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Environmental and human health risk assessments for potentially toxic elements in the soils of a prospective phosphate mining area of Hinda district, Republic of the Congo

R. R. C. Moubakou Diahou[1,2,4] · G. B. Dallou[1,2] · J. S. Sondzo[1,2] · H. Bounouira[3] · Y. Maazouzi[3] · R. Cherkaoui El Moursli[4] · C. Bouka Biona[1]

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Abstract
Soils from a prospective phosphate mining area in the Hinda district of the Congo were analyzed using the ICP-MS technique in order to assess the environmental pollution and human health risks presented by potentially toxic elements (PTEs). The results showed that the mean concentrations of PTEs exceeded the global crustal average. Environmental pollution was assessed, showing the study area polluted by PTEs. Human health risk was also assessed, with the results showing the level of cancer risk greater for children than that for adults, indicating that children are more susceptible to the carcinogenic effects of PTEs than their adult counterparts.

Keywords Potentially toxic elements · Soil contamination · Prospective phosphate mining area

Introduction

Economic development due to rapid urbanization and industrialization, as well as agricultural activities, disturbs the geochemical cycle of several elements, particularly trace elements. Some of these elements are essential to human health at acceptable concentrations (oligo-elements) [1], but others are particularly toxic for living organisms, and these are known as potentially toxic elements (PTEs) [2]. These elements can originate from natural processes, such as volcanic eruption and rock weathering, but they can also derive from various human activities, such as mining, agriculture, etc. [3].

✉ R. R. C. Moubakou Diahou
foxrussellrolph@gmail.com

1 Faculty of Sciences and Techniques, Marien Ngouabi University, BP 69, Brazzaville, Republic of Congo

2 Laboratory of Nuclear Physics and Applications (LPNA), National Institute for Research in Exact and Natural Sciences (IRSEN), P.O Box 2400, Brazzaville, Congo

3 National Center for Energy, Science and Nuclear Techniques (CNESTEN), Rabat, Morocco

4 ESMAR Research Unit, Faculty of Sciences, Mohammed V University, 4 Avenue Ibn Battouta, B.P. 1014, Rabat, Morocco

Soil serves many functions aside from feeding plants, such as filtering rainwater and storing all kinds of contaminants of natural or artificial origin. It hosts an intense and complex system of life. Soil is now largely accepted as the part of the environment that is most exposed to contamination by trace elements [4, 5], and this matter has attracted increasing attention around the world [6–10]. Many studies related to trace element pollution in soils have focused on assessing the concentrations and the ecological and environmental risks they present [4, 11–13]. Indeed, due to their accumulation and non-biodegradable nature in soils, trace elements can have adverse effects on the ecosystem and human health [4, 9]. For instance, high levels of PTEs in soil have an irreversible influence on plant growth by altering the soil's properties and structure [14], and they can cause substantial harm to the human body through dermal contact and ingestion [15]. This is especially true for children, who are more vulnerable than adults in terms of risk assessment indices [16].

A survey of this kind has never been carried out in this part of the world. Considering the mining history of the Republic of the Congo and the number of mining sites operated by mining companies to meet international requirements [17, 18], as well as abandoned mines [19] in the country, it is prudent to consider the health of those living around mining areas. This issue had attracted increasing attention

from researchers and public authorities in the Republic of the Congo.

Moreover, no information is available about the effects of potentially toxic elements on the health of people living around a prospective phosphate mining area in the Hinda district of the Republic of Congo. Thus, collecting some baseline data about soil pollution in this prospective phosphate mining area will be vitally important for protecting human health and informing future research. The main aims of this study were therefore as follows: (1) Determine the concentrations of seven (7) selected potentially toxic elements (As, Cu, Cd, Hg, Cr, Pb, and Zn) in soil samples collected from different villages in Hinda district. (2) Assess the current soil contamination in the study area in terms of the contamination factor (C_f) and the pollution load index (PLI). Finally, (3) investigate the carcinogenic health risks of potentially toxic elements according to the proposed methods of the United States Environmental Protection Agency [20]. This should help control pollution and enable preventive measures to be taken in the study area prior to exploiting phosphate ore resources.

