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Article

Bioaccumulation of metals and metalloids in soils and in the earthworm *Hyperiodrilus africanus* from uncontrolled landfills in Kinshasa, Democratic Republic of the Congo

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Abstract: To better understand the ecological impact of pollutants from uncontrolled landfills and to assess the potential risks they pose to terrestrial ecosystems and public health, soil samples were collected from uncontrolled landfills in three municipalities of Kinshasa and analyzed for 17 metals and metalloids (including metals Fe, Zn, Mn, Cu, Pb, Cr, Co, Sn, Ni, Cd, Sc, Ag, Mo, and Hg, and metalloids Se, As, Sb) using ICP-MS and AAS. The following decreasing order of elemental concentrations was generally observed in soils: Fe > Zn > Mn > Cu > Pb > Cr > Co > Sn > Ni > Cd > Se > As > Sb > Sc > Ag > Mo > Hg. The Geoaccumulation Index (Igeo) and the Enrichment Factor (EF) indicated very severe to extremely severe soil contamination by metals, with high enhancement of Cu, Zn, As, Ag, Cd, Sb, Pb, and Hg concentrations. Furthermore, several ecotoxicological indices, such as the Potential Ecological Risk Index (RI), highlighted serious soil pollution, particularly in the samples from the landfill receiving industrial waste at Limete municipality. Therefore, the use of these soils from uncontrolled landfills for fertilization of agricultural fields, as farmers currently do, poses a serious risk to public health. Concentrations of metals and metalloids were determined also in the earthworm *Hyperiodrilus africanus*, collected in the same areas, and the earthworm bioaccumulation factor (on a dry weight basis) displayed values greater than one in most samples and up to 15.3. This bioaccumulation of metals and metalloids from the soil suggests that earthworms can be used as a bioremediation agent for contaminated soils. Based on the results from this research, several recommendations are made to improve the pollution control and to protect public health.

Keywords: uncontrolled landfills; toxic metals; *Hyperiodrilus africanus*; Igeo index; Kinshasa

1. Introduction

Uncontrolled landfills represent a significant environmental and public health challenge worldwide. Such informal waste disposal sites, in general missing proper design, management, and control, are a consequence of the fast population growth, rapid urbanization, and lack of investment in waste management infrastructures [1,2]. Unlike regulated landfills, the uncontrolled landfills fail to isolate waste from the surrounding environment, and the waste piles leachates, especially when rainwater flows through the waste piles, spread in the environment and do contaminate air, soil, and water resources.

The waste piles leachates usually contain harmful substances, including toxic metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As), persistent organic pollutants, and pharmaceutical drugs, which are of particular concern because of their environmental persistence, toxicity, and bioaccumulation potential. When released into the soil, organic and inorganic pollutants pose significant risks to soil health, plant growth, and, ultimately, to human health through their transfer in food chains [3–6]. These uncontrolled landfills also generate pathogenic bacteria and facilitate the proliferation of disease vectors, such as insects and rodents, that represent serious threats to ecosystems and to public health [7]. Similarly, the uncontrolled release of greenhouse gases into the atmosphere, like methane, a byproduct of organic waste decomposition, contributes to climate change. Furthermore, these sites pose socio-economic risks also, particularly in low-income areas, where marginalized communities are disproportionately affected by the pollution and health hazards associated with the improper waste disposal [8,9].

In this region, farmers have the practice of collecting soil under the waste piles, which are enriched in decomposing organic waste, to use it as a fertilizer in agricultural fields. This practice likely contributes to the transfer of pollutants out of landfills and promotes the contamination of healthy agricultural soils. Nevertheless, the pollution of agricultural soils by this practice has not been assessed.

Abatement of soil pollution demands innovative and sustainable solutions for remediation. Among various strategies explored so far, bioremediation, i.e., the use of biological organisms to restore contaminated environments, has emerged as a promising approach [10–14]. Earthworms, long regarded as key players in soil ecosystems, are increasingly recognized for their potential role in bioremediation [15,16]. Earthworms significantly enhance soil structure, aeration, and nutrient cycling through their burrowing and feeding activities [17]. Furthermore, their ability to bioaccumulate and biodegrade organic and inorganic pollutants makes them valuable agents for mitigating soil and water contamination [18].

Soil decontamination by earthworms is better known as vermiremediation [18]. This approach leverages biotic and abiotic interactions, as well as the life cycle, burrowing, and feeding activities of earthworms, to transform, degrade, or eliminate contaminants from the soil [19]. These organisms remove pollutants both directly, by absorbing and digesting them, and indirectly, by stimulating the growth of beneficial microorganisms that aid in soil decontamination [20]. Several mechanisms contribute to this process. Through vermiextraction, earthworms absorb contaminants from the substrate via their epidermis and digestive system, accumulating them in their bodies. Vermitransformation (digestion by earthworms) breaks down organic pollutants as they pass through the earthworm’s gut, where microorganisms and enzymes convert them into less toxic forms. Meanwhile, drilo-degradation takes place within the 2 mm zone surrounding earthworm burrow walls, known as the drilosphere [19,21]. This area, enriched by worm residues, mucus secretions, and castings, becomes a microbial hotspot with significant potential for degrading organic compounds [18]. By processing waste materials such as heavy metals, hydrocarbons, and pesticides, earthworms not only detoxify soils but also promote the decomposition of organic matter and the recovery of soil fertility [22,23].

