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Evaluation of heavy metal content and potential ecological risks in soil samples from wild solid waste dumpsites in developing country under tropical conditions

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ABSTRACT

Solid waste management constitutes a major concern and unresolved problem in most parts of the world, particularly in developing countries where solid waste is disposed in unregulated dumpsites in the public spaces. This practice can lead to contamination of environmental compartments such as soil, surface and groundwater which could negatively impact human health. In this study, surface soil samples were collected from 15 selected solid waste dumpsites in Kinshasa City (Democratic Republic of the Congo) to examine the heavy metal content and potential environmental risks. The results highlighted a high concentration of metals in soil samples compared to local background values and international threshold. The average concentration of metals in all soil samples followed generally the order: Zn>Pb > Cu >Cr> Co> Cd> As> Hg. The calculated pollution indexes including Geo-accumulation, Enrichment Factor, Contamination degree and Potential Ecological Risk, revealed polymetallic contamination dominated by several of these metals in which Zn, Cu, Pb and Hg were of greatest concern indicating high environmental risks. This work showed that illegal wild landfills represent a real danger for the environment and human health. Due to the toxicity of heavy metals, the measures to establish a monitoring program that address uncontrolled landfills and solid waste management and disposal are recommended to reduce the load of contaminants in soils which can reach surface and groundwater. On the other hand, the use of manures from these dumpsites for agricultural purposes should be discouraged because they may be easily absorbed at alarming levels by vegetables.

1. Introduction

Solid waste management (SWM) is a major concern for most great agglomerations of many countries. There is a practical problem for many densely populated developing countries (Mavakala et al., 2016; Marshall and Farahbakhsh, 2013; Henry et al., 2006). It is estimated that municipal solid waste (MSW) generation in South Asia, Latin America, and Sub-Saharan Africa will double or triple by 2050, making up to 35% of the world's MSW. (World Bank Report, 2018). Several factors contribute to the generation of MSW and complicate its management. Notable are population growth, cultural and socioeconomic aspects, policy, rapid urbanization and industrialization, tourism, governance and institutional issues, inequality and the rise in living standards in the community, and international influences (World Bank Report, 2018; Mavakala et al., 2017; Marshall and Farahbakhsh, 2013; Guerrero et al., 2013). Lower-income countries are characterized by ineffective SWM, because of a lack of appropriate infrastructure and planning, insufficient financial resources, technical expertise and community attitude (Marshall and Farahbakhsh, 2013). Consequently, open dumping of wastes without treatment or selective collection is the most common method used for disposal of MSW in most of low and lower-middle income countries such as Sub-Saharan Africa and south and south of Asia (Salvia et al., 2021; World Bank Report, 2018; Wijesekara et al., 2014). On other hand the MSW from these countries is characterized

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with different fractions including electronic wastes, plastics, industrial and biomedical wastes, glass, battery, paper, and the organic fraction containing hazardous substances such as toxic metals and organic pollutants. Consequently, disposal of these types of wastes by open dumping technic without selective collection leads to high pollution which can directly or indirectly pose great danger to the environmental compartment (soil, water and sediment) living organisms and human health (World Bank Report, 2018; Wijesekara et al., 2014; Salvia et al., 2021; Mavakala et al., 2016; Nienie et al., 2017; Bhat et al., 2022).

The problem of waste management severely affects the cleanliness in several large cities of the DRC. The city of Kinshasa is the most affected and characterized by the persistent problem of SWM caused by several aspects, mainly the rapid population growth and anarchic/rapid urbanization. Urban rivers, public spaces and abandoned plots are habitually used for MSW disposal. Consequently, our field observation demonstrated that there are more than 500 wild waste dumpsites across Kinshasa City with an estimated volume of solid waste accounts of more than 587′920 m^3 during the year 2017 (Mavakala et al., 2017). Furthermore, there is just one controlled municipal landfill (Mpasa landfill) which has been operational since the year 2010 and is not operational for this moment (Mavakala et al., 2016). With increasing many uncontrolled dumpsites, policymakers have the responsibility to regulate waste disposal in the public space. To support this, the city's mayor initiated an operation called Kin Bopeto (Kinshasa Clean) to clean up the city. However, the inefficient SWM system in Kinshasa has severe negative consequences for the rivers and groundwater located in the city. In our past studies, we have found that rivers and groundwater in the area are heavily polluted with heavy metals, persistent organic pollutants, pathogens, and antibiotic resistance genes. (e.g., Mwanamoki et al., 2014; 2015; Kapembo et al., 2016: 2019; Tshibanda et al., 2014; Kilunga et al., 2017; Laffite et al., 2016; A. 2020; Al Salah et al., 2019; D.M.M. 2020). Additionally, it has been demonstrated that the use of polluted surface and groundwater for the agricultural purpose of the peri-urban areas of Kinshasa leads to the accumulation of toxic metals and POPs in fresh produces (Ngweme et al., 2020; 2021). To our best knowledge, these previous researches performed in the area did not evaluate the potential environmental risks of waste disposal/dumpsites on soil pollution status across the city of Kinshasa. Soil is usually regarded as the ultimate sink for toxic metals from dumpsites discharged into the environment.

The analysis of soils in relation to their toxic metals content is helpful for the assessment of environmental pollution and provide crucial information on the valuation of anthropogenic activities and potential risks to the residents living around wild dumpsites (Kasassi et al., 2008; Akanchise et al., 2020; Aja et al., 2021). Consequently, the overall objective of this research was to assess the pollution status of soils subject to the effects of wild dumps of wastes and to evaluate the potential environmental risks. The assessment was based on (i) determination of the concentration of toxic metals (Cr, Co, Cu, Zn, As, Cd, Pb and Hg) in soil from dumpsites, and (ii) evaluation of the potential environmental risks based on the calculation of pollution indexes including the Geoaccumulation Index (Igeo), Contamination Factor (CF), Contamination Degree (CD), Ecological Risk Factor (Eri) and Potential Ecological Risk Index (RI). Finally, assessed parameters are powerful tools for processing, analyzing, and conveying environmental information to decision-makers, managers, technicians, and the public to optimize SWM systems and limit the potential human and environmental impacts.