Materials and methods

Study area

The Republic of the Congo is split between twelve (12) departments, and one of these is the Kouilou department, which alternates between dry and wet seasons. The wet seasons typically occur in March–April–May (MAM) and September–October–November (SON), while the dry seasons are usually in June–July–August (JJA) and December–January–February (DJF). The area also has a tropical climate, and it is geologically characterized by white quartzite with schistose intercalation.

Hinda district is within the Kouilou department alongside the Kakamoeka, Madingo-Kayes, Mvouti, Nzambi, and Tchiamba-Nzassi districts (Fig. 1), and it is more affected by anthropogenic activities. It is located at latitude 4°36′48″ S and longitude 12°02′37″ E about 34 m above sea level. It has an approximate population of 32,995 people. The average temperature is 24.5 °C, while the average annual precipitation is 1746 mm [21].

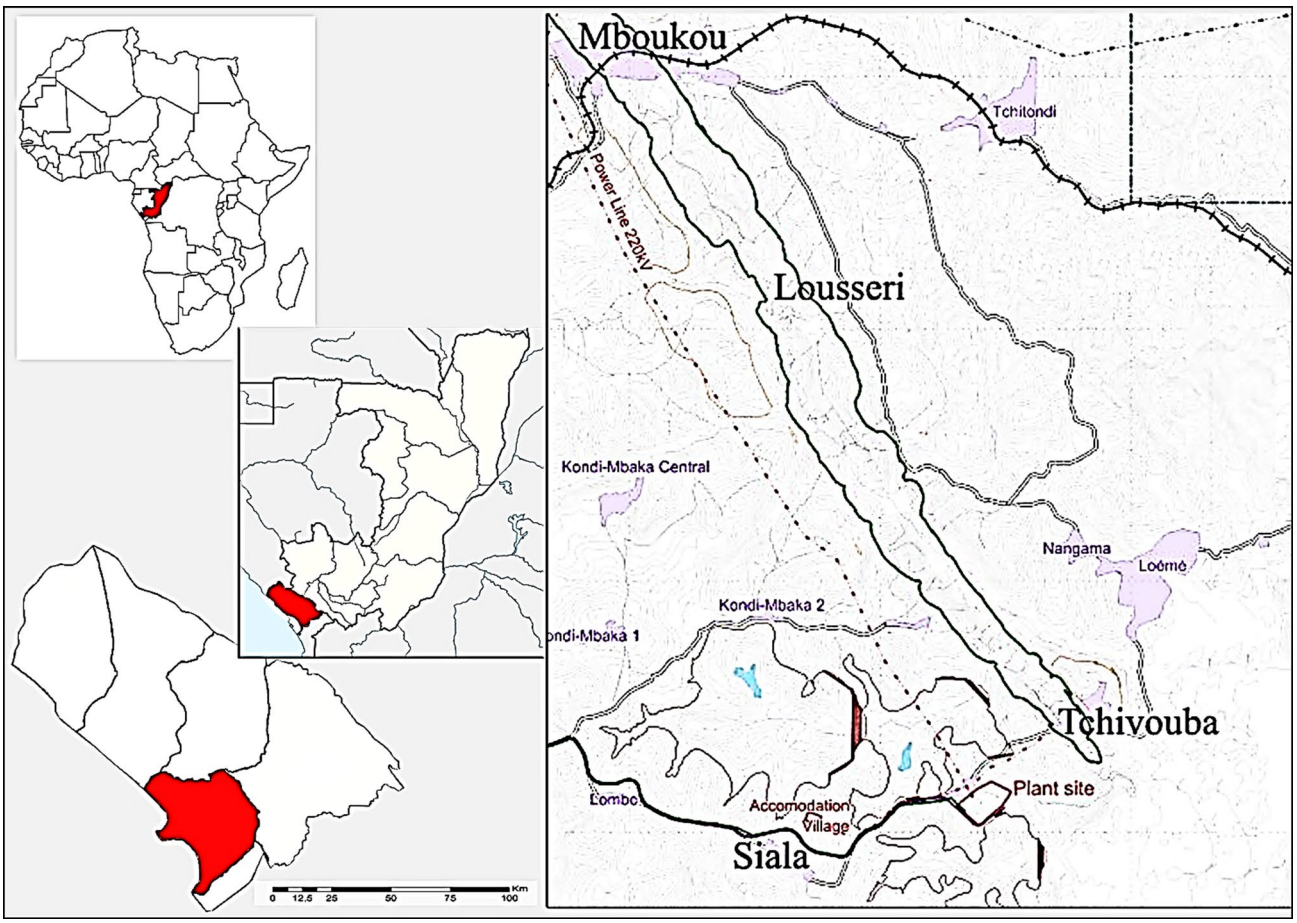

Fig. 1 Study area of Hinda district in the Republic of the Congo [21]

This study was conducted around four (4) villages in Hinda district (Mboukou, Siala, Louceri, and Tchivouba), because these villages have been listed as potential sites for phosphate mining by the COMINCO Resources Ltd. mining company. The deposit comprises a large, structurally controlled and confined sedimentary accumulation of primary biogenic and secondary phosphate mineralization. There are two main phosphate-bearing sedimentary layers. The Grey Maastrichtian (Gm) upper cretaceous layer represents the primary source of phosphate rock, with it providing 90% of the ore. The upper layers of the Gm have been subjected to tropical weathering and decarbonatation, with the resulting weathered layer being designated the Beige Maastrichtian (Bm) [21].

Sample collection, preparation, and analysis

Samples were collected at about 10 cm below the surface after removing any vegetal cover. A total of 24 soil samples were collected at each village. They were collected from different locations identified by COMINCO Company Ltd., and these were detected in the study area by the iron bars that had been driven into the earth and surrounded with cement. Each sampling point was associated with coordinates from a Garmin GPS system, and the samples were stored in clean, labelled