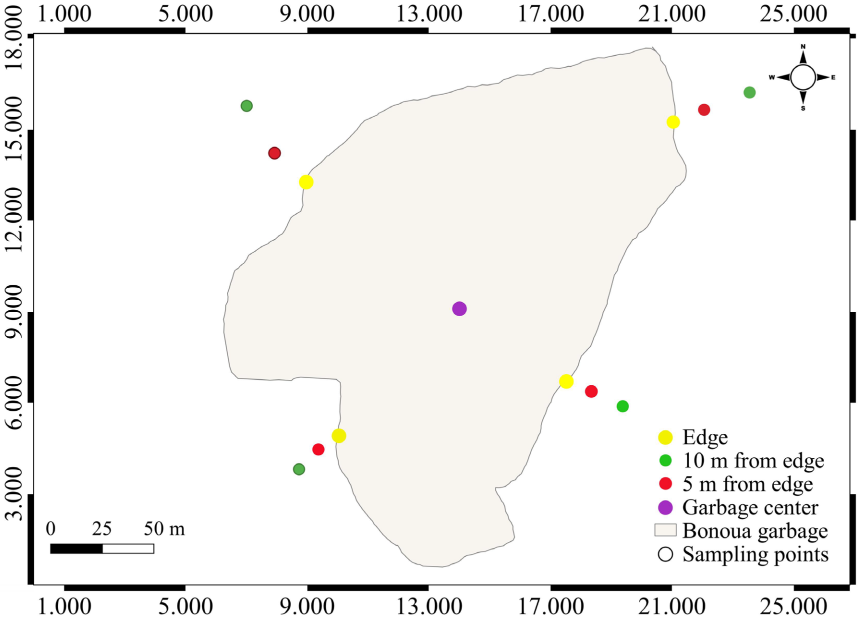

Figure 2. Soil sampling points.

Soil samples were taken from 30 cm × 30 cm × 30 cm soil profiles at the sampling points. Soil samples were taken from the 0 - 15 cm and 15 - 30 cm horizons, resulting in two soil samples for each soil profile with an individual mass of 200 g.

2.4. Determination of the Physico-Chemical Parameters of Soil

Soil organic matter content was determined following the method MA. 1010-PAF 1.0, using Nabertherm muffle furnace (Lilienthal, Germany) (CEAEQ, 2003). Soil pH (water) was determined according to the method MA. 205-pH 1.0 (CEAEQ, 2014) using Hach HQ40d multimeter (Loveland, USA).

2.5. Determination of Heavy Metals Concentrations

The choice of species was based on their abundance, woody character, and life cycle (perennial or annual). We chose annual and non-woody species to facilitate the determination of heavy metals in the entire plant. Among annual and non-woody plants, abundant species were selected because these species were assumed to withstand environmental conditions (landfill soil), and may therefore accumulate heavy metals. We also selected rare species to know the behavior of these species toward heavy metals. This approach led to the selection of three species: *Phyllanthus amarus*, *Alternanthera sessilis*, and *Amaranthus spinosus*. Entire plants were harvested and rinsed thoroughly with ultrapure water before drying. Plant samples were cut and dried at room temperature for a week on carefully cleaned benches to avoid cross-contamination. Soil samples were also dried on cleaned benches. Once dried, the soil and plant samples were ground separately using an electric blender (Omni International, Kennesaw, Georgia). The different grindings were sieved using a (plastic) sieve with a mesh diameter of 250 µm. After sieving, the shreds were carefully homogenized with a spatula before the metal determination phase. The heavy metals concerned were titanium (Ti), chromium (Cr), copper (Cu), strontium (Sr), tin (Sn), tellurium (Te), lead (Pb), and arsenic (As). These metallic elements were determined using an Epsilon 1 X-ray fluorescence spectrometer (Malvern Panalytical, Netherlands). Ten (10) g of plant crushed material or 3 g of soil were sampled in the XRF cup and read over 22 min. The spectrometer was calibrated beforehand using pure standards of the metals concerned. Thus, pure standards of titanium 1000 µg/ml (Specpure™), chromium 1000 µg/ml (Fisher Chemical™), copper 1000 µg/ml (SPEX CertiPrep™), tin 1000 µg/ml (Fisher ChemicalTM), and tellurium 1000 µg/ml (Chem LabTM) were used. In the same vein, strontium 1000 µg/ml (Fisher chemical™), lead 1000 µg/ml (Chem LabTM), and arsenic, 1000 µg/ml (Thermo Fisher ChemicalTM) standards were used. Soil and plant matrix blanks were made from sea sand and wood powder respectively. One hundred (100) g of each matrix blank was washed with (2 × 500) ml of an aqueous solution of 2% HNO_3, then rinsed with 500 ml of ultrapure water before being completely air-dried. These matrix blanks were spiked to give references of 0 mg/kg, 50 mg/kg, 100 mg/kg, 250 mg/kg, 500 mg/kg, 700 mg/kg, 850 mg/kg, and 1000 mg/kg for each metal and blank type. The calibration curve was constructed for each metal. The metal contents of the samples were determined from the equations of the calibration curves whose linear regression model is described by Equation (1).