2. Materials and methods

2.1. Study area and sampling procedure

This research was conducted in Kinshasa metropolis, capital and largest city of DRC (Fig. 1), located between 3.9° and 5.1° south latitude and 15.2° and 16.6° east longitude, with a mean altitude of 240 m above sea level. Kinshasa is one of the largest urban areas in the world with more than 16,000,000 inhabitants and covering 9965 km^2. The climate is tropical with dry and wet seasons, with an average annual temperature of 21–30 °C and an average annual rainfall of about 124 mm. The city of Kinshasa is a decentralized administrative entity and subdivided into 24 municipalities. Fifteen uncontrolled dumpsites identified between October 2016 and January 2018 (sampling period) were selected for this study. These dumpsites are located mainly in the river banks and centers of 11 municipalities named Kalamu, Limete, Ndjili, Kitambo, Kimbaseke, Nsele, Ngaliema, Lingwala, Lemba, Selembao and Matete (Fig. 2).

Before collection, dumpsite sampling points were cleared of waste. From each point, approximatively 300 g of surface soil samples 2–10 cm were manually collected using a clean plastic spoon and transferred into 1.5 L plastic bottles. According to their dimension, 2–6 samples were taken from each dumpsite in triplicate. The sampling distance between each replicate was approximately 20 cm. Samples from selected 15 dumpsite points (D1-D15) are labelled D1S ($n = 3$), D2S ($n = 2$), D3S ($n = 2$), D4S ($n = 3$), D5S ($n = 3$), D6S ($n = 2$), D7S ($n = 6$), D8S ($n = 6$), D9S ($n = 6$), D10S ($n = 4$), D11S ($n = 5$), D12S ($n = 6$), D13S ($n = 6$), D14S ($n = 4$) and D15S ($n = 6$). For their conservation, once collected, soil samples were kept in an icebox at about 4 °C and transported to the analytical platform of the department of Forel, the University of Geneva for analysis within 72 h. GPS coordinates of sampling sites are presented in Table-1.

2.2. Soil grain size, organic matter and water content analysis

The soil particle grain size was determined using a laser Coulter® LS-100 diffractometer (Beckman Coulter, Fullerton, CA, USA) according to the procedure described by Loizeau et al. (1994). The soil water and organic matter (OM) content were determined by loss on ignition at 60 °C (overnight) and 550 °C (for 1 h in a Salvis oven), respectively.

2.3. Analysis of heavy metals in soil samples

The analysis of metals (*Sc*, Cr, Co, Cu, Zn, As, Cd and Pb) in soil samples was performed using the method as described by Thevenon et al. (2012) and Mavakala et al. (2016) with minor modification. Briefly, around 20 mg of soil samples were lyophilized at −45 °C during 72 h, homogenized and digested in Teflon bombs and glass ceramic hotplate with suprapur acids. The digestion procedure comprises 3 heating steps followed by evaporation: (a) 1.5 mL of suprapur HNO_3 (65%), (b) a mixture of 1 mL of suprapur $HClO_4$ (70%) and 1 mL of suprapur HF (40%), and (c) one additional treatment with 1 mL of suprapur HNO_3 (65%). The samples were evaporated completely between each step. Finally, samples were diluted to 10 mL with 1% of suprapur HNO_3 solution. The analysis of metals in digested soil samples was performed using Inductive Coupled Plasma-Mass Spectroscopy (ICP-MS, Agilent 7700x, Santa Clara, CA, USA). Collision/reaction cell (He mode) and the interference equations were performed to remove eventual spectral interferences that might otherwise the results. A Multi-element standard solutions (Merck IV) prepared at different concentrations (0, 0.2, 1, 5, 20, 50, 100, 150 and 200 μg L^{-1}) were used for calibration.

The detection limit was calculated as 3 times the standard deviation of the blanks (3xSD blank values), and was less than 0.001 μg L^{-1} for all analysed metals. The certified reference material STSD-2 was used for quality control of soil samples analysis. The results of STSD-2 for all analysed metals by ICP-MS were in the certified range, with recovery values ranged between 97.5 to 98.9%. The metal concentrations in soil samples was expressed in ppm (mg kg^{-1} dry weight). Standard deviations of 3 replicate measurements were below 3%, and chemical blanks for procedure were less than 1% of the sample signals.

The mercury (Hg) analysis in soil samples was carried out using Advanced Mercury Analyser (AMA 254, Altec s.r.l., Czech Rep.) following the method described by Bravo et al. (2011). For Hg analysis by AMA, the detection limit was 0.005 mg kg^{-1}, with recovery values of 97.6%.

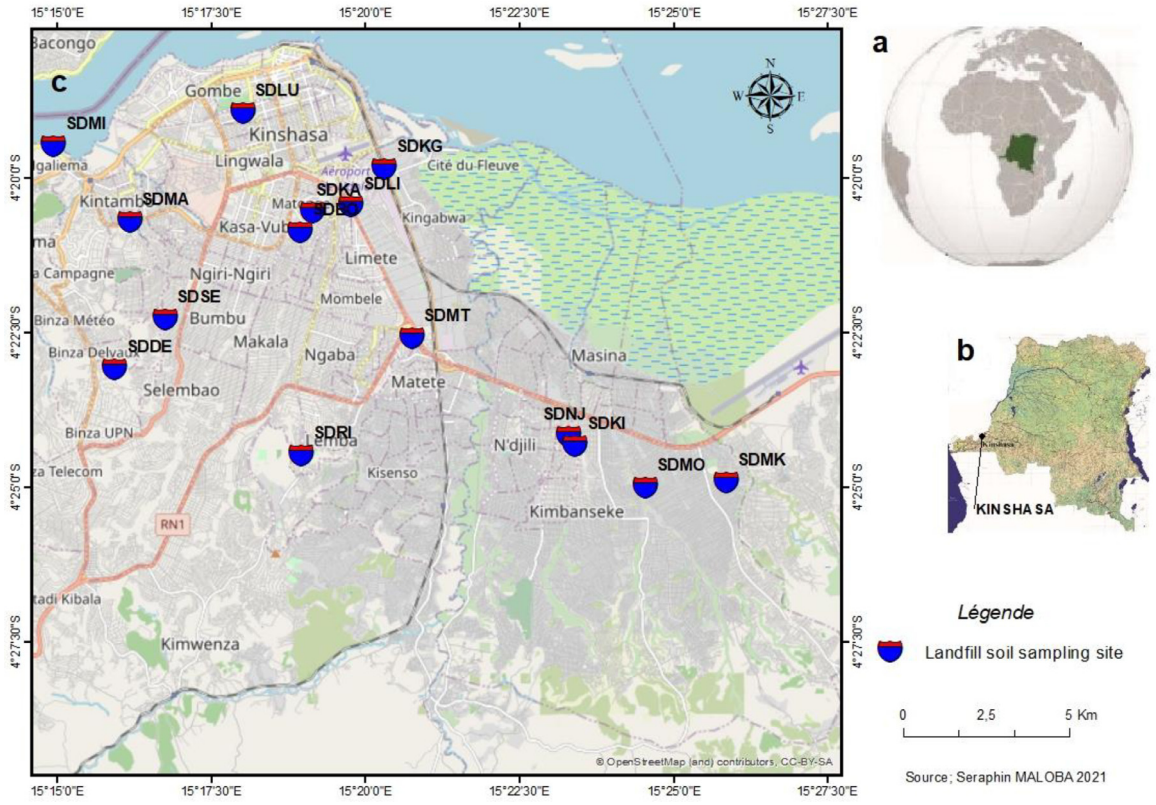

Fig. 1. Adapted Google Map indicating (a) Democratic Republic of the Congo location in Africa continental map, (b) Kinshasa location in Democratic Republic of the Congo map, (c) sampling sites location in selected municipalities of Kinshasa.

