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RESEARCH

Soil quality and heavy metal contamination in an open dumpsite in Navrongo, Ghana

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Abstract The increasing proximity of the Dudumbia dumpsite, an open dumpsite in Navrongo, Ghana, to human settlements necessitates an investigation of the soil quality to safeguard the environment from heavy metal toxicity. This study examined the impact of waste dumping activities on the physicochemical properties of the soil, as well as the level of heavy metal (Pb, Cd, Ni, Cr, As, Hg, Cu, Mn, and Zn) contamination and associated risks. Various contamination and risk assessment tools were used, including the geoaccumulation index (*Igeo*), pollution load index (*PLI*), potential ecological risk (*Er*), and potential ecological risk index (*PERI*). The study found significant improvements in notable soil attributes such as phosphorus (P), organic carbon (C), total nitrogen (N), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), and effective cation exchange capacity, with percentage increases ranging from 50.8 to 2078.3%. *Igeo* values ranged from 2.07 to 6.20, indicating contamination levels from moderate to extreme. The *PLI* and *PERI* values were 16.241 and 1810, respectively. The *Er* values for the heavy metals ranged from 36 to 607, indicating ecological risk levels from low to very high, with Cd and Hg posing very high risks. These results suggest that while the dumpsite soil shows improvements in some characteristics favourable for plant cultivation, waste dumping significantly contributes to heavy metal contamination. The soil at the dumpsite is deteriorated and poses significant health risks, particularly due to Cd and Hg. Therefore, remediation efforts should prioritise mitigating the risks posed by Cd and Hg.

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Introduction

Human activities generate vast quantities of waste originating from various sources, including residential, commercial, industrial, agricultural, and institutional activities (Buenrostro et al., 2001; Kumar et al., 2024). Many different kinds of waste are generated, including organic waste (e.g. food scraps, yard waste, animal waste), inorganic waste (e.g. plastics, metals, glass), hazardous waste (e.g. chemicals, medical waste), municipal solid wastes (e.g. food wastes, packaged goods, disposable goods, used electronics), and commercial and industrial wastes (e.g. demolition debris, incineration residues, refinery sludges) (EPA, 2023). The increase in global population, urbanisation, and economic activities has led to a corresponding rise in waste production, posing significant challenges for waste management systems worldwide (Amasuomo & Baird, 2016).

Effective waste management practices are essential to mitigate the adverse environmental and health impacts of waste. These practices include waste reduction, reuse, recycling, energy recovery, and disposal (EPA, 2023). However, in many African countries, as well as other underdeveloped and developing regions, sustainable waste management practices such as reuse, recycling, and energy recovery face numerous challenges, including limited infrastructure, inadequate funding, and lack of regulatory enforcement (Dissanayake et al., 2022). Consequently, open dumpsites are a common waste management practice in these areas due to their low cost (Aluko et al., 2022). These sites are often characterised by the uncontrolled disposal of diverse categories of untreated wastes (Kumar & Agrawal, 2020). Pollutants, especially heavy metals, leach from these waste materials into the surrounding environment, accumulating in the soil and potentially entering the food chain (Sharma & Kumar, 2021). This contamination can have long-lasting adverse effects on both the environment and human health (Briffa et al., 2020; Shah et al., 2018).

The proximity of polluted sites to human settlements heightens the risks associated with environmental contamination. Residents living near polluted sites are exposed to higher levels of pollutants, which can lead to various health issues, including respiratory problems, skin disorders, and other chronic conditions (Briffa et al., 2020; Capelo et al., 2022). The presence of heavy metals in the environment is particularly concerning due to their toxicity and persistence (Ali et al., 2019).

The Dudumbia dumpsite in Navrongo, Ghana, exemplifies an unsustainable waste management practice. Moreover, the expansion of settlements in Navrongo is prominent, with development encroaching closer to the Dudumbia dumpsite. This increasing proximity heightens the risk of exposure to environmental pollutants, including heavy metals, for the local population. Addressing the potential contamination at the Dudumbia dumpsite is critical to protect public health and ensure sustainable living conditions for the community.

This study aims to identify a suitable control site with similar characteristics to the Dudumbia dumpsite and use it to examine changes in physicochemical properties, as well as the level and risk of heavy metal (Pb, Cd, Ni, Cr, As, Hg, Cu, Mn, and Zn) contamination resulting from open waste dumping activities. These heavy metals are common environmental contaminants with associated human health risks linked to anthropogenic activities. The outcomes of this research provide insights into which heavy metals should be the focus of environmental regulations and monitoring plans at the site. Furthermore, understanding the heavy metal pollution status of the dumpsite soil will be valuable for planning potential remediation efforts to safeguard the biota in the environment.

Materials and methods

Sampling sites

Dudumbia dumpsite lies along Navrongo-Paga road, in the Kassena Nankana Municipal in the Upper East Region of Ghana (Fig. 1). It is on the left side of the N10 road and on the left side when moving from Navrongo towards Paga.