polyethylene bags. The samples were then transferred to CNESTEN (the Nuclear Center for Energy Sciences and Nuclear Techniques) for conditioning and treatment. Once there, the samples were oven dried at 70 °C until the weight became constant before being ground into powder form with an agate mortar and then sieved for storage in polyethylene containers. Precautionary measures were taken to avoid any contamination.

Dissolution procedure and analysis

Soil samples were placed in a 50 ml tube with 5 ml of nitric acid (HNO_3) [22]. Some 3 ml of hydrofluoric acid (Hf) from Merck KGaA, 64,271 Darmstadt were also added to the tube at this point. After one hour, seven (7) drops of oxygenated water (H_2O_2) and two (2) spoons of boric acid (H_3BO_3) [23] were added to the solution, which was then left overnight to facilitate the sample's digestion [24–26].

After 24 h, the digested solution was further digested in a microwave (ETHOS EASY, milestone Connect) for 1 h before being transferred to the tube and filled with H_2O_2 to about 50 ml. Finally, the diluted solution was weighed [23].

Soil from ANALYSIS ISE2012.1 was used as the standard reference material for quality assurance purposes. This standard reference material and the background sample were prepared in the same manner as the samples.

Quality assurance and quality control were carried out using duplicates, method blanks, and a certified reference material (CRM) that was a multi-element solution with seven (7) components, namely 0.001 mg/l each of Ba, Bi, Ce, Co, In, Li, and U (CPA chem, Ref. No: 161D. D001.2.5N05C.L5 of 29/05/2020). Standard solutions provided by Merck (Darmstadt, Germany) were used for calibration curves. In the present study, all the solutions were prepared using ultrapure water. The analytical precision was considered to be ± 10%. The 24 soil samples from each village were digested and analyzed alongside one sample of the CRM. All the analyses were conducted in duplicate, with the mean values being used for data analysis. ICP-MS with an iCAP Q (Thermo Scientific) with a branded sample changer TELEDYNE (ASX-560) was used for sample analysis, while qualitative and quantitative analysis were carried out using the iCAP Q software. The recoveries of rare earth elements in the spiked quality control samples varied from 96.1% to 107.3%.