This study focused on the examination of metals and metalloid concentrations in soils and earthworms from uncontrolled landfills at N'djili, Limete, and Lemba municipalities of Kinshasa, in the Democratic Republic of the Congo (DR Congo). Through the determination of elemental concentrations in soil and in earthworm tissues, it was aimed to better understand the ecological impact of pollutants from landfills and to assess potential risks associated with their presence in terrestrial ecosystems. Furthermore, the attributes of an indigenous earthworm, *Hyperiodrilus africanus*, were assessed as a potential soil bioremediation agent.

2. Materials and methods

a. Description of study sites and sampling procedures

Three informal landfills located in the city of Kinshasa, within the municipalities of N'djili, Limete, and Lemba, were selected as the study area (**Figure 1**). The selection was based on the distinct nature of their predominant activities: industrial activities in Limete, artisanal activities in N'djili, and agriculture and domestic activities in Lemba [24,25].

Figure 1. Uncontrolled landfills of: **(A)** N'djili; **(B)** Limete; **(C)** Lemba municipalities; **(D)** earthworm *Hyperiodrilus africanus* (Photos by Akonga).

In these municipalities, farmers use the soil grabbed underneath uncontrolled landfills to fertilize their agricultural soils and even grow crops on sites once used as landfills. This practice may introduce contaminants present in the landfills into the food chain, but this was not checked so far.

Soil and earthworm samples were collected from the three landfill areas for analysis of metals and metalloids. The sampling campaign took place in July 2023 (dry season) and was repeated in December 2023 (rainy season).

Subsoil samples were collected using a plastic shovel at the periphery of the waste heaps and transferred into 1.5 L plastic bottles. These subsoil samples, each made of 4 subsamples pooled in one sample weighing 250–300 g, were grabbed in each landfill at a depth of approximately 0.3 m below the ground surface. A total of six composite soil samples (i.e., three collected during the wet season and three collected during the dry season) were labeled as follows: SN1 (dry season), SN2 (wet season) for N'djili landfill; SLI1 (dry season), SLI2 (wet season) for Limete landfill; and SLE1 (dry season), SLE2 (wet season) for the Lemba landfill (**Figure 2**).

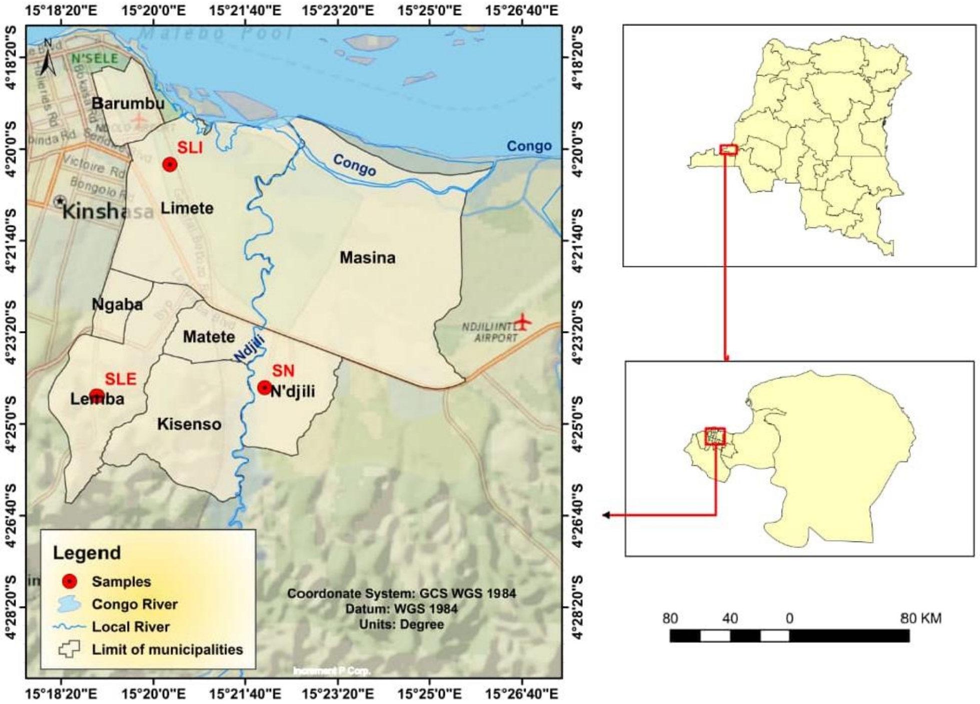

Figure 2. Study areas and location of investigated uncontrolled landfills in the municipalities of N'djili, Limete, and Lemba.

Earthworm samples of the species *Hyperiodrilus africanus* (20 specimens per site; average weight of an individual earthworm of about 0.8 g) were collected in December 2023 at the landfills of the three sites using a plastic shovel to dig the soil at the periphery of the waste heaps. These samples were identified as EN (N'djili), ELI (Limete), and ELE (Lemba). All samples were stored at 4 ℃ and transported refrigerated to the analytical laboratory platform of the University of Geneva for analysis.

b. Soil physicochemical characteristics

The soil samples were sieved using a 2 mm nylon sieve to remove stones and other coarse debris and thoroughly homogenized. Aliquots of sieved soil samples were used for determination of the physicochemical parameters of soils.