Waste dumping activities at the site commenced in the 1980s when the area was characterised by a dense forest. It is now a cleared land serving as a central waste site shared by both Navrongo and a neighbouring town, Paga. As years go by, the forests around the

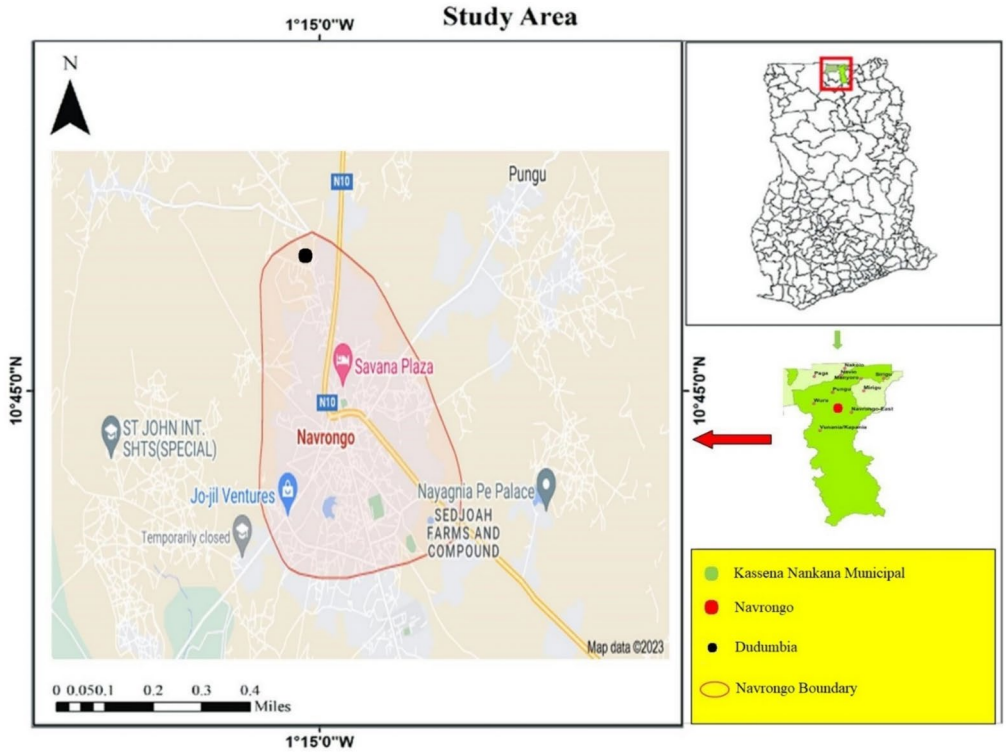

Fig. 1 Schematic representation highlighting the Dudumbia dumpsite within Navrongo Municipal Area

dumpsite are being cleared and houses are being built near the dumpsite.

Various types of waste were identified at the dumpsite, including domestic, agricultural, and industrial refuse. This assortment comprises hospital wastes such as used syringes, needles, and test kits, as well as expired beverages and canned products like tomatoes, mackerel, and canned milk. Additionally, it includes discarded toilets, damaged car tyres, car parts, spoiled fruits, vegetables, deceased animals, wood, papers, and plastics, among others. Moreover, the activities of waste scavengers were observed at the site, as they picked what they considered valuable disposables. Some were seen burning tyres to extract the metallic components.

The control site selected is about 250 m away from the dumpsite. Situated across the primary N10 road along the Navrongo-Paga route, it stands in direct opposition to the dumpsite (Fig. 2).

Furthermore, in the aerial view illustrated (Fig. 2), the prominent red road extends past the control site and serves as a designated landing area for helicopters visiting both Navrongo and Paga. The control site is an undeveloped area with a clean history, devoid of any waste dumping activities or other actions that could directly raise the concentration of heavy metals on the site.

Soil sampling

The soil samples were collected in May 2023, from both the study site (Dudumbia dumpsite) and the control site. The dumpsite was demarcated into four zones, and ten grab samples were collected from each zone at regular intervals, ensuring comprehensive coverage. Stainless steel shovel, spade, and hand trowel were used to clear the refuse over the topsoil, loosen the topsoil particles, and collect grab samples within a consistent depth of 0–20 cm, respectively. Approximately 200 g of soil was collected at each sampling spot. The same approach was applied at the control site. This resulted in a total of eighty

Fig. 2 Aerial view illustrating the location of the dumpsite and the control site (captured using Maptive Online Mapping Software)

samples, each of which was kept in a sampling bag for subsequent treatments.

Sample preparation

Sampling units collected from both the dumpsite and the control site soils were mixed thoroughly to form separate aggregate soil samples. This process ensured the creation of distinct aggregate samples representing the dumpsite soil and the control site soil. Both aggregate samples were air-dried in a well-ventilated dust-free area at ambient conditions, spread out in thin layers to facilitate the natural evaporation of moisture. During air-drying, manual techniques were employed for gentle disaggregation, ensuring the removal of any clumps or compacted material. After air-drying and disaggregation, they were each sieved through 2-mm mesh and each mixed thoroughly. Subsequently, 500 g each of both the study site soil sample and the control site soil sample were weighed and taken for physicochemical characterisation. Finally, 50 g was taken from each

of the remaining portions of the study site soil sample and the control site soil sample. They were dried at 110 °C to constant weight using a drying oven, allowed to cool down outside the oven, and kept in a desiccator until needed for digestion. The soil sample treatments for the measurement of the concentrations of volatile heavy metals Hg and As did not involve drying at 110 °C.

Physicochemical characterisation

Soil pH was determined using a glass calomel electrode (in soil/water, 1:2.5) (FAO, 2021a) and readings taken from the H1 9017 microprocessor pH meter. The determination of total nitrogen and available phosphorus was performed through Kjeldahl digestion and distillation procedures (Bremner, 1996) and the Bray and Kurtz P-1 method (Sims, 2009), respectively. Soil organic carbon content was determined using the Walkley–Black procedure (Nelson & Sommers, 1983). The concentrations of exchangeable cations (potassium, sodium, calcium, and magnesium) were determined by employing the ammonium acetate method (Thomas, 1983). Soil's texture experiment was determined by the hydrometer method (Huluka & Miller, 2014), and the type of soil was determined using the United States Department of Agriculture (USDA) Natural Resources Conservation Service's Soil Textural triangle (Groenendyk et al., 2015). Soil electrical conductivity was measured by a unified standard (soil/water, 1:5) (FAO, 2021b).