Assessment of PTE pollution in the samples

To assess the PTE contamination levels in the samples from the study area, the contamination factor (CF) and pollution load index (PLI) were considered. These metrics are described in Table 1. The background concentration used in this present study relates to the upper continental crust (UCC) [27].

Table 1 The metrics used to assess PTE contamination levels in the soil samples from the study area

Parameter	Equation	Conditions
Contamination factor (CF) [28, 29]	$C_f^i = \frac{C_i}{B_i}(1)$ Where C_i is the concentration (mg/kg) of metal i in the samples and B_i is the background concentration (mg/kg) value for metal i	CF < 1: Low contamination 1 < CF < 3: Moderate contamination 3 < CF < 6: Considerable contamination CF > 6: High concentration [30, 31]
Pollution Load Index (PLI) [30, 32, 33]	$PLI = \left(C_f^1 \times C_f^2 \times C_f^3 \times \cdots C_f^n\right)^{1/n}$ (2) Where C_f^n is the contamination factor of metal i	PLI < 1: Not polluted PLI > 1: Polluted [34]

Table 2 Parameters used for the present study

Parameters	Symbols	Units	Values		References
			Children	Adults	
Body weight	BW	Kg	10	60	Present study
Exposure duration	ED	Years	5	30	Present study
Exposure frequency	EF	Days/years	350	250	[38]
Skin surface area	SA	cm^2	2373	6032	[39]
Soil intake ratio	IR	mg/day	200	100	[9]
Skin adherence factor	AF	mg/cm^2	0.2	0.07	[40]
Lifetime	LT	Years	70	70	Present study
Average time	AT	Days	25,550	25,550	Present study

Human health risk assessment

The risk to human health was assessed for the adults and children residing in the study area, which as mentioned above is a prospective phosphate mining area. Phosphate rocks are visible on the ground of the study area, such as in agricultural fields and around people's dwellings. It was therefore important to assess the carcinogenic health risks posed by potentially toxic elements due to accidental ingestion, dermal contact, and inhalation by the local population.

However, as the phosphate in the study area was in a rock state, we focused our study on the two pathways of ingestion and dermal contact.

The average daily doses for ingestion (ADD_{ing}) and dermal contact (ADD_{derm}) were calculated to assess the risks according to the following equations [35, 36]:

$$ADD_{ing} = \frac{C_s \times IR \times EF \times ED}{BW \times AT} \times 10^{-6} \quad (3)$$

$$ADD_{derm} = \frac{C_s \times SA \times AF \times ABS \times EF \times ED}{BW \times AT} \times 10^{-6} \quad (4)$$

The carcinogenic risk (CR), meanwhile, was assessed using the following equation [10]:

$$CR = \sum_{i=1}^{n} ADD_i \times SF_i \quad (5)$$

where SF_i corresponds to the carcinogenic slope factor of metal *i* (mg/kg/day).

Furthermore, the total carcinogenic risk (TCR) is defined as:

$$TCR = \sum_{i=1}^{n} CR_i \quad (5)$$

The acceptable range of this is thought to be between 10^{-6} and 10^{-4} [37].

Each factor is defined in Tables 2 and 3.