For the determination of soil electrical conductivity (EC) and pH, 5 g of each soil sample were placed in a test tube, and 2 mL of milli-Q (MQ) water were added. The test tubes were sealed and vigorously shaken for 30 min using a mechanical stirrer. After allowing the solids to decant, the supernatant was used to measure the soil electrical conductivity (EC) and pH with an HQ40D multiparameter probe from

HACH (Auckland, New Zealand).

The soil water content (WC) was determined in soil aliquots by calculating the weight loss after drying the soil aliquot in an oven at 100 °C until constant weight. The soil organic matter (OM) content was determined through the weight loss of dry soil aliquots after combustion for 1 h at 550 °C in a muffle furnace (Salvis AG, Lucerne, Switzerland). The carbonate content was estimated based on further weight loss of the 550 °C combusted samples after heating them at 1000 °C for 1 h using the same muffle furnace.

The soil particle grain size was analyzed using approximately 1 g of fresh soil. Following 5 min of ultrasonic dispersion of this soil aliquot in deionized water, particle grain size was determined with a Coulter LS-100 laser diffractometer (Beckman Coulter, Fullerton, CA, USA) [26,27].

c. Analysis of mercury (Hg) in soils

The total mercury (Hg) content in soil and earthworm samples was analyzed using the Direct Mercury Analyzer DMA 80-III (MWS GmbH). This method is based on atomic absorption spectroscopy with cold vapor (CV-AAS). The procedure involved the combustion of samples, the amalgamation of mercury in a gold trap, and the measurement of gaseous mercury with the analyzer. The Hg recovery yield was higher than 90%.

As an analytical quality control procedure for the determination of total Hg in soil samples, the certified reference material (CRM) TORT-3 from the National Research Council, Canada, was prepared and analyzed in parallel with the samples, following the Feststoffe Schnell method (no drying temperature, burning temperature: 750 °C). For earthworm samples, the certified reference material DORM-4 from the National Research Council, Canada, was used, and the Kunstoff method was applied (drying temperature: 400 °C, combustion temperature: 750 °C). The results of both CRM analyses were in good agreement, within ±10%, with the certified values.

Results of total mercury concentrations in the materials analyzed are expressed in mg kg^{-1} (dry weight) [28].

2.1. Analysis of metals and metalloids in soils

Soil samples were prepared for mineralization in acids following the protocol outlined in the Federal Soil Ordinance (Osol) 814.12 from Switzerland [29]. The samples were dried in an oven at 60 °C until constant weight and finely ground. An aliquot of about 1 g of soil, accurately weighted, was digested in 10 mL of 2 M HNO_3 using Teflon digestion vessels and heated at 100 °C for 16 h. After cooling to room temperature, the samples were centrifuged at 4000 rpm for 15 min to remove any refractory particles. The acidic supernatants were diluted (1:200) with 1% suprapur HNO_3 and analyzed using inductively coupled plasma mass spectrometry (ICP-MS). The recovery yield values were higher than 90% for most elements targeted in this study.

As the analytical quality assurance control, the certified reference material STSD-1 (National Research Council, Ottawa, Ontario, Canada) was processed and analyzed alongside the soil samples. Results from the analysis of this CRM were in good agreement, within ±10%, with the certified values.

Results for the elemental concentrations determined in the samples were expressed in mg kg^{-1} (dry weight).

2.2. Analysis of metals and metalloids in earthworms

The analytical protocol for the determination of metals and metalloids in earthworms was adapted from Suami et al. [30], originally designed for oysters and crayfish, but with modifications based on methods by Rashed [31] and Sivaperumal et al. [32]. Earthworms were washed, dissected to remove the gut contents, and the tissues of 20 specimens bulked to make a sufficiently large sample and weighed. Samples were then freeze-dried (Adolf Kühner, Birsfelden, Switzerland) and ground into a fine powder.

Accurately weighed aliquots of approximately 1 g of the powdered samples were digested in 10 mL of a 3:1 mixture of suprapur HNO_3 (65%, Merck KGaA, Darmstadt, Germany) and $HClO_4$ (70%, Merck KGaA, Darmstadt, Germany) using Teflon digestion vessels and heated overnight at 110 °C. After cooling to room temperature, the sample solutions were centrifuged to remove any remaining insoluble particles, the supernatant was collected and diluted with 1% suprapur HNO_3, and the acid solution was analyzed using ICP-MS. Ultrapure water (Millipore, Milli-Q, 18MW, Merck, Darmstadt, Germany) was used for all acid dilutions.

For the purpose of analytical quality control, the certified reference material DORM-4 (National Research Council, Ottawa, Ontario, Canada) was used to test the accuracy of determinations. Aliquots of this CRM were prepared and analyzed alongside the samples, and the results were in good agreement, within ±10%, with the certified values.

Results of the elemental concentrations were expressed in mg kg^{-1} (dry weight).

2.3. Parameters used in the evaluation of soil pollution

Soil pollution was evaluated using two parameters: the Enrichment Factor (EF) and the Geoaccumulation Index (Igeo) [33]. The occurrence of soil pollution by metals and metalloids was identified using the *EF*, calculated through the following equation:

$$\mathrm{EF} = [M/Sc]_{\mathrm{sample}}/[M/Sc]_{\mathrm{background}} \quad (1)$$

where *M* represents the concentration of the heavy metal in the soil sample or geochemical background, and *Sc* is the concentration of scandium in the same sample and in the average background. Therefore, scandium (*Sc*) was used to normalize analytical results. The metal concentrations in the Upper Continental Crust (UCC) were used as the geochemical background concentrations for *Sc* and for the analyzed metals *M* [34].