Fig. 2. Some of studied dumpsites: A. D2S located in the municipality of Kalamu (Pont Bongolo); B. D13S located in the municipality of Kimbanseke (Mokali); C. D11S located in the municipality of Limete (petit boulevard); and D. D14S located in the municipality of Selembao. Photos taken by Bienvenu Mavakala in January 2018.

Except *Sc* (used for the evaluation of potential risks), the analysed metals were selected according their toxicity in studied environmental compartment (Mavakala et al., 2016).

2.4. Evaluation of potential environmental risks

For the evaluation of the possible environmental risks/contamination level, following indexes were determined. These indexes are very important to evaluate the soil/sediment pollution status and the potential ecological risks posed by heavy metals in dumpsites (e.g. Aja et al., 2021; Akanchise et al., 2020; A. Laffite et al., 2020; Mavakala et al., 2016; Weihua et al., 2010).

(i) *Enrichment Factor (EF) and Geoaccumulation Index (Igeo)*

The enrichment factor (EF) and geoaccumulation index (Igeo) in soil samples were calculated as described by (Maanan et al., 2004; Zhang et al., 2007; Gong et al., 2008; Varol, 2011;) using the following equations. Scandium (*Sc*) was used for normalization according to our previous study performed in the region (Mwanamoki et al., 2015; Mavakala et al., 2016).

The Enrichment Factor (EF) was determined using the following equation:

$$EF = \frac{\left(\frac{Metal}{Sc}\right)_{sample}}{\left(\frac{Metal}{Sc}\right)_{Background}} \quad (1)$$

Metal: Concentration of metal in analysed samples.

Sc: Concentration of Scandium in analysed samples.

Geo-accumulation index was originally stated by Muller in 1969 in order to determine and define metal contamination in sediments by comparing current concentrations with pre-industrial levels.

The geoaccumulation index (I_{geo}) was calculated by the following equation:

$$Igeo = log_2\left(\frac{C_n}{1.5\ B_n}\right) \quad (2)$$

Cn = Concentration of metals (n) examined in the soil samples.

Bn = Concentration of the metal (n) geochemical background.

1.5 = Lithospheric effect background correlation matrix factor.

Factor 1.5 is used because of possible variations in background values for a given metal in the environment as well as very small anthropogenic influences. These values were calculated using the metal mean and lithogenic background values (Mwanamoki et al., 2015; Mavakala et al., 2016).

(ii) *Contamination Factor (CF)*

The contamination factor (CF) is used to quantify the contamination status of pollutants in the soil based on their concentrations in the sample and their background concentration (Martin and Meybeck, 1979). It is an effective tool for monitoring the pollution over a period of time and it is computed as follows:

$$CFn = \left(\frac{C_n}{B_n}\right) \quad (3)$$

Where Cn represents the concentration of a metal n in the contaminated soil and Bn, the concentration of background for a metal n. Contamination classes are defined (Förstner et al., 1989; Håkanson, 1980; Rubio et al., 2000) as follows: CF< 1 (low contamination), 1< CF < 3 (moderate contamination), 3 < CF < 6 (considerable contamination), 6 < CF (very high contamination). The measured results in the soil were used to portray the classification of metal contamination of As, Cr, Cu, Co, Cd, Hg, Pb and Zn.

(iii) *Contamination Degree (CD)*

The degree of contamination allows the estimation of a priori polymetallic contamination for each sampling point and was calculated by the following formula:

$$CD = \sum CFi \quad (4)$$

$i = 1\ldots\ldots m$, m is the count of the heavy metal species. In this study, the value of m is equal to 8.

This index is associated with four quality classes Hankanson: CD < 8 (low contamination),

8 ≤ CD < 16 (moderate contamination), 16 ≤ CD < 32 (high contamination), 32 ≤ CD (very high contamination) (Hankanson, 1980).

(iv) *Ecological Risk Factor (Eri)*

The potential ecological risk index was developed by Hakanson (Hankanson, 1980). It has been employed to evaluate the harmful effects of contaminants on the environment and humans. It also reflects the toxicity and ecological sensitivity of the concentration of contaminants (Hakanson, 1980; Weihua et al., 2010; Suresh et al., 2012). Initially, it was used as an evaluation tool for sediment pollution in the aquatic environment. It had been successfully used for risk assessment of soils, dust and air (Suresh et al., 2012; Ogunkunle and Fatoba, 2013; Riyad et al., 2015; Osipova et al., 2016). For a single metal, the ecological risk factor is determined by the following equation:

$$Eri = \text{Tri x CFi} \quad (5)$$

Where Tr_i is the toxic-response factor for a given substance or the biological toxic factor of a single element, and CF_i is the contamination factor of element i. Tri = 40 for Hg, 30 for Cd, 10 for As, 5 for Co, 5 for Cu, 5 for Pb, 2 for Cr, 1 for Zn (Hånkanson, 1980; Islam et al., 2014; Weihua et al., 2010).

The following terminologies are used to describe the risk factor: Eri<40, low ecological risk;

40<Eri <80, moderate ecological risk; 80<Eri<160, considerable ecological risk; 160<Eri<320, high ecological risk; and 320<Eri, very high ecological risk.

(v) *The potential ecological risk index (RI)*

The potential ecological risk index for various heavy metals in the soil was similar to the level of contamination defined as the sum of the single potential ecological risks factor. This method comprehensively considers the synergy, toxic level, concentration of the heavy metals and ecological sensitivity of heavy metals (Singh et al., 2002). It represents the sensitivity of various biological communities and possible risks caused by heavy metals. The potential ecological risk index of all the measured heavy metals was computed using (Eq. (6)).

$$RI = \sum \text{Eri} \quad (6)$$

$i = 1 \ldots\ldots m$

Where Eri is the single index of ecological risk factor, and m is the count of the heavy metal species. The $m = 8$ includes As, Cr, Cu, Co, Cd, Hg, Pb and Zn.