$$y = ax + b \Rightarrow x = \left(y - b\right)/a \tag{1}$$

where y = radioactivity intensity (cps/mA), x = metal concentration (mg/kg), a = slope, b = intercept.

Fidelity was assessed by determining repeatability and reproducibility (interlaboratory reproducibility). Repeatability was achieved using matrix blanks spiked with 50 mg/kg metal. For each matrix blank, the metal content was determined over 15 consecutive days by the same operator, at a rate of 10 readings per day. The same matrix blanks (50 mg/kg) were used to measure intralaboratory reproducibility over 15 days. During this period, three reading sequences separated by 5 days, at a rate of 10 readings per day, were carried out. The latter task was carried out by a different operator from the one who performed the repeatability. Coefficients of variation (CV) and relative standard deviations were determined according to Equations (2) and (3) (Kpan et al., 2022).

$$CV(\%) = \frac{\sigma_{n-1}}{\overline{x}} \times 100 \tag{2}$$

$$\text{RSD } R(\%) = 100(C - C_r)/C_r \tag{3}$$

where CV = coefficient of variation (%), σ_{n-1} = standard deviation, ($\overline{x}$) = mean (mg/Kg), Cr = real concentration C = mean of determined concentrations.

Detection limits (LODs) were calculated using three times the square root of the background. For this purpose, the matrix blanks were measured ten times under the best conditions chosen for this type of analysis, using the calibration curves obtained (Spolnik et al., 2005). The limits of quantification (LOQ) were set at three times the LOD.

2.6. Determination of the Bioconcentration Factor (BCF)

The bioconcentration factor was calculated as the ratio of the plant's heavy metals content to that of the soil (Equation (4)). It is used to determine the capacity of a plant species to accumulate a trace metal (Yoon et al., 2006):

$$\text{BCF} = \frac{\text{Concentration of metals in plant}}{\text{Concentration of metals in soil}} \tag{4}$$

where BCF = Bioconcentration factor.

2.7. Statistical Analysis

Data were analyzed using SATISTICA 7.1 software. A one-factor analysis of variance (ANOVA) was performed for all parameters to compare the metal contents of the samples. Tukey's HSD test was used, and the significance level was set at 5%.

3. Results

3.1. Floristic Composition and Diversity

The floristic inventory identified 62 plant species in 50 genera and 28 botanical families. The most represented botanical families in terms of number of individuals are Amaranthaceae (25.18%) and Euphorbiaceae (12.65%). The most represented species are *Amaranthus spinosus* (18.25%) and *Phyllanthus amarus* (10.10%), which belong to the Amaranthaceae and Phyllantaceae families respectively (**Table 1**).

3.2. Phyco-Chemical and Analytical Parameters

The pH values of soil were 8.28 ± 0.04 (Landfill center), 8.12 ± 0.05 (Landfill edge), 7.77 ± 0.02 (5 m from the landfill edge) and 7.29 ± 0.06 (10 m from the landfill edge). The organic matter content was 11.6% ± 0.12% (Landfill center), 10.4% ± 0.11% (Landfill edge), 9.82% ± 0.06% (5 m from the landfill edge) and

Table 1. Plant species collected at the Bonoua landfill site.