The pollution level was further assessed using the Igeo parameter, calculated as follows:

$$\mathrm{Igeo} = \mathrm{Log}_2[M]/1.5[B] \quad (2)$$

where *M* is the concentration of metal in the soil sample and *B* is the concentration of the same metal in the geochemical background. The multiplicative factor 1.5 increases the average concentration of metal *M* in the UCC in order to account for natural variations in the geochemical background [33].

2.4. Calculation of ecological risk parameters

Soil pollution poses ecotoxicological threats to biota, and their severity depends upon the contamination level. To assess the contamination level of heavy metals in soil, the Contamination Factor (CF) was calculated as follows [35,36]:

$$\mathrm{CF} = (M/B) \tag{3}$$

where M is the concentration of heavy metals in the soil sample and B is the concentration of heavy metals in the geochemical background.

The polymetallic contamination level for each soil sample was evaluated by the calculation of the Contamination Degree (CD) parameter using the following equation [37]:

$$\mathrm{CD} = \Sigma \mathrm{CF}_m \tag{4}$$

where CF_m represents the Contamination Factor of each metal, m. The metals Hg, Cd, As, Co, Cu, Pb, Cr, and Zn were included in this calculation.

To assess the ecological impact of heavy metals, the Ecological Risk Index (Er_m), reflecting the toxicity and sensitivity to each pollutant [38], was calculated through the equation:

$$\mathrm{Er}_m = \mathrm{Tr}_m \times \mathrm{CF}_m \tag{5}$$

where Tr_m is the Toxic Response Factor for each metal, with values as follows: Hg (40), Cd (30), As (10), Co (5), Cu (5), Pb (5), Cr (2), and Zn (1) [39].

The Potential Ecological Risk Index (RI) for each sample, accounting for the combined toxic effects and ecological sensitivities of biota, was calculated as [39]:

$$\mathrm{RI} = \sum \mathrm{Er}_m \tag{6}$$

where Er_m is the ecological risk index for the metal m.

2.5. Bioaccumulation factor (BAF)

The bioaccumulation factor (BAF) was calculated to quantify the transfer of metals and metalloids from the uncontrolled landfill soils to the earthworm tissues. The following equation [40,41] was used:

$$\mathrm{BAF} = Cew/Cs \tag{7}$$

where Cew is the concentration of the metal in earthworms (mg kg^{-1} dw) and Cs is the mean concentration of the same metal in the soil (mg kg^{-1} dw).

3. Results and discussion

a. Physicochemical characteristics of uncontrolled landfill soils and earthworm samples

The results for water content, total organic matter, carbonate, pH, electrical conductivity, and mean particle grain size for soils and earthworms from uncontrolled landfills are summarized in **Table 1**.

Table 1. Physico-chemical parameters of soil samples and earthworm samples from three uncontrolled landfills in Kinshasa.

GPS coordinates	Sampling site	Sample (season)	WC (%)	OM (%)	Carbonate (%)	pH	EC (µS cm^{-1})	Clay (%)	Silt (%)	Sand (%)
Soil samples										
S04°24′20.2″ E015°22′01.0″	N’djili	SN1 (dry)	3.2	13.2	5.6	7.9	1152.8	2.8	70.3	26.9
		SN2 (wet)	22.1	10.7	4.9	8.8	690.5	1.5	48.6	49.9
S04°24′29.3″ E015°18′58.8″	Limete	SLI1 (dry)	7	12.1	6.1	7.6	1037.7	2.5	53	44.5
		SLI2 (wet)	23.8	37.6	12.4	7.7	487.3	2.7	45.1	52.2
S04°33′79.5″ E015°33′85.3″	Lemba	SLE1 (dry)	8.3	11	2.2	8	831.5	0.9	40.1	59
		SLE2 (wet)	28	21	4.6	9	601	1	48	51
Earthworm samples										
S04°24′20,2″ E015°22′01,0″	N’djili	EN	15	31	5.05					
S04°24′29,3″ E015°18′58,8″	Limete	ELI	3.9	52	14.3					
S04°33′79.5″ E015°33′85.3″	Lemba	ELE	2.7	51	17.08					

The water content of soils (WC) varied with sample location and season of the year. It varied from 3.2% (dry season) to 22.1% (wet season) for N’djili samples; from 7% (dry season) to 23.8% (wet season) for Limete samples; and from 8.3% (dry season) to 28% (wet season) for Lemba samples. In earthworms, the WC was 15% (N’djili samples), 3.9% (Limete samples), and 2.7% (Lemba samples).

The organic matter (OM) content of soil samples varied among sites and with the season. It was determined at 13.2% (SN1) and 10.7% (SN2) in N’djili samples; 12.1% (SLI1) and 37.6% (SLI2) in Limete samples; 11% (SLE1) and 63% (SLE2) in Lemba samples. In earthworms, the OM content was 31% (N’djili), 52% (Limete), and 51% (Lemba).

The calcium carbonate ($CaCO_3$) content was determined at 5.6% (dry season) and 4.9% (wet season) for N’djili, 6.1% (dry season) and 12.4% (wet season) for Limete, and 2.2% (dry season) and 4.6% (wet season) for Lemba. The earthworm samples showed the following values for carbonate content: 5.05% for N’djili, 14.3% for Limete, and 17.08% for Lemba.