The following terminology was used for the potential ecological risk index: RI<150, low ecological risk or low ecological pollution level; 150≤RI<300/moderate ecological pollution level or moderate ecological risk; 300≤RI<600, considerable ecological risk or severe ecological pollution level; and RI>600, very high ecological risk or serious ecological pollution level (Hånkanson, 1980; Gong et al., 2008; Riyad et al., 2015).

2.5. Statistical analysis

Triplicate measurements have been performed on selected sediment samples. The statistical treatment of the data has been realized using SigmaStat 11.0 (Systat Software, Inc., USA). Statically processing data

Table 1
GPS location of sampling sites and physicochemical parameters of soil from studied dumpsites.

Site	Sampling site	Longitude	Latitude	WC (%)	MO (%)	Clay (%)	Silt (%)	Sand (%)	Mean grain size (μm)
D1S	Kalamu_Pont_Kalamu	15° 19′9.9″	4° 20′33.5″	6.49	0.05	1.72	12.30	69.49	175.25
D2S	Kalamu_Pont Bongolo	15° 18′57.5″	4° 20′ 53.0″	5.74	0.07	6.33	27.21	34.54	78.48
D3S	Limete_1ere rue	15°19′47.1″	4° 20′ 28.0″	1.06	0.06	11.65	42.42	29.18	66.88
D4S	Ndjili_Quartier 11	15′ 23′ 18.8″	4° 24′ 10.7″	1.00	0.06	1.52	7.74	66.83	171.70
D5S	Kitambo_Pont_Makelele	15° 16′ 11.9″	4° 20′ 42.6″	31.10	0.13	8.44	62.38	66.47	29.86
D6S	Kimbaseke_Bakwanga	15°23′ 24.8″	4° 24′203″	8.36	0.03	1.98	10.47	44.19	120.00
D7S	Masina_Mikonga	15°25′ 51.9″	4° 24′55.7″	21.82	0.09	0.74	17.45	68.66	140.55
D8S	Ngaliema_Delvaux	15° 15′ 56.7″	4° 23′05.7″	16.69	0.09	0.78	11.22	87.24	198.35
D9S	Lingwala_Lufungula	15°18′01.7″	4° 18′ 56.7″	17.18	0.09	6.40	40.32	48.52	49.93
D10S	Lemba_Righini	15°18′58.2″	4° 24′ 28.7″	22.29	0.07	1.50	19.09	78.82	153.60
D11S	Limite_Kingabwa	15°20′ 19.2″	4°19′ 50.8″	6.31	0.09	1.09	13.99	76.14	158.85
D12S	Ngaliema_Mimosa	15°14′ 57″	4° *19′ 29.1″*	17.32	0.09	3.85	38.94	57.66	63.48
D13S	Kimbaseke_Mokali	15°23′ 93.5″	4° 24′ 60.4″	18.78	0.11	3.16	60.03	47.37	40.04
D14S	Selembao_Makelele	15° 16′45.6″	4° 22′ 16.9″	22.90	0.05	1.01	10.82	71.03	206.85
D15	Matete_Camp riche	15°20 ’46.1″	4° 22′35.8″	22.74	0.07	1.32	22.59	68.67	110.31
Min				1.00	0.03	0.74	7.74	29.18	29.86
Max				31.10	0.13	11.65	62.38	87.24	206.85

Table 2
Average and range concentration (mg kg^{-1} dry soil) of metals in soil samples from studied dumpsites.

Sampling Site		*Sc*	Cr	Co	Cu	Zn	As	Cd	Pb	Hg
DS1	Average	0.04	6.08	2.71	22.81	291.53	0.46	0.24	35.12	0.16
	Range	0–0.07	4.48–8.63	0.89–4.75	17.04–32.39	124.95–466.2	0.33–0.63	0.2–0.33	20.08–57.77	0.09–0.25
DS2	Average	0.12	10.18	1.71	37.61	259.33	0.69	0.54	136.08	0.28
	Range	0.1–0.14	8.83–11.32	1.39–2.18	31.77–44.27	236.19–272.36	0.55–0.79	0.49–0.6	58.88–262.15	0.24–0.35
DS3*		0.02	9.91	1.85	36.26	315.41	0.57	0.53	72.61	0.56
DS4	Average	0.05	7.23	1.61	22.95	223.91	0.49	0.35	57.41	0.17
	Range	0–0.12	5.37–8.43	1–2.14	20.32–27.88	180.8–260.58	0.45–0.55	0.27–0.47	51.33–60.57	0.14–0.22
DS5	Average	0.10	11.70	7.95	43.05	1324.64	0.75	0.76	104.55	0.19
	Range	0.05–0.16	8.01–14.4	1.18–11.78	25.51–66.34	226.22–2189.52	0.35–1.12	0.33–1.1	86.53–120.6	0.13–0.24
DS6	Average	0.02	4.61	1.09	42.26	147.45	0.38	6.19	45.30	0.11
	Range	0–0.04	4.24–4.98	0.83–1.34	39.73–44.78	105.85–189.05	0.29–0.47	0.18–12.2	41.2–49.4	0.1–0.13
DS7	Average	0.19	22.65	1.85	131.29	294.92	1.50	1.09	241.61	0.14
	Range	0.01–0.71	3.86–93.34	0.48–0.78	17.38–570.40	103.43–707.01	0.37–5.06	0.32–2.29	68.86–405.64	0.03–0.21
DS8	Average	0.62	12.24	4.04	50.20	573.72	1.00	2.20	91.20	0.27
	Range	0.38–1.13	8.37–14.69	0.87–14.46	21.76–96.47	75.23–1603.55	0.73–1.36	0.43–10.15	52.72–171.12	0.06–0.90
DS9	Average	0.67	12.53	1.90	32.54	260.01	0.89	0.58	57.87	1.01
	Range	0.55–0.76	10.96–14.6	1.52–2.27	21.77–47.61	138.16–381.48	0.69–1.24	0.37–0.94	39.18–80.28	0.61–1.44
DS10	Average	0.28	8.12	0.71	21.19	175.24	0.84	0.37	45.39	0.10
	Range	0.14–0.5	3.43–12.16	0.37–1	6.16–28.73	81.6–328.97	0.41–1.1	0.07–0.86	5.83–130	0–0.15
DS11	Average	0.86	24.10	2.99	125.01	257.29	1.98	0.32	117.18	0.18
	Range	0.59–1.47	12.79–39.69	1.97–4.48	26.78–204.49	162–402.98	1.1–3.07	0.23–0.46	49.63–263.08	0.06–0.37
DS12	Average	0.93	42.75	6.89	311.03	600.39	6.27	7.20	452.68	0.08
	Range	0.04–1.33	3.53–146.72	0.47–19.19	10.78–677.54	106.18–1312.29	0.35–22.43	0.21–30.56	70.41–1102.38	0.03–0.18
DS13	Average	0.23	25.66	9.53	51.09	9864.93	1.15	2.73	242.29	2.69
	Range	0.13–0.49	4.96–124.33	0.47–53.28	8.42–233.27	189.09–57,330.38	0.37–4.34	0.2–13.93	18.79–1239.42	0.17–15.04
DS14	Average	0.33	9.18	1.36	36.13	290.67	1.21	2.56	59.81	0.08
	Range	0.17–0.51	4.86–15.84	0.37–2.91	13.96–58.42	78.52–487.63	0.35–2.74	0.4–5.53	22.84–90.86	0.02–0.15
DS15	Average	0.23	13.17	2.01	41.38	239.59	1.13	1.50	64.54	0.28
	Range	0.1–0.39	4.55–24.36	0.78–6.15	12.49–70.57	103.14–491.16	0.38–1.46	0.24–4.89	17.63–102.17	0.07–9.03