Species (number of individuals)	Family	TNI	PF(%)
Alchornea cordifolia (2); *Euphorbia hirta* (26); *Euphorbia thymifolia* (15); *Euphorbia trinervia* (3); *Jatropha gossypiifolia* (23); *Manihot esculenta* (10); *Ricinus communis* (25)	Euphorbiaceae	104	12.65
Alternanthera sessilis (1); *Amaranthus spinosus* (150); *Amaranthus hybridus* (2); *Celosia argentea* (53); *Centrosema pubescens* (1)	Amaranthaceae	207	25.18
Basella alba (2)	Basellaceae	2	0.24
Brachiaria deflexa (1); *Cassia sieberiana* (5); *Eleusine indica* (5); *Panicum repens* (45); *Urochloa maxima* (9); *Zea mays* (3)	Poaceae	68	8.27
Capsicum annuum (6); *Solanum anomalum* (2); *Solanum lycopersicum* (15); *Solanum macrocarpon* (4); *Solanum nigrum* (3); *Solanum rugosum* (4)	Solanaceae	34	4.14
Ceiba pentandra (1)	Caricaceae	1	0.12
Cassia sieberiana (5); *Neustanthus phaseoloides* (3); *Indigofera hirsuta* (2); *Senna occidentalis* (13); *Vigna unguiculata* (8)	Fabaceae	31	3.77
Ceiba pentandra (1)	Bombacaceae	1	0.12
Citrullus lanatus (30); *Cucumis Sativus* (3); *Melothrias phaerocarpe* (22)	Cucurbitaceae	55	6.69
Cleome gynandra (15); *Cleome viscosa* (29); *Sieruela rutidosperma* (18)	Capparaceae	62	7.54
Corchorus aestuans (2); *Corchorus olitorius* (14); *Hibiscus sabdariffa* (1); *Triumfetta pentandra* (7)	Malvaceae	24	2.92
Cyperus amabilis (62); *Cyperus betafensis* (15); *Mariscus ligularis* (3)	Cyperaceae	80	9.73
Eclipta prostrata (2)	Asteraceae	2	0.24
Ficus exasperata (2)	Moraceae	2	0.24
Heliotropium indicum (2)	Boraginaceae	2	0.24
Ipomoea batatas (16); *Ipomoea cairica* (1)	Convolvulaceae	17	2.07
Laporte aaestuans (5)	Urticaceae	5	0.61
Lawsonia inermis (1)	Lythraceae	1	0.12
Musa tropicana (4)	Musaceae	4	0.49
Ocimum monostachyum (7)	Lamiaceae	7	0.85
Passiflora edulis (1); *Passiflora foetida* (4)	Passifloraceae	5	0.61
Philodendron sp (2)	Araceae	2	0.24
Phyllanthus amarus (83)	Phyllantaceae	83	10.10
Portulaca oleracea (11)	Portulacaceae	11	1.34
Senna alata (2)	Caesalpiniaceae	2	0.24
Talinum fruticosum (5)	Talinaceae	5	0.61
Terminalia catappa (4)	Combretaceae	4	0.49
Trianthema portulacastrum (1)	Aizoaceae	1	0.12

TNI: total number of individuals in each family; PF: percentage of families (%).

7.79% ± 0.04% (10 m from the landfill edge). The coefficients of determination for all calibration curves were very close to 1 (0.9995 - 0.9997). The probability (p) values associated with Fisher's F-test were below 5%. This indicates a good correlation between metal contents and spectrometer responses (**Table 2**).

Figure 3 shows calibration curves for Fe, Pb and As.

The relative limits of quantification for soil are between 3 mg/Kg and 15 mg/Kg, while those for plants are between 2.1 mg/Kg and 18 mg/Kg (**Table 3**).

Relative standard deviation and coefficients of variation for repeatability and reproducibility were below 5% (**Table 4**).

Table 2. Characteristics of metal calibration curves.

Metal	Equation of linear regression	R^2	F-test value
Iron (Fe)	$y = 15.304x + 97.979$	0.9995	<0.0001
Titanium (Ti)	$y = 13.848x + 68.91$	0.9996	<0.0001
Chromium (Cr)	$y = 16.321x + 81.93$	0.9996	<0.0001
Copper (Cu)	$y = 15,834x + 76.022$	0.9996	<0.0001
Tellurium (Te)	$y = 14.195x + 90.88$	0.9995	<0.0001
Lead (Pb)	$y = 14.91x + 66.935$	0.9996	<0.0001
Strontium (Sr)	$y = 14.455x + 72.623$	0.9996	<0.0001
Tin (Sn)	$y = 14.81x + 70.052$	0.9997	<0.0001
Arsenic (As)	$y = 14.054x + 68.588$	0.9996	<0.0001