All soil samples exhibited a basic pH, ranging from 7.6 to 9. The EC values for soil samples were 1152.8 µS cm^{-1} (dry season) and 690.5 µS cm^{-1} (wet season) for N’djili samples, 1037.7 µS cm^{-1} (dry season) and 487.3 µS cm^{-1} (wet season) for Limete, and 831.5 µS cm^{-1} (dry season) and 601 µS cm^{-1} (wet season) for Lemba samples.

In general, the soil grain size analysis showed a high percentage of silt (40.1% to 70.3%) and sand (26.9% to 59%) and a low clay content (0.9% to 2.8%). The soils from the three municipalities were silty and sandy, with texture and composition varying across sites.

b. Concentrations of metals and metalloids in soils and earthworms

The concentrations of metals and metalloids in both soil samples (mg kg^{-1} dw) and earthworms *Hyperiodrilus africanus* (mg kg^{-1} dw) from uncontrolled landfills were determined using ICP-MS and DMA. The results are presented in **Table 2**, which also includes the results for the CRM analysis.

In general, the highest concentrations of the analyzed elements were found in Limete, followed by N'djili and Lemba landfills. Across most of the studied sites, the concentration of elements followed this order: Fe > Zn > Mn > Cu > Pb > Cr > Co > Sn > Ni > Cd > Se > As > Sb > Sc > Ag > Mo > Hg.

The uncontrolled landfills in the municipalities of N'djili and Limete, primarily receiving waste from industrial and artisanal activities, are large waste dumps and thus important sources of metal pollutants such as copper (Cu), zinc (Zn), cadmium (Cd), and lead (Pb). The main sources of these pollutants could be the waste from metal plating, welding, and machining. Additionally, the improper disposal of electronic waste (e-waste), including printed circuit boards, wires, and batteries, can also release Cu, Pb, and Cd. Industrial paints and coatings frequently also contain Pb and Zn, further increasing the potential pollution originated in these landfills. Regarding the artisanal sources, the small-scale metalworking workshops discard metal scraps, polishing residues, and plating chemicals containing Cu, Zn, and Pb. The informal recycling and repair of batteries and electronic devices also introduce Pb, Cd, and Cu into waste dumpsites. Furthermore, certain glazes and pigments used in traditional pottery contain Pb and Cd also, thus adding contaminants to the informal landfills.

Table 2 shows the concentrations of various elements (Sc, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Mo, Ag, Cd, Sn, Sb, Pb, and Hg) in the tissues of the earthworm *Hyperiodrilus africanus*. The data indicates that metal concentrations in *Hyperiodrilus africanus* were generally higher than concentrations in the surrounding soil. This trend is further confirmed by the calculated bioaccumulation factor (BAF), which was often greater than one, with a maximum value of 15.3 for Selenium (Se) at the N'djili site.

The elevated metal concentrations in *Hyperiodrilus africanus* highlight the availability of metals in uncontrolled landfills across N'djili, Limete, and Lemba, as well as the earthworm's remarkable ability to accumulate heavy metals. When compared to *Pontoscolex corethrurus*, another earthworm species collected from the CECOMAF agroecosystem in Kinshasa, Democratic Republic of Congo [27], *Hyperiodrilus africanus* displayed significantly higher metal concentrations in its tissues. Previous studies have also shown that *Hyperiodrilus africanus* possesses a high potential for bioremediation of soils contaminated by metals and petroleum hydrocarbons [42,43]. Consequently, *Hyperiodrilus africanus* appears to be a promising candidate for the bioremediation of sites contaminated by metallic pollutants. It is important to highlight that bioaccumulation leads to the concentration of heavy metals in earthworm tissues, playing a role in soil decontamination. However, this process may also increase heavy metal concentrations within the food chains, posing potential health risks to both humans and animals. As a result, ecosystems can be disrupted, as the accumulation of these pollutants may harm species essential to biodiversity and threaten the ecological balance.

Table 2. Concentrations of metals and metalloids in soils (mg kg^{-1} dw) and earthworms *Hyperiodrilus africanus* (mg kg^{-1} dw).