* No replicate performed.

(Spearman’s rank-order correlation) was performed using Sigma Stat Systat Software, Inc, San Jose, CA, USA. Spearman Parameters include toxic metals (As, Cr, Cu, Co, Cd, Hg, Pb and Zn), mean grain size and organic matter were analyzed in the surface sediments and soils.

3. Results and discussion

3.1. Physicochemical characteristics of soil

The results of soil characteristics including GPS sampling site, particle grain size, OM, and WC are shown in Table 1. The maximum and minimum values of OM in soil samples from landfill ranged from 0.03 to 0.13%, respectively. No significant difference in total OM was observed among all samples (triplicate) from the same site. The results of this study indicate that the soil from studied sites is not polluted by organic matter (Poté et al., 2008). It was observed that 40% of the study sites had silty soil texture, which can effectively stabilize heavy metals with oxidative reductive potential (ORP) (Zhang et al., 2014). For all samples, the sand values ranged from 29.18 (site D3S) to 87.24% (site D8S), silt from 7.74 (site D4S) to 62.38% (site D5S) and clay from 0.74(site D7S) to 11.65% (site D3S). Organic matter in soil is associated with soil textures (sand, silt, clay) and decomposition, and it is also a good indicator of soil health. (Rattan et al., 2005). Hence, low organic matter in soil may be associated with the low silt and clay content in study sites. (Shang and Tiessen, 2003).

3.2. Metal concentrations in the surface soil

The average and range of heavy metals concentration in soil samples from the fifteen sampling sites are presented in Table 2. In general, the heavy metal concentrations varied significantly with the sampling area. It is noted that the concentrations of three heavy metals including Pb, Zn

and Cu were found considerably higher in most of the soil samples compared to background values (in mg kg^{-1}, data from Mwanamoki et al., 2015; Mavakala et al., 2016) of 11.57 (Cr), 0.69 (Co), 5.88 (Cu), 7.15 (Zn), 0.07 (Cd), 3.28 (Pb) and 0.03 (Hg). The contents of several heavy metals in soils were measured in the following order:

$$Zn > Pb > Cu > Cr > Co > Cd > As > Hg$$

For example, in the soils from the area D5S (SDMA1, SDMA2, SDMA3), the heavy metal concentration ranged from 8.01 to 14.4, 1.18–11.78, 25.51–66.34, 226.22–2189.52, 0.33–1.1, 0.9–1.1, 86.53–120.6 and 0.13–0.24 mg kg^{-1} for Cr, Co, Cu, Zn, As, Cd, Pb and Hg, respectively. For the soils from landfill D12S (SDMI1, SDMI2, SDMI3 SDMI4, SDMI5 and SDMI6), the metal concentrations ranged between 3.53 and 146.72, 0.47–19.19, 10.78–677.54, 106.18–1312.29, 0.35–22.43, 0.21–30.56, 70.41–1102.38 and 0.03–0.18 mg kg^{-1} for Cr, Co, Cu, Zn, As, Cd, Pb and Hg, respectively. Stations D5S, D7S, D9S, D11S and D12S showed the highest heavy metal contents. For soil analysis, D12S has a high maximum concentration of Pb (1102.68 mg kg^{-1}) and Cu (677.54 mg kg^{-1}), while D5S has a high concentration of Zn (2 189.52 mg kg^{-1}). In the present study, the highest concentration of Hg (15.04 mg kg^{-1}) was detected in the site D13S, whereas the highest level of Cd was detected in the site D6S with a value of 12.2 mg kg^{-1}. At all study sites, the zinc concentration ranged between 78.52 and 57,330.38 mg kg-1. Notably, at site D13S, the highest concentration of Zn (57,330.38 mg kg^{-1}) was remarkably more elevated than other investigated metals. For other investigated metals, the concentration ranged between 0 and 15.04 mg kg^{-1} for Hg, 0.07 to 30.56 mg kg^{-1} for Cd, 6.16 to 677.54 mg kg^{-1} for Cu, 5.83 to 1239.42 mg kg^{-1} for Pb, 3.43 to 146.72 mg kg^{-1} for Cr, 0.29 to 22.43 mg kg^{-1} for As, and 0.37 to 53.28 mg kg^{-1} for Co. The behavior of metals and soil properties can influence heavy metals in the soil at various depths. (Devarajan et al., 2015). Additionally, leaching from upper soil to vertical migration can also affect soil accumulation. In this study, the results corroborated with those of previous studies indicating that MSW contributes to elevated levels of heavy metal pollution compared to those in less human-impacted areas (Sahli et al., 2014; Gupta et al., 2014; Njagi et al., 2016; Jinal et al., 2017; Oluwagbemiga et al., 2019; Murana et al., 2019; Ogundele et al., 2020). This makes the soils from these dumpsites unsuitable for agricultural use in investigated areas (Ngwene et al.; 2020). Overall, the highest concentration value for all analysed metals is found in the area of D12S. The pollution at this site might be attributed to the intense industrial activities performing around this site. In addition, this site includes several uncontrolled landfills near the Congo River. These studied landfills contain different waste materials, including batteries, glass residues, plastics, scrapped vehicles, and metals with old paint. It turns out that most heavy metals in soil samples are the result of numerous point and non-point sources. In many urban areas of Congo, heavy metal contamination is associated primarily with industrial, agrochemical, and human activities involving different alloys, pigments, fungicides, fertilizers, insecticides, cooking utensils, batteries, and vehicular emissions, oil burning, waste incineration, old tires, construction, and demolition. As a result, when these products are thrown into the dumpsite, the elements present in the wastes are leached away and accumulated at the topsoil and can be adsorbed due to greater affinity between metals and soil organic matter (Amadi, 2011; Mavakala et al., 2016; Khan et al., 2017; Lane et al., 2020).