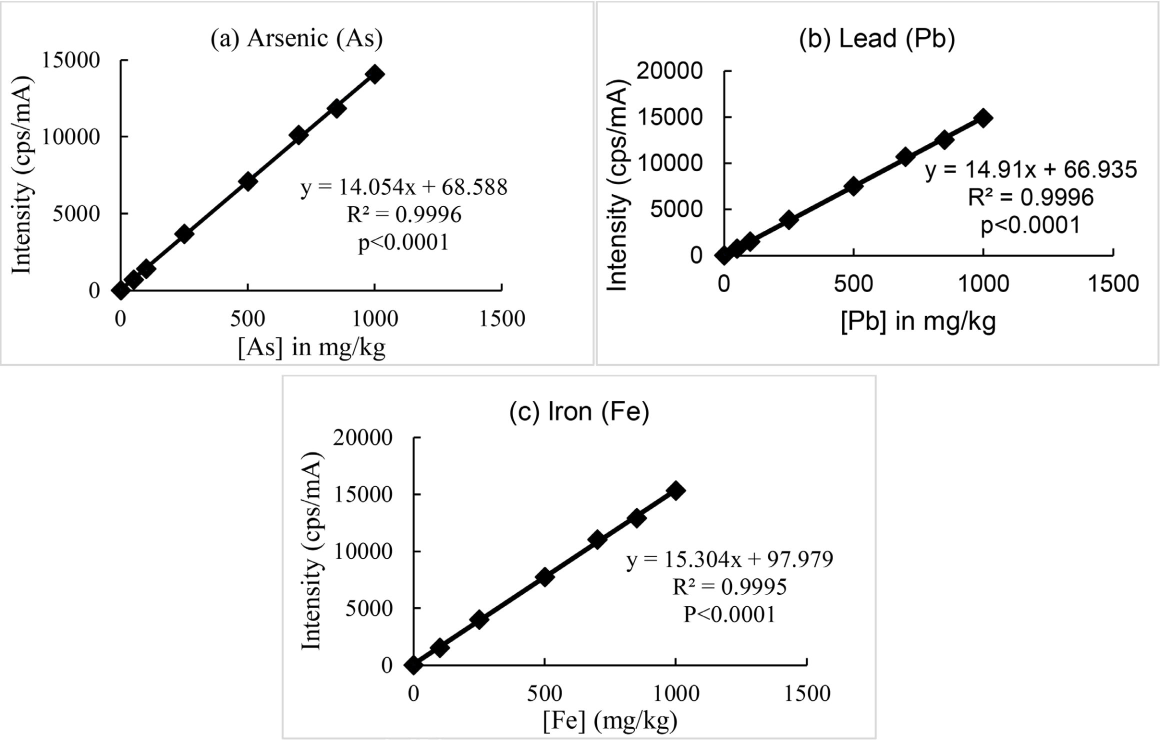

Figure 3. Calibration curves for Fe, Pb and As.

Table 3. Detection and quantification limits of the analysis.

Metal	Measurement time = 22 minutes			
	LOD (mg/kg)		LOQ (mg/kg)	
	Soil	Plant	soil	Plant
Fe	2.0	1.5	6.0	4.5
Ti	3.0	2.0	9.0	6.0
Cr	2.0	3.0	6.0	9.0
Te	4.0	6	12	18.0
Sr	1.0	1.0	3.0	3.0
Sn	5.0	4.0	15.0	12.0
Pb	1.0	0.5	3.0	1.5
As	1.0	0.7	3.0	2.1
Cu	3.0	3.0	9.0	3.0