	Sample (season)	**Sc**	**Cr**	**Mn**	**Fe**	**Co**	**Ni**	**Cu**	**Zn**	**As**	**Se**	**Mo**	**Ag**	**Cd**	**Sn**	**Sb**	**Pb**	**Hg**
Soil samples																		
Limit of detection		ND	0.0001	0.0001	0.0289	0.0001	0.0001	0.0023	0.0013	0.0006	ND	0.0042	0.0004	0.0001	ND	0.0007	0.0021	ND
N’djili	SN1 (dry)	0.3	10.9	69.4	4415.3	2.9	3.1	158.6	563	1	0.6	0.3	0.4	0.6	1.3	0.9	81.6	0.08
	SN2 (wet)	0.3	5.5	50.4	4767.8	3.5	4.4	50.8	270.1	1.3	0.2	0.2	0.1	0.4	0.8	0.5	49.5	0.067
Limete	SLI1 (dry)	0.7	16.8	153.5	8333.7	16.7	11.3	82.8	1177.8	2.7	1	0.5	1.1	**3**	2.8	1.4	81.7	0.075
	SLI2 (wet)	1.4	32.1	264.6	15,749.4	10.7	9.9	58.8	817.4	2.3	3.7	0.6	0.2	8.5	11.9	1.9	127.3	0.048
Lemba	SLE1 (dry)	0.3	3.9	40	2733.3	2.4	1.1	7.9	89.6	1	0.4	0.2	0.2	0.1	0.3	0.2	37.7	0.057
	SLE2 (wet)	0.2	8.2	61.1	3249.9	0.6	3.2	10.1	83.2	1	0.2	0.3	0.1	0.2	0.4	0.3	9.4	0.066
STSD1	Ref.values	ND	28	3740	35,000	14	18	36	165	17	ND	2	0.3	0.8	ND	2	34	ND
	Det.values	7.2	27.1	3699.5	33,369	13.9	17.6	33.4	151.8	15.3	13.3	1.7	0.2	0.6	0.3	1.5	32.6	ND
TORT-3	Ref.values	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.292
	Det.values	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.283
Earthworm samples																		
Limite of detection			0.0002	0.0002	0.0112	0.0001	0	0.0008	0.002	0.0001	ND	0.0016	0.0004	0.0001	ND	0.0007	0.0023	ND
N’djili	EN		13.9	193.8	7578.2	10.8	7.2	116.6	812.2	2.5	6.1	1.8	0.3	2.2	1.5	0.8	40.3	0.118
Limete	ELI		17.4	295.7	10,393.5	15.5	10.5	91.8	1313.8	4.4	6.4	2.8	0.4	2.6	4.6	0.5	33	0.06
Lemba	ELE		9.3	179.3	6283.8	1.8	4.8	37.6	280.9	2.5	4.3	1.7	0.3	1	1.1	0.2	24	0.087
BAF	N’djili		1.7	3.235	1.7	3.4	1.9	1.1	1.9	2.2	15.3	7.2	1.2	4.4	1.4	1.1	0.6	1.6
	Limete		0.71	1.414	0.9	1.1	1	1.3	1.3	1.8	2.7	5.1	0.6	0.5	0.6	0.3	0.3	1
	Lemba		1.5	3.5	2.1	1.2	2.2	4.2	3.3	3	14	6.8	2	6.7	3.1	1	1	1.4
DORM-4	Ref.values		1.87	3.17	343	ND	1.34	15.7	51.6	6.87	ND	ND	0.0252	0.299	ND	ND	0.404	0.412
	Det.values		1.78	3.14	337	ND	1.32	15.1	49.8	6.79	ND	ND	0.0245	0.283	ND	ND	0.393	0.398

Note: Total variation coefficients for triplicate measurements were smaller than 5% for ICP-MS analysis; ND—Not determined.

c. Pollution and ecological risk parameters

The anthropogenic and geogenic origins of metals and metalloids in soils were identified using the Geoaccumulation Index (Igeo) and Enrichment Factor (EF) indices. The calculated Igeo and EF values are presented in **Table 3**. These indices facilitate the classification of pollution levels and degree of heavy metal enrichment in soil samples [44].

Table 3. Geoaccumulation Index (Igeo) and Enrichment Factor (EF) values calculated for metals and metalloids in soil samples.

Igeo		**Cr**	**Mn**	**Fe**	**Co**	**Ni**	**Cu**	**Zn**	**As**	**Se**	**Mo**	**Ag**	**Cd**	**Sn**	**Sb**	**Pb**	**Hg**
N'djili	SN1 (dry)	−2.3	−3.7	−3.6	−2.4	−3.3	2.1	2.4	−1.2	−7	−2.9	2.4	2	−2.7	1.6	1.4	−0.1
	SN2 (wet)	−3.3	−4.2	−3.5	−2.1	−2.8	0.4	1.3	−0.8	−8.6	−3.5	0.4	1.4	−3.4	0.7	0.7	−0.3
Limete	SLI1 (dry)	−1.6	−2.6	−2.7	0.2	−1.4	1.1	3.5	0.3	−6.2	−2.2	3.9	4.4	−1.6	2.2	1.4	−0.2
	SLI2 (wet)	−0.7	−1.8	−1.7	−0.5	−1.6	0.6	2.9	0	−4.3	−1.9	1.4	5.9	0.5	2.7	2.1	−0.8
Lemba	SLE1 (dry)	−3.8	−4.5	−4.3	−2.6	−4.8	−2.2	−0.2	−1.2	−7.6	−3.5	1.4	−0.6	−4.8	−0.6	0.3	−0.6
	SLE2 (wet)	−2.7	−3.9	−4	−4.6	−3.2	−1.9	−0.4	−1.2	−8.6	−2.9	0.4	0.4	−4.4	0	−1.7	−0.3
EF		**Cr**	**Mn**	**Fe**	**Co**	**Ni**	**Cu**	**Zn**	**As**	**Se**	**Mo**	**Ag**	**Cd**	**Sn**	**Sb**	**Pb**	**Hg**
N'djili	SN1 (dry)	11.4	4.2	4.6	10.6	5.7	232.6	290.8	24.4	0.4	7.3	293.3	224.5	8.7	165	149.6	52.4
	SN2 (wet)	5.8	3.1	5	12.8	8.1	74.5	139.5	31.8	0.1	4.9	73.3	149.7	5.3	91.7	90.8	43.9
Limete	SLI1 (dry)	7.5	4	3.7	26.2	8.9	52	260.7	28.3	0.3	5.2	345.7	481	8	110	64.2	21
	SLI2 (wet)	7.2	3.5	3.5	8.4	3.9	18.5	90.5	12	0.6	3.1	31.4	681.5	17	74.6	50	6.7
Lemba	SLE1 (dry)	4.1	2.4	2.9	8.8	2	11.6	46.3	24.4	0.3	4.9	146.7	37.4	2	36.7	69.1	37.3
	SLE2 (wet)	12.9	5.6	5.1	3.3	8.8	22.2	64.5	36.7	0.2	11	110	112.2	4	82.5	25.9	64.8