Soil sample digestion

Soil digestion was performed using the *aqua regia* method (Adesewa & Morenikeji, 2017). A 1 g of prepared soil sample was weighed into a 250-mL beaker, and 15 mL of freshly prepared aqua regia was added. The beaker containing the mixture was covered with a watch glass and heated gently on a hot plate in a fume hood at approximately 60–70 °C until brown fumes disappeared, and the volume of the mixture was reduced to approximately 5–3 mL. The mixture was removed from the hotplate, allowed to cool, and diluted with 20 mL of distilled deionised water (DDW). The resulting mixture was filtered through Whatman 42 filter paper into a 100-mL standard volumetric flask. The filtrate was diluted to a final volume of 100 mL using DDW. The resulting solution was transferred into a plastic bottle and kept for the analysis of heavy metals. The digestion was performed in multiple replicates for the dumpsite soil and the control site soil.

Heavy metal contamination and risk assessment

The heavy metal contamination and risk assessment of the Dudumbia dumpsite soil were conducted through a multi-step approach. This involved determining the concentration of the heavy metals, statistically comparing the measured concentrations with those of the control site, evaluating the geoaccumulation index (*Igeo*) of each heavy metal, comparing the concentrations of the heavy metals with permissible limits in soils established by international guidelines, assessing the potential ecological risk of individual heavy metals and their overall potential ecological risk (*PERI*), and evaluating the pollution load index (*PLI*).

Heavy metal analysis by atomic absorption spectrophotometry

Solutions obtained from the digestion procedure were sequentially introduced into an Agilent 240 AA atomic absorption spectrophotometer (AAS), manufactured by Agilent Technologies, USA. The instrument was calibrated beforehand for measuring heavy metal concentrations in aqueous solutions. The formula used for the calculation of the mg/kg concentrations of the heavy metals in the soils is as follows:

$$A = \frac{BV}{M} \quad (1)$$

where B represents the concentration (in mg/L) of the heavy metal present in the solution prepared for metal analysis as measured from AAS, V is the volume (in L) of the solution prepared for AAS analysis, and M (in kg) is the mass of the soil sample subjected to acid digestion.

Correction for moisture content was made to obtain the concentration of the volatile elements Hg and As in a dried (to constant weight) sample of the

soil. The correction was calculated using the following formula:

$$\text{Concentration of Hg/As in the dried soil} = \frac{\text{initial measured concentration (mg/kg)}}{\text{dry weight fraction of soil sample}} \quad (2)$$

Statistical analysis

The acquired data on metal concentrations in the dumpsite soil and the control site soil obtained from replicate measurements were summarised using means and standard deviations.

Contamination level and risk assessment

The geoaccumulation index (*Igeo*) (Asamoah et al., 2021; Muller, 1969) for each metal was determined to assess the extent of soil contamination resulting from waste dumping activities at the Dudumbia dumpsite. The higher the *Igeo*, the more contaminated the site is with respect to a particular heavy metal. The formula used for the calculation of *Igeo* is as follows:

$$Igeo = \log_2\left(\frac{Cn}{1.5Bn}\right) \quad (3)$$

where *Cn* is the concentration of the heavy metal in the sample (mg/kg), and *Bn* is the background concentration of the heavy metal (mg/kg). The concentrations of the heavy metals in the control site soil were used as the background concentrations.

The *Igeo* values of the heavy metals in the dumpsite soil were interpreted using the *Igeo* classification. According to the classification, $Igeo < 0$ indicates that the study site is uncontaminated with the heavy metal; $0 < Igeo < 1$ indicates that the study site is uncontaminated/moderately contaminated with the heavy metal; $1 < Igeo < 2$ indicates that the study site is moderately contaminated with the heavy metal; $2 < Igeo < 3$ indicates that the study site is moderately/strongly contaminated with the heavy metal; $3 < Igeo < 4$ indicates that the study site is strongly contaminated with the heavy metal; $4 < Igeo < 5$ indicates that the study site is strongly/extremely contaminated with the heavy metal, and $5 < Igeo$ indicates that the study site is extremely contaminated with the heavy metal (Muller, 1969).

The pollution load index (*PLI*) (Rahmanian & Safari, 2022) of the heavy metals in the dumpsite soil was determined to examine the overall contamination status. Heavy metal *PLI* of the dumpsite soil was determined using the equation:

$$PLI = \sqrt[z]{\frac{C_n^1}{B_n^1} \times \frac{C_n^2}{B_n^2} \times \frac{C_n^3}{B_n^3} \times \ldots \frac{C_n^{zth}}{B_n^{zth}}} \quad (4)$$

where C_n^{zth} is the measured concentration of the zth heavy metal in the dumpsite soil, and B_n^{zth} is the background concentration of zth heavy metal.

The value obtained was interpreted using the *PLI* classification. According to the classification, $PLI < 1$ indicates perfection, $PLI = 1$ suggests that only baseline levels of the pollutants are present, and $PLI > 1$ suggests deterioration of the site quality.

Potential ecological risk (*Er*) (Hakanson, 1980; Karimian et al., 2021) for each heavy metal under study was evaluated to determine the ecological risk associated with its contamination in the dumpsite soil. *Er* for a heavy metal in the dumpsite soil was determined using the equation:

$$Er = T^i \times \frac{C_n}{B_n} \quad (5)$$

where T^i is the toxic response factor of heavy metal i. The values for Pb, Cd, Ni, Cr, As, Hg, Cu, Mn, and Zn are 5, 30, 5, 2, 10, 40, 5, 1, and 1, respectively. *Cn* is the measured concentration of the heavy metal in the sample (mg/kg); *Bn* is the background concentration of the metal (mg/kg).