Table 4. Repeatability and reproducibility data

Metals	Measurement time = 22 minutes			
	Repeatability C = 50 mg/kg n = 10		Reproducibility C = 50 mg/kg n = 10	
	Soil	Plant	soil	Plant
Fe	A = 49.48 ± 0.54 CV (%) = 1.09 RSD (%) = 1.00	A = 49.32 ± 0.63 CV (%) = 1.27 RSD (%) = 1.36	A = 49.43 ± 0.50 CV (%) = 1.05 RSD (%) = 1.14	A = 49.53 ± 0.69 CV (%) = 1.40 RSD (%) = 0.93
Ti	A = 49.52 ± 0.37 CV (%) = 0.75 RSD (%) = 0.96	A = 49.35 ± 0.40 CV (%) = 0.82 RSD (%) = 1.30	A = 49.42 ± 0.20 CV (%) = 0.41 RSD (%) = 1.16	A = 49.29 ± 0.60 CV (%) = 1.20 RSD (%) = 1.42
Cr	A = 49.51 ± 0.33 CV (%) = 0.67 RSD (%) = 0.98	A = 49.30 ± 0.50 CV (%) = 1.02 RSD (%) = 1.41	A = 49.39 ± 0.26 CV (%) = 0.53 RSD (%) = 1.21	A = 49.46 ± 0.20 CV (%) = 0.40 RSD (%) = 1.08
Te	A = 49.55 ± 0.33 CV (%) = 0.66 RSD (%) = 0.89	A = 49.36 ± 0.56 CV (%) = 1.12 RSD (%) = 1.27	A = 49.04 ± 0.51 CV (%) = 1.05 RSD (%) = 1.91	A = 49.33 ± 0.36 CV (%) = 0.76 RSD (%) = 1.34
Sr	A = 49.90 ± 0.23 CV (%) = 0.46 RSD (%) = 0.21	A = 49.15 ± 0.54 CV (%) = 1.09 RSD (%) = 1.71	A = 49.23 ± 0.26 CV (%) = 0.53 RSD (%) = 1.53	A = 49.39 ± 0.29 CV (%) = 0.58 RSD (%) = 1.21
Sn	A = 49.51 ± 0.47 CV (%) = 0.94 RSD (%) = 0.98	A = 49.24 ± 0.45 CV (%) = 0.91 RSD (%) = 1.52	A = 49.37 ± 0.39 CV (%) = 0.79 RSD (%) = 1.25	A = 49.39 ± 0.46 CV (%) = 0.92 RSD (%) = 1.22
Pb	A = 49.42 ± 0.41 CV (%) = 0.84 RSD (%) = 1.16	A = 49.29 ± 0.42 CV (%) = 0.86 RSD (%) = 1.42	A = 49.34 ± 0.39 CV (%) = 0.80 RSD (%) = 1.31	A = 49.45 ± 0.48 CV (%) = 0.98 RSD (%) = 1.10
As	A = 49.41 ± 0.36 CV (%) = 0.74 RSD (%) = 1.17	A = 49.43 ± 0.20 CV (%) = 0.40 RSD (%) = 1.14	A = 49.37 ± 0.22 CV (%) = 0.45 RSD (%) = 1.25	A = 49.37 ± 0.36 CV (%) = 0.72 RSD (%) = 1.26

Continued

Cu	A = 49.41 ± 0.46 CV (%) = 0.93 RSD (%) = 1.16	A = 49.24 ± 0.25 CV (%) = 0.51 RSD (%) = 1.52	A = 49.23 ± 0.43 CV (%) = 0.89 RSD (%) = 1.54	A = 49.43 ± 0.51 CV (%) = 1.03 RSD (%) = 1.14

A = average (n = 3; mg/g); CV = coefficient of variation, RSD = relative standard deviation.

Table 5. Metal content in soil.

Metals	Metal content of landfill soil (mg/kg)	
	Edge	Center
Ti	25,799.17	35,586.67
Cr	450.4	573.53
Cu	373.65	313.28
Sr	448.08	569.9
Sn	743.8	840.75
Te	633.6	680.81
Pb	171.63	162.35
As	45.35	62.9

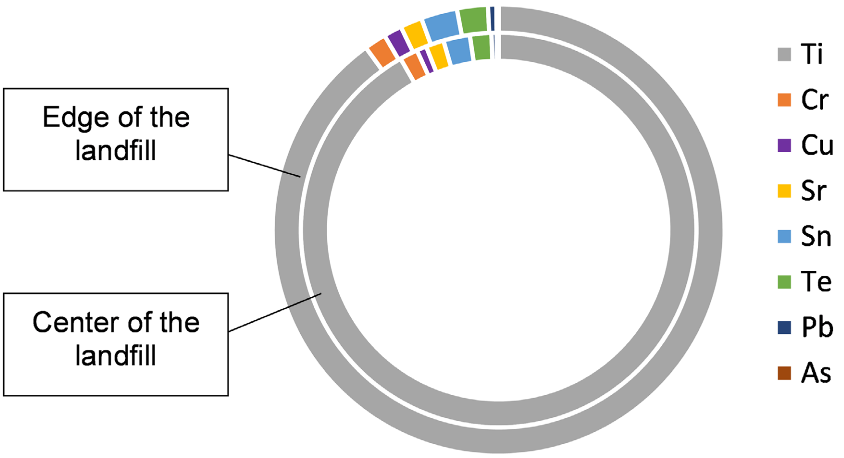

Figure 4. Metal content diagram for Bonoua landfill.