Igeo classification

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

EF classification

EF < 1: no enrichment
EF < 3: minor enrichment
EF 3–5: moderate enrichment
EF 5–10: moderate to severe enrichment
EF 10–25: severe enrichment
EF 25–50: very severe enrichment
EF > 50: extremely severe enrichment

Generally, the soil samples were classified into class 0 (Igeo ≤ 0): "practically unpolluted", or class 1 (0 < Igeo < 1): "unpolluted to moderately polluted" for Cr, Mn, Fr, Co, Ni, Cu (samples SN2, SLI2, SLE1, SLE2), Zn (samples SLE1, SLE2), As, Se, Mo, Ag (SN2, SLE2 samples), Cd (SLE1, SLE2 samples), Sn, Sb (SN2, SLE1, SLE2 samples), Pb (SN2, SLE1, SLE2 samples), and Hg. Some samples were classified into higher pollution classes, such as class 2 (1< Igeo < 2): “moderately polluted” for Cu (SN1, SLI1), Zn (SN1, SN2), Ag (SN1, SLI2, SLE1), Cd (SN1, SN2), Sb (SN1, SLI1), Pb (SN1, SLI1, SLI2); class 3 (2< Igeo < 3): “moderately to heavily polluted” for Zn (SLI2), Sb (SLI2); class 4 (3< Igeo < 4): “heavily polluted” for Zn (SLI1), Ag (SLI1), Cd (SLI1); or class 5 (5< Igeo < 6): “extremely polluted” for Cd (SLI2).

Based on results for the Enrichment Factor (**Table 3**), the EF values indicate no enrichment (EF < 1) for Se in all samples; minor enrichment (EF < 3) for Mn (SLE1), Fe (SLE1), Co (SLE2), Ni (SLE1), and Sn (SLE1), while the majority of samples indicate an enrichment degree ranging from moderate to extremely severe enrichment for Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Mo, Ag, Cd, Sn, Sb, Pb and Hg. These findings indicate that the uncontrolled landfills contribute significantly to metal pollution of soils in the areas investigated.

The results for ecological risk parameters, including the Contamination Factor (CF), Potential Ecological Risk Factor (Eri), Contamination Degree (CD), and Ecological Risk Index (RI), are summarized in **Table 4**. Most soil samples showed low-level contamination (CF < 1) for Sc, Cr, Mn, Fe, Co (SN1, SN2, SLE1, SLE2); Ni, Cu (SLE1, SLE2); As (SN1, SN2, SLE1, SLE2); Se, Sn (SN1, SN2, SLI1, SLE1, SLE2); Sb (SLE2); Pb (SN2); and Hg (SLE2). However, several samples displayed CF values ranging from “moderate contamination” to “very high contamination” for Co, Cu, Zn, As, Ag, Cd, Sn, Sb, Pb, and Hg. The CD values indicated moderate contamination for samples SN2, SLE1, and SLE2; high contamination for the SN1 sample; and very high contamination for samples SLI1 and SLI2.

Based on the Eri values, sample SL2 indicated a low ecological risk for Hg, while all samples showed the same risk level for As, Co, Cu, Pb, Cr, and Zn. However, samples SN1, SN2, SLI1, SLE1, and SLE2 exhibited moderate ecological risks for Hg. Similarly, samples SLE1 and SLE2 showed moderate ecological risks for Cd; sample SN2 indicated a considerable ecological risk for Cd; SN1 presented a high ecological risk for Cd; SLI1 and SLI2 showed a very high ecological risk for Cd.

For the RI parameter, except for samples SLE1 and SLE2, which indicated low ecological pollution levels, all the other samples exhibited moderate to severe environmental pollution risks.

Results obtained from the analyses of soil samples and from the calculation of ecological parameters clearly demonstrated that the uncontrolled landfills are a source of toxic elements that contaminate the soils in the vicinity. Furthermore, through the farmers practice of using such soils as fertilizers, there is a larger spread of contamination and higher hazards to public health.

Table 4. Ecological risk parameters calculated for metals and metalloids in soil samples.

Site	**Sample**	**CF**																	**CD**
		Sc	**Cr**	**Mn**	**Fe**	**Co**	**Ni**	**Cu**	**Zn**	**As**	**Se**	**Mo**	**Ag**	**Cd**	**Sn**	**Sb**	**Pb**	**Hg**	
N'djili	SN1 (dry)	0	0.3	0.1	0.1	0.3	0.2	6.3	7.9	0.7	0	0.2	8	6.1	0.2	4.5	4.1	1.4	27.2
	SN2 (wet)	0	0.2	0.1	0.1	0.4	0.2	2	3.8	0.9	0	0.1	2	4.1	0.1	2.5	2.5	1.2	15
Limete	SLI1 (dry)	0.1	0.5	0.3	0.2	1.7	0.6	3.3	16.6	1.8	0	0.3	22	30.6	0.5	7	4.1	1.3	59.9
	SLI2 (wet)	0.1	0.9	0.4	0.4	1.1	0.5	2.4	11.5	1.5	0.1	0.4	4	86.7	2.2	9.5	6.4	0.9	111.3
Lemba	SLE1 (dry)	0	0.1	0.1	0.1	0.2	0.1	0.3	1.3	0.7	0	0.1	4	1	0.1	1	1.9	1	6.5
	SLE2 (wet)	0	0.2	0.1	0.1	0.1	0.2	0.4	1.2	0.7	0	0.2	2	2	0.1	1.5	0.5	1.2	6.2