The values obtained were interpreted using the *Er* ecological risk classification. $Er < 40$ indicates low risk; 40–80 indicates moderate risk; 80–160 indicates considerable risk; 160–320 indicates high risk, and $Er > 320$ indicates very high risk.

PERI (Hakanson, 1980; Karimian et al., 2021; Wang et al., 2022) was calculated to evaluate the overall ecological risks associated with heavy metal contamination in the dumpsite soil. It was calculated using the equation:

$$PERI = \sum T^i \times \frac{C_n}{B_n} \quad (6)$$

The value obtained was interpreted using the *PERI* ecological risk classification. According to the classification, $PERI < 150$ indicates low ecological risk,

150–300 indicates moderate ecological risk, 300–600 indicates strong ecological risk, and *PERI* > 600 indicates quite strong ecological risk.

The concentrations of the heavy metals in the dumpsite soil were also examined for compliance with WHO permissible limits in soil. This is crucial for indicating pollution (Adagunodo et al., 2018). A breach often necessitates remediation to reduce contamination and mitigate health risks.

Analytical quality control

To ensure the reliability of our results, rigorous quality control measures were implemented during both sampling and analysis stages. Analytical-grade reagents were used throughout the study. Multiple samples were collected from various parts of the dumpsite and the control site, ensuring wide coverage and representativeness. Distinct sets of sample collection and treatment tools were dedicated to each site to prevent cross-contamination of the studied pollutants. Calibration standard reagents for each heavy metal were used to prepare five standard solutions covering a concentration range specific to each heavy metal (0–15 mg/L for lead, 0–1.5 mg/L for cadmium, 0–10 mg/L for nickel, 0–6 mg/L for chromium, 0–1.5 mg/L for arsenic, 0–10 mg/L for mercury, 0–5 mg/L for copper, 0–3 mg/L for manganese, and 0–10 mg/L for zinc). These solutions were crucial for establishing a strong correlation (with $r^2 = 0.99$) between absorbance readings from AAS and the corresponding heavy metal concentrations. The linear regression equations derived from these calibration plots (Table 6) were characterised by intercepts at the origin and were utilised to assess unknown concentrations of heavy metals in solutions using the same instrument. Additionally, a blank sample analysis was conducted to monitor and correct any potential reagent errors during the determination of heavy metal concentrations in the solution of the heavy metals obtained after the digestion of the soil sample. The blank sample was prepared by carrying out the digestion process without the soil sample, following the same procedure as for the soil sample, and diluting the resulting solution for AAS analysis. The concentrations of the heavy metals in the blank solution were measured and found to be 0 ppm for each metal.

Results and discussion

Physicochemical characteristics

The control site exhibits close similarity in soil texture and porosity with the dumpsite soil (Table 1; Fig. 4). These similarities, along with its location within the same geographical area and its uncontaminated history, make the control site a good reference point for accurately assessing the impact of waste dumping activities on the dumpsite soil. The observed differences can be attributed to the activities at the dumpsite.

The pH of the dumpsite soil is slightly higher than that of the control site (Table 2). This suggests the presence of a higher concentration of basic cations in the dumpsite soil (Neina, 2019). Similarly, the elevated electrical conductivity in the dumpsite soil compared to the control site soil indicates an increase in the concentration of dissolved ions, which could include both essential and heavy metal ions (Abira, 2008). These observations align with higher concentrations of calcium (Ca), magnesium (Mg), potassium

Table 1 Physical properties of the soil samples

	Sand (%)	Silt (%)	Clay (%)	Texture (%)	Porosity (%)	WRC (%)
Dumpsite	78.00	16.00	6.00	Loamy sand	35.00	23.00
Control site	84.00	12.00	4.00	Loamy sand	35.14	11.00

Table 2 Chemical properties of the soil samples

	pH	EC (S/m)	*P* (mg/kg)	OC %	TN	Ca cmol/kg	Mg	K	Na	eCEC
Dumpsite	8.48	1.69	7.52	2.07	0.20	28.89	1.93	5.01	0.89	36.76
Control	8.01	0.17	2.31	1.36	0.13	3.64	1.28	0.23	0.19	5.40

(K), and sodium (Na) in the dumpsite soil compared to the control site soil. The rise in the concentrations of these elements may be attributed to the decomposition of organic waste materials at the dumpsite, leading to the release of soil nutrients such as cations (Asare & Száková, 2023). This explanation corresponds to the results obtained for nitrogen, organic matter, organic carbon, and phosphorus, which also show higher concentrations in the dumpsite soil compared to the control site soil.

Moreover, the dumpsite soil demonstrates a notably greater water retention capacity (Table 1). This observation aligns with the findings regarding organic matter. It is plausible that the higher water retention capacity of the dumpsite soil is attributed to a higher organic matter content, considering that organic carbon is known to enhance soil's water-holding abilities (Ankenbauer & Loheide, 2017; Rawls et al., 2003). Thus, it is reasonable to assume that the increased presence of organic matter in the dumpsite soil is the underlying factor contributing to its enhanced water retention capacity.

The dumpsite soil not only boasts greater nutrient abundance but also exhibits a significantly heightened capacity for retaining and exchanging crucial cations, including Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}. This is evident in the measured effective cation exchange capacity (eCEC), with the dumpsite soil displaying a markedly higher eCEC value in contrast to the control site soil (Table 2). The characteristics developed by the dumpsite soil hold substantial potential for promoting nutrient availability, thereby offering favourable conditions for plant growth (Headlee et al., 2014).