3.3. Metal Content of Landfill Soil

The most abundant metal in the soil samples was titanium, with mean contents of 35,586.67 mg/kg (landfill center) and 25,799.17 mg/kg (edge), while the least abundant metal was arsenic, with mean contents of 62.9 mg/kg (landfill center) and 45.35 mg/kg at the edge (Table 5).

Metal contents vary in the order Ti > Sn > Te > Cr > Sr > Cu > Pb > As in both the edge soil and the soil at the center of the load (Figure 4).

Generally, metal levels were slightly higher in soil samples taken from the center of the landfill than in soil samples taken from the edge of the landfill, with the exception of copper and lead.

3.4. The Metal Content of Plants

The most abundant metal in the plants was titanium, with mean contents of 2945.55 ± 994.81 mg/kg (*Phyllanthus amarus*), 2221.33 ± 376.20 mg/kg (*Alternanthera sessilis*) and 2009.53 ± 504.60 (*Amaranthus spinosus*). This metal was followed by strontium, with mean levels of 1018.7 ± 279.45 mg/kg (*P. amarus*), 755.23 ± 204.25 mg/kg (A. sessilis), and 941.28 ± 421.45 mg/kg (*A. spinosus*). The least abundant metals in plants were lead at 34.94 ± 46.04 mg/kg (*P. amarus*), 25.10 ± 24.76 mg/kg (*A. sessilis*) and 19.42 ± 21.86 mg/kg (*A. spinosus*), and arsenic at 9.00 ± 10.83 mg/kg (*P. amarus*), 5.49 ± 6.70 mg/kg (A. sessilis) and 2 ± 2.64 mg/kg (A. spinosus). The average chromium contents of the three plant species were statistically identical ($p > 0.05$) at 271.0 ± 133.03 mg/kg (*Phyllanthus amarus*), 239.57 ± 59.61 mg/kg (*Alternanthera sessilis*), and 194.90 ± 79.98 mg/kg (*Amaranthus spinosus*). The same was true for strontium and lead ($p>0.05$). On the other hand, the average titanium content of *Phyllanthus amarus* was higher than those of *Alternanthera sessilis* and *Amaranthus spinosus*, which belong to the same homogeneous group a ($p < 0.05$). The same observation was made for strontium and tellurium. The mean copper content of *Alternanthera sessilis* (574.652 ± 60.29 mg/kg) was higher than that of *Phyllanthus amarus* (441.5 ± 139.79 mg/kg) and *Amaranthus spinosus* (221.97 ± 43.72 mg/kg). Average arsenic levels were higher in *Phyllanthus amarus* (9.00 ± 10.83 mg/kg) than in *Alternanthera sessilis* (5.49 ± 6.70 mg/kg) and *Amaranthus spinosus* (2.00 ± 2.64 mg/kg) (**Table 6**).

Table 6. Comparison of average contents of plant species.

Heavy metal	Metal content (mg/kg)		
	Phyllanthus amarus	*Alternanthera sessilis*	*Amaranthus spinosus*
Ti	2945.55 ± 994.81^b	2221.33 ± 376.20^a	2009.53 ± 504.60^a
Cr	271.0 ± 133.03^a	239.57 ± 59.61^a	194.90 ± 79.98^a
Cu	441.5 ± 139.79^b	574.652 ± 60.29^c	221.97 ± 43,72^a
Sr	1018.7 ± 279.45^a	755.23 ± 204.25^a	941.28 ± 421.45^a
Sn	473.59 ± 84.27^b	330.45 ± 30.12^a	318.93 ± 42.67^a
Te	429.64 ± 75.43^b	309.01 ± 34.18^a	280.90 ± 36.49^a
Pb	34.94 ± 46.04^a	25.10 ± 24.76^a	19.42 ± 21.86^a
As	9.00 ± 10.83^b	5.49 ± 6.70^{ab}	2.00 ± 2.64^a (<LOQ)

On the same line, the means of lines bearing different alphabetical exponents (a, b, and c) are significantly different at the 5% threshold. On a line, the means followed by the same alphabetical letter are not significantly different at the 5% threshold; <LOQ: below the limit of quantification.