3.3. Geoaccumulation index (Igeo), enrichment factor (EF), contamination degree (CD) and potential ecological risk index (RI)

Enrichment Factor (EF) and Geoaccumulation Index (Igeo) are indicators widely used to evaluate the intensity of anthropogenic contaminants in the soils. They provide a quantitative criterion for characterizing the sediment according to the degree of metal pollution (Adamo et al., 2005). Geoaccumulation index (Igeo) and Enrichment factor (EF) values for selected metals in soil samples from Landfills are given in Table 3. In accordance with the Igeo values calculated using Eq. (1), the toxicity of metals at the studied sites was classified as follows: Zn>Pb>Cd>Hg>Co>Cu>As>Cr. Zn pollution was determined to be extremely severe at the site D5S (6.02), while heavy to extremely severe pollution was found at the sites D12S (4.52), D13S (4.16), and they were classified under class 5. About 60% of sites were in class 4 as heavily polluted with Zn and unpolluted to moderately polluted with Cu.

D6S, D11S and D12S showed extremely polluted categories for Pb (D6S) and Cu (D11S and D12S). All samples were practically unpolluted for Cr. Co, As, Pb, and Hg did not show extreme pollution. However, D7S and D12S were in class 5 as heavily polluted by Cd and D9S heavily contaminated with Hg.

The enrichment factor (EF) value results are shown in Table 3. Overall, most study sites have extremely high enrichment for Zn, Pb, Cu, Hg, and Co and moderate enrichment for As and Cr. In soil sample sites D1S, D2S, D3S, D4S, D5S, D6S and D7S, Zn, Cu and Pb were highly enriched. Further, D13S and D14S samples for Zn had extremely high enrichment values, while D11S, D12S, D14S and D15S samples for Cu showed extremely high enrichment values. It was observed that there was some extremely enrichment in D1S, D2S, D3S, D4S, D5S, D6S, and D9S for Hg. In addition, there was some enrichment in D3S, D4S, D5S, D6S, D7, D8S, and D14S for Cd. Co was extremely enriched in D1S, D3S, D4S, D5S, and D6S sampling sites. Cd showed the highest EF value (3 142.63) among the investigated toxic metals, while Cr presented the lowest (0.53). In summary, it was found that Cu, Cd, Zn, Hg, Pb, Cd, Zn, Pb and Co had the highest EF values, suggesting they could have originated from anthropogenic sources. (Mavakala et al., 2016; Mwanamoki et al., 2015; Mata et al., 2020).

The Contamination factor (CF), ecological risk factor (Eri) and potential ecological risk index (RI) results in sampling sites are presented in Table 4a, 4b. For all 15 studied wild dumps, CF (derived from Eq. (3)) for Co, Cu, Zn, Cd, Pb, Hg and Cu are higher than 1. All sites have low-to-moderate contamination with Cr and As, except for sites D11S (1.72) and D12S (3.55). We noted that all sites were moderately to very highly contaminate with Zn (97.39), Cd (60.68), Pb (36.37) and Co (36.27). The results showed polymetallic contamination dominated by five metals (Co, Pb, Zn, Cd, and Hg) when analyzed using the degree of contamination (DC).

The CD values calculated using Eq. (3) of some landfills are greater than 24, ranging from 24.63(D10S) to 167.86 (D5S), indicating a very high polymetallic contamination. This very high value is mainly due to Zinc, Cadmium, Lead, Cobalt and mercury, whose contributions are of the order of 34%, 21%, 13%, 13% and 12%, respectively. According to the study, zinc and Cadmium contribute considerably to pollution in all cases.

Based on the ecological risk factor Eri value in soils (computed from Eq. (4)), Cd (1 820, 41) in site D6S was the most severe and implied a very high-risk condition, followed by 1 373.07 (D9S), whereas Cr showed the lowest value (0.26) in station D6S. Also, Pb and Zn presented their highest values of 181.84 (D7S) and 97.39 (D5S), respectively.

The potential ecological risk index (RI) obtained from Eq. (5) (Table 4) shows soils such as D6S (2027.31), D9S (1609.76), D12S (171.27); D3S (987.54); D14S (823.25); D5S (749.51); D7S (709.79) and D2S (594.11) are much more hazardous than soils such as D10S (197.03) (Fig. 3). A considerable ecological risk is associated with D11S (423.82) and D8S (499.24). In addition, D1S (296.72) and D10S (291.52) are classified as moderate ecological risk.

Heavy metal pollution status in different locations of a landfill is various. The distribution of metals in soil can vary significantly because of the diversity of the wastes which are not homogeneous in dumpsites (Mavakala et al., 2016; 2017). Besides, soil/sediment physicochemical properties can influence heavy metals distribution in contaminated sites. The metal concentrations generally decrease with depth (Devarajan et al., 2015; Adler et al., 2016; Aja et al., 2021).

Table 3
EF and Igeo values for Cr, Cu, Zn, Cd, Pb, and Hg in surface soil from Kinshasa municipalities' dumpsites.

EF

Sites	Cr	Co	Cu	Zn	As	Cd	Pb	Hg
D1S	2.60	148.26	165.69	315.49	7.42	35.59	69.97	81.90
D2S	2.65	46.54	161.07	150.61	6.51	45.79	111.42	76.71
D3S	11.79	257.58	739.47	821.19	23.55	217.73	432.12	772.39
D4S	7.93	196.89	356.17	507.20	16.22	105.96	303.59	182.52
D5S	3.43	343.04	172.75	921.21	7.30	79.01	143.94	65.16
D6S	6.82	187.76	1071.26	477.29	19.87	3142.63	335.13	196.36
D7S	1.89	26.39	229.87	131.37	6.66	90.49	324.78	42.65
D8S	0.71	13.40	39.09	39.34	1.84	12.03	19.53	9.83
D9S	0.53	9.13	20.80	24.28	1.29	7.94	12.07	51.04
D10S	0.97	9.89	49.16	36.54	3.71	10.50	13.15	17.33
D11S	0.64	13.11	77.63	19.65	2.17	3.12	19.01	6.76
D12S	0.75	13.23	131.86	31.83	3.29	24.98	28.18	1.95
D13S	1.10	18.54	45.20	169.24	3.27	25.78	27.97	41.20
D14S	0.69	10.92	53.65	56.63	2.65	64.20	27.24	8.19
D15S	1.32	16.01	64.20	48.78	4.88	31.77	38.60	31.65