Table 3 Comparison of heavy metal concentrations (based on 20 replicates) in the dumpsite soil and the control site soil

Heavy metal	Concentration in dumpsite soil ± SD (mg/kg)	Concentration in control site soil ± SD (mg/kg)
Pb	8.22 ± 0.48	1.14 ± 0.13
Cd	9.84 ± 0.42	0.36 ± 0.03
Ni	11.92 ± 0.69	1.07 ± 0.05
Cr	22.00 ± 0.98	0.63 ± 0.04
As	2.10 ± 0.09	0.33 ± 0.09
Hg	0.11 ± 0.01	0.010 ± 0.001
Cu	48.05 ± 4.40	6.50 ± 0.89
Mn	171.08 ± 7.55	20.69 ± 1.09
Zn	96.16 ± 1.40	0.85 ± 0.33

The results obtained align with those of a prior study conducted by Simeon and Ambah (Simeon & Ambah, 2013), which similarly demonstrated the enhancement of soil physicochemical properties conducive to soil nutrient nourishment due to the influence of municipal solid waste.

Heavy metal contamination and risk assessment

Following the analysis of multiple replicates for heavy metal concentrations in both dumpsite and control site soils, it is noteworthy that the mean concentrations of all the heavy metals in the dumpsite soil consistently exceed those in the control site soil (Table 3; Figs. 5, 6, 7, 8, 9, 10, 11, 12, and 13).

These results unequivocally demonstrate that the waste disposal operations at the Dudumbia dumpsite have notably and consistently elevated the concentrations of Pb, Cd, Ni, Cr, As, Hg, Cu, Mn, and Zn in the dumpsite soil. This elevation in heavy metal concentrations can be attributed to the types of waste disposed of at the site.

Considering the sampling site description, the co-occurrence of elevated Cd and other metals and the presence of specific types of waste, such as canned products (tomatoes, mackerel, and canned milk) (Al Zabadi et al., 2018; Maduabuchi et al., 2006), discarded car parts (Elinder, 2019), dumped tyres (Adeyi & Oladoye, 2020; Shakya et al., 2006), plastics (Turner & Filella, 2021), and burning activities at the site (Adeyi & Oladoye, 2020; Soubra et al., 2021), suggest a possible correlation. The contribution of Pb could result from the deposition of Pb-containing materials such as vehicle battery remnants and metallic or alloy waste (Twumasi et al., 2016). The contribution of Hg could be from waste from electrical and electronic equipment such as batteries and fluorescent lamps and medical equipment wastes like thermometers and sphygmomanometers (Chalkidis et al., 2020; Cheng & Hu, 2012).

The contribution of waste dumping activities to the heavy metals in the dumpsite soil is further supported by the *Igeo* values of the heavy metals (Fig. 3), which evaluates the enrichment measure of each heavy metal in the dumpsite soil. The *Igeo* values indicate contamination levels ranging from moderate (*Igeo* value of 2.07) to extreme (*Igeo* value of 6.20).

Furthermore, the findings reveal a range of contamination intensities among the heavy metals. As

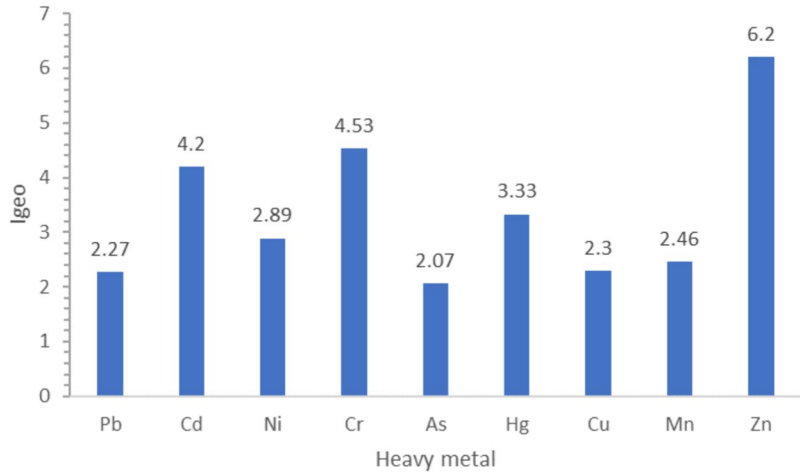

Fig. 3 Geoaccumulation index calculated for the heavy metals. *Igeo* < 0 indicates dumpsite soil is uncontaminated with the metal; 0 < *Igeo* < 1 indicates uncontaminated/moderately contaminated; 1 < *Igeo* < 2 indicates moderate contamination; 2 < *Igeo* < 3 indicates moderately/strongly contaminated; 3 < *Igeo* < 4 indicates strongly contaminated; 4 < *Igeo* < 5 indicates strongly/extremely contaminated, and 5 < *Igeo* indicates extremely contaminated

Table 4 Heavy metals concentration in the dumpsite soil (based on 20 replicates) and WHO permissible limits. WHO permissible limits of heavy metals in dry soil (Ogunlana et al., 2020; Ojiabo et al., 2020)

Heavy metal	Mean concentration in dumpsite soil ± SD (mg/kg)	WHO permissible limit (mg/kg)
Pb	8.22 ± 0.48	50
Cd	9.84 ± 0.42	3
Ni	11.92 ± 0.69	50
Cr	22.00 ± 0.98	100
As	2.10 ± 0.09	20
Hg	0.11 ± 0.01	2
Cu	48.05 ± 4.40	100
Mn	171.08 ± 7.55	2000
Zn	96.16 ± 1.40	300

exhibits the lowest contamination level, followed by Pb, Cu, Mn, Ni, Hg, Cd, and Cr, with Zn presenting the highest degree of contamination.