3.5. Metal Bioconcentration by Plant Species

Bioconcentration factors for *Phyllanthus amarus* ranged from 0.08 (Ti) to 2.27 (Sr). BCFs ranged from 0.06 (Ti) to 1.83 (Cu) for *Alternanthera sessilis*. Concerning *Amaranthus spinosus*, BFC fluctuated between 0.03 (As) and 2.10 (Sr). Metal bioconcentration factors (BCFs) for all three plant species were greater than 1 for strontium, regardless of the soil sampling area (center or edge of the landfill). *Phyllanthus amarus*, *Alternanthera sessilis*, and *Amaranthus spinosus* are therefore strontium-accumulating species. Similarly, copper BCF values were greater than 1 for *Phyllanthus amarus* and *Alternanthera sessilis*. These two plant species are therefore copper accumulators (**Table 7**).

Table 7. Metal bioconcentration factors in plants.

Heavy metal		BCF		
		Phyllanthus amarus	*Alternanthera sessilis*	*Amaranthus spinosus*
Ti	1	0.08	0.06	0.06
	2	0.11	0.09	0.08
Cr	1	0.47	0.42	0.34
	2	0.60	0.53	0.43
Cu	1	1.41	1.83	0.71
	2	1.18	1.54	0.59
Sr	1	1.79	1.33	1.65
	2	2.27	1.69	2.10
Sn	1	0.56	0.39	0.38
	2	0.64	0.44	0.43
Te	1	0.63	0.45	0.41
	2	0.69	0.44	0.44
Pb	1	0.22	0.15	0.12
	2	0.20	0.15	0.11
As	1	0.14	0.09	0.03
	2	0.20	0.12	0.04

(1): BFC for landfill center; (2): BFC for landfill edge.

4. Discussion

The flora of the Bonoua landfill is composed of 62 species divided into 28 families and 50 genera. Within this flora, nine (09) species are dominant, namely *Amaranthus spinosus*, *Phyllanthus amarus*, *Cyperus amabilis*, *Celosia argentea*, *Panicum repens*, *Citrullus lanatus*, *Cleome viscosa*, *Euphorbia hirta*, and *Ricinus communis*. The high number of plant species on the Bonoua load corroborates the findings of Nguemte et al. (2017), who inventoried 106 plant species belonging to 76 genera and 30 families on polluted sites in four cities in Cameroon. The presence of several plant species in the Bonoua landfill could be explained by the probable nutrient-rich nature of the soil. Indeed, in general, landfills contain large quantities of organic waste whose decomposition releases into the soil the minerals necessary for plant development, even if mineral contents may decline over time (Masse et al., 2017). Furthermore, the bioconcentration factor (BCF) of ETMs varies greatly from one plant species to another and according to the type of metal. Anisi, according to the BCF, *Phyllanthus amarus*, and *Alternanthera sessilis* are copper-accumulating species (BCF > 1). *Phyllanthus amarus*, Alternanthera sessilis, and *Amaranthus spinosus* are Strontium-accumulating plants, given that the BCF > 1 (**Figure 5**).

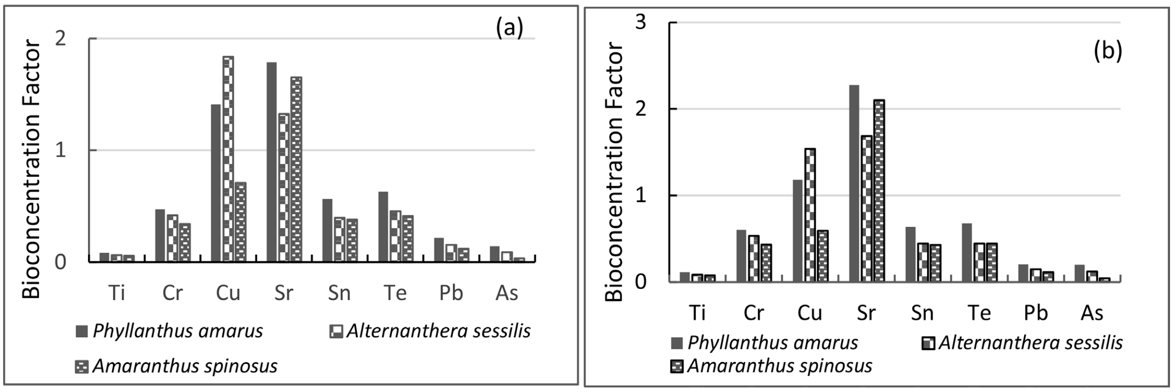

Figure 5. Histogram comparing metal bioaccumulation factors in plant species. (a) BCF relative to the soil at the center of the landfill; (b) BCF relative to the soil at the edge of the landfill.