EF<1: No enrichment
EF<3: Minor enrichment
3<EF<5: Moderate enrichment
5<EF<10: moderately severe enrichment
10<EF<25: severe enrichment
25< EF<50: very severe enrichment
EF>50: extremely severe enrichment

Igeo

Sites	Cr	Co	Cu	Zn	As	Cd	Pb	Hg
D1S	-3.36	2.47	-0.17	3.56	-1.85	0.41	1.39	1.62
D2S	-2.34	1.79	0.78	3.49	-1.04	1.77	3.05	2.52
D3S	-2.41	2.04	0.76	3.72	-1.41	1.80	2.79	3.63
D4S	-2.74	1.90	-0.05	3.26	-1.70	1.00	2.52	1.79
D5S	-2.05	4.60	0.80	6.02	-0.96	2.48	3.34	2.20
D6S	-3.51	1.27	0.98	2.62	-1.97	5.34	2.11	1.34
D7S	-2.82	0.98	1.29	3.29	-1.01	2.76	4.60	1.67
D8S	-1.99	2.25	0.99	3.81	-0.61	2.10	2.80	1.81
D9S	-2.07	2.03	0.41	3.44	-0.79	1.83	2.44	4.52
D10S	-2.64	0.71	0.22	2.60	-0.70	0.80	1.12	1.52
D11S	-1.57	2.79	2.54	3.37	0.19	0.72	3.32	1.83
D12S	-0.88	3.25	3.76	4.52	1.24	4.17	4.34	0.49
D13S	-3.10	0.97	-0.55	4.16	-1.53	1.45	1.57	2.13
D14S	-2.71	1.26	0.75	3.64	-0.78	3.82	2.58	0.85

Igeo ≤ 0 Class 0 - practically unpolluted
0 < Igeo < 1 Class 1 - unpolluted to moderately polluted
1< Igeo < 2 Class 2 - moderately polluted
2< Igeo < 3 Class 3 - moderately to heavily polluted
3 < Igeo < 4 Class 4 - heavily polluted
4 < Igeo < 5 Class 5 - heavily to extremely polluted
5 < Igeo Class 6 - extremely polluted

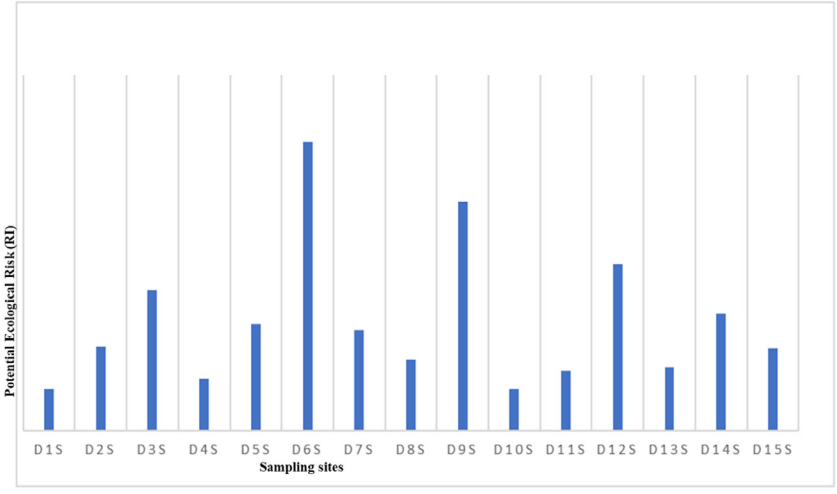

Fig. 3. Potential Ecological risk (RI) assessment of heavy metal concentration in soil samples from studied dumpsites.

3.4. Correlation between parameters

Correlation analyses between metals were calculated to investigate metals possible sources in soils; e.g., for the site D13S (Fig. 2B), the Spearman's rank-order correlation values are presented in Table 5. Correlation results showed that grain size and Hg were not correlated with heavy metals. The mechanism of accumulation and distribution of metals controlled by grain size and organic matter are not significant statistically. Grain size does not correlate with the metals studied, indicating that the transport of contaminants (toxic metals) does not depend on grain size neither in the river nor in soil (Kilunga et al., 2017). The positive correlation for Co/MO (r = 0.62, p<0.05) and Zn/MO (r = 0.68, p<0.001) indicating their bioavailability. Besides, according to correlation analysis Hg could have derived

Table 4
Calculated CF, CD, Eri and RI values for soil and sediments from Kinshasa municipalities' dumpsites.

Contamination Factor (CF)									
Site	Cr	Co	Cu	Zn	As	Cd	Pb	Hg	**DC**
D1S	0.15	8.32	1.34	17.72	0.42	2.00	3.93	4.60	38.46
D2S	0.30	5.20	2.59	16.84	0.73	5.12	12.46	8.58	51.81
D3S	0.28	6.18	2.55	19.71	0.57	5.23	10.37	18.54	63.43
D4S	0.23	5.59	1.45	14.40	0.46	3.01	8.62	5.18	38.93
D5S	0.36	36.27	2.62	97.39	0.77	8.35	15.22	6.89	**167.86**
D6S	0.13	3.63	2.97	9.22	0.38	60.68	6.47	3.79	87.27
D7S	0.21	2.95	3.70	14.71	0.75	10.13	36.37	4.78	73.60
D8S	0.38	7.15	2.99	20.99	0.98	6.42	10.42	5.25	54.58
D9S	0.36	6.14	2.01	16.33	0.87	5.34	8.12	34.33	73.48
D10S	0.24	2.46	1.75	9.08	0.92	2.61	3.27	4.30	**24.63**
D11S	0.51	10.34	8.79	15.50	1.72	2.46	14.99	5.33	59.64
D12S	0.81	14.27	20.42	34.33	3.55	26.95	30.40	2.11	**132.84**
D13S	0.17	2.95	1.03	26.90	0.52	4.10	4.44	6.55	46.66
D14S	0.23	3.60	2.54	18.64	0.87	21.14	8.97	2.70	58.67
D15S	0.30	3.66	2.11	11.16	1.12	7.27	8.83	7.24	41.68
Ecological_Risk index (Eri)									
Sites	Cr	Co	Cu	Zn	As	Cd	Pb	Hg	**RI**
D1S	0.29	8.32	2.67	17.72	4.17	59.95	19.65	183.96	296.72
D2S	0.59	5.20	5.17	16.84	7.28	153.62	62.30	343.10	**594.11**
D3S	0.57	6.18	5.10	19.71	5.65	156.80	51.87	741.66	**987.54**
D4S	0.45	5.59	2.90	14.40	4.60	90.22	43.08	207.21	**368.46**
D5S	0.72	36.27	5.24	97.39	7.72	250.57	76.08	275.52	**749.51**
D6S	0.26	3.63	5.94	9.22	3.84	1820.41	32.35	151.66	**2027.31**
D7S	0.42	2.95	7.39	14.71	7.45	303.97	181.84	191.04	**709.79**
D8S	0.75	7.15	5.99	20.99	9.83	192.58	52.10	209.84	**499.24**
D9S	0.72	6.14	4.02	16.33	8.65	160.27	40.58	1373.07	**1609.76**
D10S	0.48	2.46	3.51	9.08	9.21	78.25	16.33	172.20	291.52
D11S	1.01	10.34	17.58	15.50	17.16	73.89	74.97	213.37	**423.82**
D12S	1.63	14.27	40.84	34.33	35.48	808.42	152.00	84.30	**1171.27**
D13S	0.35	2.95	2.06	26.90	5.20	122.93	22.22	261.94	**444.56**
D14S	0.46	3.60	5.07	18.64	8.71	634.07	44.84	107.87	**823.25**
D15S	0.61	3.66	4.22	11.16	11.17	217.96	44.14	289.57	**582.48**