Values 16.241 and 1810 obtained for *PLI* and *PERI*, respectively, for the dumpsite soil suggest significant deterioration in the soil quality due to heavy metal contamination, posing a very high risk to the biota in the environment.

Comparison of the concentration of heavy metals in the dumpsite soil with the WHO permissible limits (Table 4) reveals that, while heavy metals such as Pb, Ni, Cr, As, Hg, Cu, Mn, and Zn have their concentrations below the permissible limits, Cd has its concentrations exceeding its permissible limits.

Complementing this comparison are the results obtained for the potential ecological risk (*Er*) for each of the heavy metals (Table 5).

These results align with previous findings: Mn, Cu, and Pb show low ecological risk; Ni, As, and Cr show moderate ecological risks; Zn shows considerable ecological risk; and Cd and Hg show very high ecological risks.

Implications at Dudumbia dumpsite

The Dudumbia dumpsite, initially a thick forest, has undergone extensive changes over the years. It has evolved into a central waste site shared by Navrongo and the neighbouring town, Paga. This transformation has involved significant deforestation, the construction of houses nearby, and ongoing construction activities. Consequently, pollution of the soil at this site is expected to have detrimental effects on the local environment, particularly affecting nearby residents and those who come into direct contact with the dumpsite.

The *Igeo* values of all the heavy metals indicate that waste dumping activities have significantly

Table 5 Potential ecological risks for the heavy metals

Heavy metal	Pb	Cd	Ni	Cr	As	Hg	Cu	Mn	Zn
Er	36	827	56	69	63	604	37	8	110

contaminated the dumpsite soil. This implies that all the studied heavy metals contribute to the contamination and should not be excluded from the environmental regulation and monitoring plans at the dumpsite. Prioritisation for monitoring can be based on the magnitude of the *Igeo* values, which follow the following order: Zn > Cr > Cd > Hg > Ni > Mn > Cu > Pb > As.

Beyond contamination, the site exhibits deterioration and poses a very high risk as suggested by *PLI*, *PERI*, and the individual *Er* for each heavy metal. The very high ecological risks associated with Cd and Hg imply that individuals who have direct contact with the dumpsite or reside nearby are at significant risk of suffering from the adverse effects of environmental pollution by these heavy metals. In light of this, considering measures to address Cd and Hg contamination, such as soil remediation or targeted interventions, is considerable.

Conclusions

Waste dumping activities have led to improvements in some soil properties, such as phosphorus (P), organic carbon (C), total nitrogen (N), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), and effective cation exchange capacity. These improvements can enhance conditions for plant cultivation. However, our findings reveal that the activities at the dumpsite contribute significantly to contamination by all the heavy metals investigated: Zn, Cr, Cd, Hg, Ni, Mn, Cu, Pb, and As. Moreover, the dumpsite soil shows signs of significant deterioration, with Cd and Hg presenting very high ecological risks.

Given the dumpsite's proximity to human settlements, environmental regulation and monitoring plans at the site must focus on all these heavy metals to protect public health. To ensure the environment is safe, especially if future land reuse is anticipated, remediation efforts must prioritise mitigating the risks posed by Cd and Hg.

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Author contribution Olutayo Abiodun Oluyinka: conceptualisation, methodology, formal analysis, data curation, writing—original draft, writing—review and editing, visualisation, and validation. Mary-Magdalene Pedavoah: writing—original draft, writing—review and editing. James Abugri: visualisation, writing—review and editing. Emmanuel Olajide Oyelude: writing—review and editing. Richard Mosobil: writing—review and editing. Kpono Amos: field work, laboratory work, and visualisation. Donatus Akasokeba Asamannaba: field work and laboratory work. Abdul-Waris Issahaku: field work and laboratory work. Abdul-Karim Kabah Isshak: field work and laboratory work. Nsoh Ali Aberinga: field work and laboratory work.

Data availability The datasets generated and/or analysed during this study are available upon request.

Declarations

Ethics approval All authors have read, comprehended, and, as applicable, adhered to the guidelines outlined in the "Ethical Responsibilities of Authors" as stated in the Instructions for Authors.

Competing interests The authors declare no competing interests.

Appendix

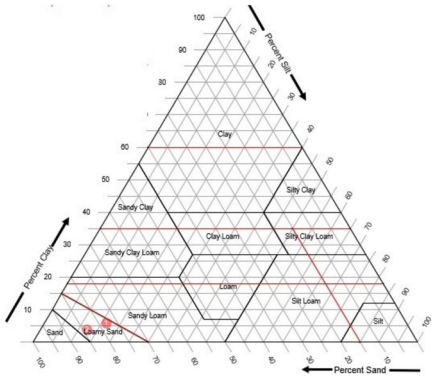


Fig. 4 Soil texture triangle comparing dumpsite soil (1) and control site soil (2) (generated using Multi-Point Texture Triangle developed by Van Lear Mark)

WORKSHEET 1

Two-Sample T-Test and CI: Conc of Pb at dumpsite (mg/Kg), Conc at control site (mg/Kg)

Method

μ_1: population mean of Conc of Pb at dumpsite (mg/Kg)
μ_2: population mean of Conc at control site (mg/Kg)
Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Conc of Pb at dumpsite (mg/Kg)	20	8.224	0.482	0.11
Conc at control site (mg/Kg)	20	1.140	0.125	0.028