Heavy metal transfer depends on both metal type and plant species. This important observation supports the results of Mirecki et al. (2015). According to these authors when considering Cd, BCF (plantain) > BCF (lettuce) > BCF (tomato) > BCF (corn). Furthermore, Mirecki et al. (2015) found that in the same plant (e.g. plantain) BCF (Cd) > BCF (Pb) > BCF (Zn) > Cu.

Given BCF > 1, *Phyllanthus amarus*, *Alternanthera sessilis*, and *Amaranthus spinosus* show an interesting phytoextraction profile for copper and strontium. Titanium levels in each of the three plant species of 2.95 mg/g for *Phyllanthus amarus*, 2.22 ± 0.38 mg/g for Alternanthera sessilis and 2.01 ± 0.50 mg/g for *Amaranthus spinosus* are above 1 mg/g, the reference threshold value for the metals As, Co, Cr, Cu, Ni, Pb, Sb, Se and Thallium (Tl) according to Rascio & Navari-Izzo (2011). These three plant species appear to be hyperaccumulators of Sr, Sn, or Te, and therefore candidates for phytoremediation despite their BCF < 1 (**Table 8**).

The presence of metals in soils and plants from landfill sites calls for waste sorting and recycling of the various categories of waste. Waste should be sorted at household, industrial, and workplace levels, separating metal from non-metal waste. This large-scale sorting will help to facilitate waste collection and recycling to avoid environmental pollution by heavy metals. Landfills need to be modernized with devices that prevent metal mobility, as metals are highly mobile in most soils (Asmoay et al., 2019; Oyewo et al., 2020). From an agronomic point of view, given the high concentration of harmful metals in landfill soil and in the plants that grow there, landfill soil should not be used as a growing medium

Table 8. Comparison of plant metal content with HRT.

Heavy metal	Metal content (mg/g)			HRT
	Phyllanthus amarus	*Alternanthera sessilis*	*Amaranthus spinosus*	
Ti	2.95 ± 0.99	2.22 ± 0.38	2.01 ± 0.50	*
Cr	0.27 ± 0.13	0.24 ± 0.06	0.19 ± 0.08	1
Cu	0.44 ± 0.14	0.57 ± 0.06	0.22 ± 0.043	1
Sr	1.02 ± 0.28	0.76 ± 0.20	0.94 ± 0.42	*
Sn	0.47 ± 0.08	0.33 ± 0.03	0.32 ± 0.04	*
Te	0.43 ± 0.08	0.31 ± 0.03	0.28 ± 0.04	*
Pb	0.03 ± 0.04	0.03 ± 0.02	0.02 ± 0.02	1
As	0.01 ± 0.01	0.01 ± 0.01	0.002 ± 0.003	1

HRT: Hyperaccumulation reference threshold according to Rascio & Navari-Izzo, 2011; (*): no reference values; A plant in which the content of one of the metals (Cr, Cu, Pb, and As) is greater than 1 mg/g is said to hyperaccumulate for this metal.

(fertilizing material) for edible plants, to avoid the transfer of metals to consumers. Similarly, landfill-derived plants should not be used to design drugs, as these plants could transfer trace metals to patients. For example, in the present study, *Phyllanthus amarus* and *Alternanthera sessilis* were found to be copper-accumulating species (BCF > 1), *Amaranthus spinosus*, *Phyllanthus amarus*, and *Amaranthus spinosus* were found to be Strontium-accumulating species (BCF > 1), even though these plants have good medicinal properties (Kassuya et al., 2005; Bhuyan et al., 2018; Sarker & Oba, 2019; Hwong et al., 2022).

5. Conclusion

The Bonoua landfill is colonized by 62 plant species belonging to 28 botanical families and 50 genera. The most abundant botanical families were Amaranthaceae and Euphorbiaceae. The most common species were *Amaranthus spinosus* and *Phyllanthus amarus*, which belong to the Amaranthaceae and Phyllantaceae families respectively. Metals such as titanium, copper, strontium, tin, tellurium, lead, and arsenic were found in both landfill soil and plant species. *Phyllanthus amarus* and *Alternanthera sessilis* accumulated copper, while *Amaranthus spinosus, Phyllanthus amarus*, and *Amaranthus spinosus* were found to accumulate strontium. The accumulative nature of *Phyllanthus amarus, Alternanthera sessilis*, and *Amaranthus spinosus* makes them candidate species for the phytoextraction of heavy metals in the context of phytoremediation of polluted soils.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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