Table 5
Spearman rank order correlation for selected parameters analyzed in the soil samples from the site.

	Cr	Co	Cu	Zn	As	Cd	Pb	Hg	OM	MGS
Cr	1	0.39	**0.90****	0.26	**0.95****	0.00	**0.53***	0.00	0.39	−0.25
Co		1	0.24	**0.95****	0.23	−0.05	0.22	−0.05	**0.62***	−0.41
Cu			1	0.12	**0.96****	0.27	**0.63***	−0.23	0.16	−0.16
Zn				1	0.11	−0.07	0.19	−0.05	**0.68****	−0.49
As					1	0.13	**0.56***	−0.18	0.25	−0.15
Cd						1	0.1	−0.24	−0.42	−0.01
Pb							1	−0.18	0.30	−0.13
Hg								1	0.11	−0.46
MO									1	−0.49
MGS										1

OM: Organic matter, MGS: Mean grain size.
* Statistically significant coefficients at the $p < 0.05$ level.
** Statistically significant coefficients at the $p < 0.01$ level.

from distinct anthropogenic wastes. However, there is a positive correlation between Cr/Cu(r = 0.90, p<0.001), Cr/As(r = 0.95, p<0.001), Cr/Pb(r = 0.53, p<0.05), Co/Zn(r = 0.95,p<0.001), Cu/As(r = 0.96, p<0.001), Cu/Pb(r = 0.63, p<0.05), As/Pb (r = 0.56, p<0.05). The observed positive correlation between Cr/Cu, Cr/As, Cr/Pb, Co/Zn, Cu/As, Cr/As, Cr/Pb, Co/Zn suggests that these metals could have originated from common sources with a similar transport pathway (Poté et al., 2008; Haller et al., 2009a, 2009b; Mata et al., 2020). In general, the similar results were observed in other sites. The correlations between metal concentrations suggest either a common or a similar geochemical behavior or origin. Many factors have an impact on the distribution of metals in sediments, including the source rock type, weathering processes, surface adsorption phenomena, and depositional conditions. Therefore, metal/metal relationships can vary significantly. In addition, heavy metals persist after being introduced into the environment by anthropogenic sources for a long period of time without becoming degraded since they do not undergo biodegradation. Based on this study, a very high risk exists for human inhabitants living nearby dumpsites, particularly children, due to extensive heavy metal pollution. In addition, there is an increased risk for the river ecosystem from the leaching of metals from these dumpsites. Thus, we recommend minimizing the pollution load through bioremediation approaches and measures to efficiently manage the urban dumpsites in the Congo.

4. Conclusion

In Kinshasa, the enormous amount of waste without separation has become a serious problem. Taken as an initiative, in this study, toxic metals were quantified and the environmental pollution index models were used to unravel the level of contamination/pollution of soils from

dumpsites in terms of toxic metals. All sampling sites are heavily contaminated by investigated metals, especially Pb, Cu, Zn and Hg. The high level of these metals can be explained by different fractions of wastes including electronic wastes, plastics, industrial and biomedical wastes, glass, battery, paper, and organic fraction in studied dumpsites. The calculated pollution indexes (Geo-accumulation, Enrichment Factor, Contamination degree and Potential Ecological Risk), showed high pollution, extremely severe enrichment and environmental risks of Zn, Cu, Pb and Hg. The pollution quantification of each metal in the study area indicated the extremely high concentration values for Zn, Pb, Cu and Hg. The different contamination indices and/or toxicity calculated revealed critical situations for several stations like D6S, D9S, and D12S. Cases of polymetallic contamination dominated by more elements were recorded (Cd, Cu, Zn and Pb are the most worrying). The potential ecological risk index of soils is as follows: D6S >D9S> D12S> D3S> D14S >D5S> D7S> D2S> D15S> D8S> D13S> D11S> D4S> D1S> D10S. The overall ecological risk index is 2 027.31, classifying the site D6S as high risk. There is a possibility that in the near future, the entire aquatic and terrestrial environments will become contaminated with toxic elements. Agricultural use of manure from landfills should be discouraged due to the toxicity of heavy metals, since plants and vegetables are easily contaminated. As stated by the authors, the waste-collection facilities should be strengthened, and policies should be put in place to separate waste at the source. Municipalities should also continue monitoring the dumping sites, particularly in areas where aquatic systems have been identified as hotspots for contamination, to prevent further contamination through leaching. Moreover, future studies should map dumpsites that are polluted with high levels of pollution and implement potential measures to prevent ecosystem degradation caused by anthropogenic activities.

Ethics statement

We confirm that the field studies and sampling did not involve misunderstanding. The funder had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript

Author contributions

PS, GG, CM, PM and JP Conceived and designed research; BM, AL, CM and JO performed research: sampling and laboratory analysis; BM, PS, AL, GG, and JP analysed data. All authors wrote and have read, reviewed and approved the manuscript before submission.

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Declaration of Competing Interest

The authors declare no conflict of interest.

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