Estimation for Difference

Difference	95% Lower Bound for Difference
7.084	6.892

Test

Null hypothesis $H_0: \mu_1 - \mu_2 = 0$
Alternative hypothesis $H_1: \mu_1 - \mu_2 > 0$

T-Value	DF	P-Value
63.62	21	0.000

Fig. 5 Two sample *t*-tests for Pb concentration in dumpsite soil versus control site soil (analysed using Minitab version 21.1.1)

WORKSHEET 1

Two-Sample T-Test and CI: Conc of Cd at dumpsite (mg/Kg), Conc at control site (mg/Kg)

Method

μ_1: population mean of Conc of Cd at dumpsite (mg/Kg)
μ_2: population mean of Conc at control site (mg/Kg)
Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Conc of Cd at dumpsite (mg/Kg)	20	9.839	0.417	0.093
Conc at control site (mg/Kg)	20	0.3570	0.0331	0.0074

Estimation for Difference

Difference	95% Lower Bound for Difference
9.4820	9.3203

Test

Null hypothesis $H_0: \mu_1 - \mu_2 = 0$
Alternative hypothesis $H_1: \mu_1 - \mu_2 > 0$

T-Value	DF	P-Value
101.37	19	0.000

Fig. 6 Two sample *t*-tests for Cd concentration in dumpsite soil versus control site soil (analysed using Minitab version 21.1.1)

WORKSHEET 1

Two-Sample T-Test and CI: Conc of Ni at dumpsite (mg/Kg), Conc at control site (mg/Kg)

Method

μ_1: population mean of Conc of Ni at dumpsite (mg/Kg)
μ_2: population mean of Conc at control site (mg/Kg)
Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Conc of Ni at dumpsite (mg/Kg)	20	11.920	0.693	0.16
Conc at control site (mg/Kg)	20	1.0690	0.0509	0.011

Estimation for Difference

Difference	95% Lower Bound for Difference
10.851	10.582

Test

Null hypothesis H_0: $\mu_1 - \mu_2 = 0$
Alternative hypothesis H_1: $\mu_1 - \mu_2 > 0$

T-Value	DF	P-Value
69.79	19	0.000

Fig. 7 Two sample *t*-tests for Ni concentration in dumpsite soil versus control site soil (analysed using Minitab version 21.1.1)

WORKSHEET 1

Two-Sample T-Test and CI: Conc of Cr at dumpsite (mg/Kg), Conc at control site (mg/Kg)

Method

μ_1: population mean of Conc of Cr at dumpsite (mg/Kg)
μ_2: population mean of Conc at control site (mg/Kg)
Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Conc of Cr at dumpsite (mg/Kg)	20	21.995	0.983	0.22
Conc at control site (mg/Kg)	20	0.6340	0.0382	0.0085

Estimation for Difference

Difference	95% Lower Bound for Difference
21.361	20.980

Test

Null hypothesis H_0: $\mu_1 - \mu_2 = 0$
Alternative hypothesis H_1: $\mu_1 - \mu_2 > 0$

T-Value	DF	P-Value
97.07	19	0.000

Fig. 8 Two sample *t*-tests for Cr concentration in dumpsite soil versus control site soil (analysed using Minitab version 21.1.1)

WORKSHEET 1

Two-Sample T-Test and CI: Conc of As at dumpsite (mg/Kg), Conc at control site (mg/Kg)

Method

μ_1: population mean of Conc of As at dumpsite (mg/Kg)
μ_2: population mean of Conc at control site (mg/Kg)
Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Conc of As at dumpsite (mg/Kg)	20	2.1025	0.0937	0.021
Conc at control site (mg/Kg)	20	0.3342	0.0931	0.021

Estimation for Difference

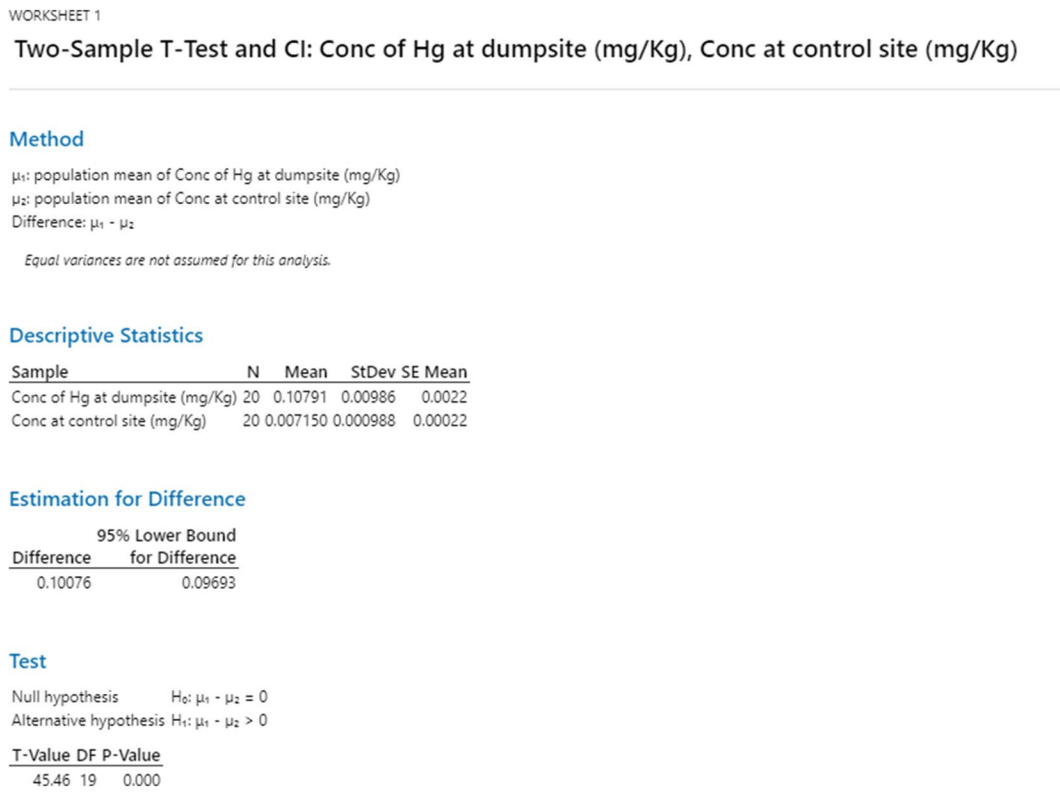
Difference	95% Lower Bound for Difference
1.7683	1.7184