Site	**Sample**	**Eri**								**RI**
		Hg	**Cd**	**As**	**Co**	**Cu**	**Pb**	**Cr**	**Zn**	
N'djili	SN1 (dry)	57,1	183.7	6.7	1.5	31.7	20.4	0.6	7.9	309.6
	SN2 (wet)	47.9	122.4	8.7	1.8	10.2	12.4	0.3	3.8	207.4
Limete	SLI1 (dry)	53.6	918.4	18	8.4	16.6	20.4	1	16.6	1052.8
	SLI2 (wet)	34.3	2602	15.3	5.4	11.8	31.8	1.8	11.5	2713.9
Lemba	SLE1 (dry)	40.7	30.6	6.7	1.2	1.6	9.4	0.2	1.3	91.7
	SLE2 (wet)	47.1	61.2	6.7	0.3	2	2.4	0.5	1.2	121.3

CF classification

CF < 1: low contamination

1< CF < 3: moderate contamination

3 < CF < 6: considérable contamination

6 < CF : very high contamination

CD classification

8 ≤ CD < 16: moderate contamination

16 ≤ CD < 32: high contamination

32 ≤ CD: very high contamination

Eri classification

Eri < 40: low ecological risk

40 < Eri < 80: moderate ecological risk

80 < Eri < 160: considerable ecological risk

160 < Eri < 320: high ecological risk

Eri > 320: very high ecological risk

RI classification

RI < 150: low ecological pollution level

150 ≤ RI < 300: moderate ecological pollution level

300 ≤ RI < 600: severe ecological pollution level

RI > 600: serious ecological pollution level

4. Conclusions

The main objectives of this study were to assess soil quality regarding pollution by metals and metalloids and to assess the bioaccumulation factor of these elements in earthworms (*Hyperiodrilus africanus*) collected from uncontrolled landfills in three municipalities of Kinshasa.

The analyses revealed seasonal variations in physicochemical parameters of soils, such as water content, pH, and electrical conductivity, across the three landfills. Water content was generally higher during the rainy season, while pH and electrical conductivity peaked during the dry season. Soil samples from N'djili and Limete, receiving waste from industrial and artisanal activities, exhibited the highest metal concentrations, particularly for Cu, Zn, and Pb. Limete samples also displayed high Cd levels, and one sample from Lemba showed a high Pb concentration.

The results for pollution parameters, namely the Geoaccumulation Index and the Enrichment Factor, indicated that soil pollution ranged from moderate enrichment to severe enrichment for a plethora of elements, namely Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Mo, Ag, Cd, Sn, Sb, Pb, and Hg.

The calculation of ecotoxicological parameters indicated that the studied soil samples from uncontrolled landfills displayed pollution levels ranging from moderate to severe.

As farmers used to collect soil from landfills for application as fertilizer, such practice clearly contributes to the spread of the toxic substances from landfill leachates into the environment.

The earthworms *(Hyperiodrilus africanus)* collected from the subsoils underneath the waste piles showed metal concentrations in general significantly higher when compared to soil samples on a dry weight basis. The calculated bioaccumulation factor values generally exceeded 1, reaching up to 15.3 for Se in N'djili, indicating a substantial bioaccumulation capacity of these earthworms. These results suggest that these earthworms can be used to decontaminate agricultural soils. A strategy for such an application can be designed nowadays.

The results from this research work in Kinshasa's uncontrolled landfills highlighted the urgency in adopting measures to prevent further contamination of agricultural soils, mitigate soil contamination, protect public health, and restore ecosystem balance. With a view to such objectives, several recommendations are proposed:

- Strengthen waste management and pollution control by implementing strict regulations for waste disposal in N'djili, Limete, and Lemba to prevent further contamination of soils; establishing designated and regulated landfill sites with proper containment measures to reduce metals (and other pollutants) leaching and to encourage the segregation and recycling of hazardous waste, particularly electronic waste (e-waste), which contributes significantly to metal pollution.
- Implement soil remediation strategies by promoting the use of earthworms, like *Hyperiodrilus africanus*, in controlled remediation projects, ensuring proper monitoring to prevent their entry into the food chain.
- Restrict agricultural use of contaminated soils by prohibiting food crop cultivation on contaminated soils in these municipalities in order to prevent the transfer of metals and metalloids in the food chain and to human consumers.
- Enhance environmental monitoring and research by establishing a long-term environmental monitoring program to track soil pollution, expanding research on bioaccumulation in other soil organisms and the impact of organic pollutants on

Hyperiodrilus africanus, and developing a database of pollution hotspots in Kinshasa to guide policy interventions and remediation efforts.
- Strengthen public awareness and community engagement by conducting educational campaigns to inform the population about the dangers of metal contamination and safe waste disposal practices, involving local stakeholders, researchers, and policymakers in designing and implementing sustainable soil management solutions, and supporting community-led cleanup initiatives to reduce waste accumulation in residential and industrial areas.

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