Test

Null hypothesis $H_0: \mu_1 - \mu_2 = 0$
Alternative hypothesis $H_1: \mu_1 - \mu_2 > 0$

T-Value	DF	P-Value
59.85	37	0.000

Fig. 9 Two sample *t*-tests for As concentration in dumpsite soil versus control site soil (analysed using Minitab version 21.1.1)



WORKSHEET 1

Two-Sample T-Test and CI: Conc of Hg at dumpsite (mg/Kg), Conc at control site (mg/Kg)

Method

μ_1: population mean of Conc of Hg at dumpsite (mg/Kg)
μ_2: population mean of Conc at control site (mg/Kg)
Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Conc of Hg at dumpsite (mg/Kg)	20	0.10791	0.00986	0.0022
Conc at control site (mg/Kg)	20	0.007150	0.000988	0.00022

Estimation for Difference

Difference	95% Lower Bound for Difference
0.10076	0.09693

Test

Null hypothesis $H_0: \mu_1 - \mu_2 = 0$
Alternative hypothesis $H_1: \mu_1 - \mu_2 > 0$

T-Value	DF	P-Value
45.46	19	0.000

Fig. 10 Two sample *t*-tests for Hg concentration in dumpsite soil versus control site soil (analysed using Minitab version 21.1.1)

WORKSHEET 1

Two-Sample T-Test and CI: Conc of Cu at dumpsite (mg/Kg), Conc at control site (mg/Kg)

Method

μ_1: population mean of Conc of Cu at dumpsite (mg/Kg)
μ_2: population mean of Conc at control site (mg/Kg)
Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Conc of Cu at dumpsite (mg/Kg)	20	48.05	4.40	0.98
Conc at control site (mg/Kg)	20	6.496	0.894	0.20

Estimation for Difference

Difference	95% Lower Bound for Difference
41.55	39.82

Test

Null hypothesis $H_0: \mu_1 - \mu_2 = 0$
Alternative hypothesis $H_1: \mu_1 - \mu_2 > 0$

T-Value	DF	P-Value
41.39	20	0.000

Fig. 11 Two sample *t*-tests for Cu concentration in dumpsite soil versus control site soil (analysed using Minitab version 21.1.1)

WORKSHEET 1

Two-Sample T-Test and CI: Conc of Mn at dumpsite (mg/Kg), Conc at control site (mg/Kg)

Method

μ_1: population mean of Conc of Mn at dumpsite (mg/Kg)
μ_2: population mean of Conc at control site (mg/Kg)
Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Conc of Mn at dumpsite (mg/Kg)	20	171.08	7.55	1.7
Conc at control site (mg/Kg)	20	20.69	1.09	0.24

Estimation for Difference

Difference	95% Lower Bound for Difference
150.39	147.44

Test

Null hypothesis $H_0: \mu_1 - \mu_2 = 0$
Alternative hypothesis $H_1: \mu_1 - \mu_2 > 0$

T-Value	DF	P-Value
88.21	19	0.000

Fig. 12 Two sample *t*-tests for Mn concentration in dumpsite soil versus control site soil (analysed using Minitab version 21.1.1)

WORKSHEET 1

Two-Sample T-Test and CI: Conc of Zn at dumpsite (mg/Kg), Conc at control site (mg/Kg)

Method

μ_1: population mean of Conc of Zn at dumpsite (mg/Kg)
μ_2: population mean of Conc at control site (mg/Kg)
Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Conc of Zn at dumpsite (mg/Kg)	20	93.16	1.40	0.31
Conc at control site (mg/Kg)	20	0.846	0.326	0.073

Estimation for Difference

Difference	95% Lower Bound for Difference
92.319	91.765

Test

Null hypothesis $H_0: \mu_1 - \mu_2 = 0$
Alternative hypothesis $H_1: \mu_1 - \mu_2 > 0$

T-Value	DF	P-Value
286.81	21	0.000

Fig. 13 Two sample *t*-tests for Zn concentration in dumpsite soil versus control site soil (analysed using Minitab version 21.1.1)

Table 6 Linear regression calibration equations obtained for measuring the unknown concentrations of the heavy metals in solution (*Y* represents absorbance, and *X* represents heavy metal concentration in the solution)

Metals	Linear regression calibration equation
Pb	$Y = 0.0136\,X$
Cd	$Y = 0.2164\,X$
Ni	$Y = 0.0416\,X$
Cr	$Y = 0.0395\,X$
As	$Y = 0.14\,X$
Hg	$Y = 0.0157\,X$
Cu	$Y = 0.1968\,X$
Mn	$Y = 0.1742\,X$
Zn	$Y = 0.091\,X$

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