Table 3 Factors used for the present study

Elements	ABS	SF_{ing}	SF_{derm}	Reference
Pb	10^{-3}	$8.5x10^{-3}$		[41]
Hg	10^{-3}			[41]
Cr	10^{-3}	0.5		[41]
Cd	10^{-3}	15		[41]
Zn	10^{-3}			[41]
Cu	10^{-3}			[41]
As	0.03	1.5	3.66	[41]

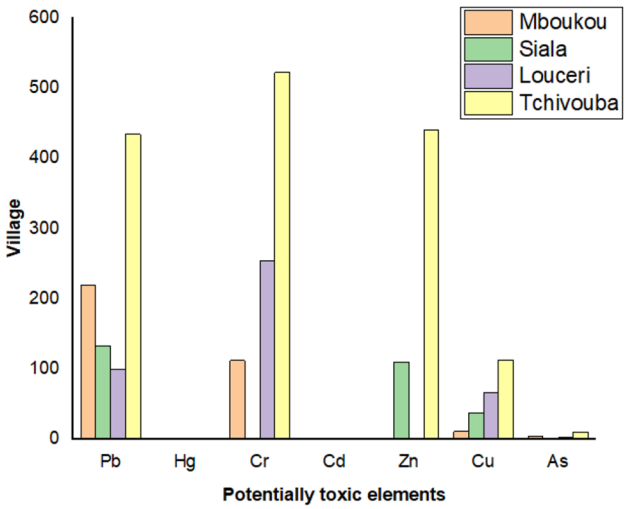

Fig. 2 Distribution of PTE concentrations (mg/kg) in the study area

Results and discussion

The mean concentrations of potentially toxic elements in the soil samples from the four villages of the Hinda district are shown in Fig. 2. The potentially toxic elements' concentrations decreased in the following order: Cr > P b > Zn > Cu > As > Cd > Hg. The highest concentrations

of all the seven potentially toxic elements were observed in Tchivouba village: Cr (500 mg/kg), Pb (434 mg/kg), Zn (440 mg/kg), Cu (113 mg/kg), As (10.48 mg/kg), Cd (1.05 mg/kg), and Hg (0.18 mg/kg). The median values exceeded global soil average values at Cr (254 mg/kg), Pb (176.5), Zn (275 mg/kg), Cu (52 mg/kg), As (5.12 mg/kg), Cd (0.11 mg/kg), and Hg (0.0265 mg/kg) [27], indicating that these potentially toxic elements have been enriched in the overall study area.

The mean total concentrations of Cr, Pb, Zn, Cu, As, Cd, and Hg were clearly greater than the equivalent average upper continental crust (UCC) values (Table 4). Furthermore, compared to other studies around the world, the concentrations of potentially toxic elements found in the present study are higher than those found in other studies, with the exception that Cd concentration was lower than that reported in one study [42]. We surmise that this high concentration is due to the phosphate galleries in Tchivouba village and the presence of phosphate rocks everywhere, such as in agricultural fields, around people's dwellings, and so on. This assumption is supported by our study of natural and artificial measurement that was carried out in the same study area [43].

Environmental and ecological risk assessment indices

The results of the soil contamination assessment based on the contamination factor (C_f) are illustrated in Fig. 3. The C_f values varied across the villages. The mean C_f values for the considered PTEs were as follows: Pb (12.31) > Hg (4.81) > Cd (3.76) > Cr (2.77) > Zn (1.96) > Cu (1.78) > As (1.01). The C_f values for Pb varied from 5.56 in Louceri to 24.11 in Tchivouba, reflecting the very high contamination levels in the study area. The values for Hg ranged from 0.33 in Mboukou to 14.63 in Tchivouba, so the contamination level was low in Mboukou village, moderate in Siala village, considerable in Louceri village, and very high in Tchivouba village. For Cr, the values ranged from 1.4 in Mboukou to 6.53 in Tchivouba, with there being moderate contamination levels in Mboukou and Louceri villages and a very high level in Tchivouba village. The Cf values for Cd varied from 0.38 in Siala to 13.29 in Tchivouba, with the contamination level being low in Siala village, moderate in Louceri village, and very high in Tchivouba village. The values for Zn ranged from 1.57 in Siala to 6.29 in Tchivouba, with the contamination level being moderate in Siala village but very high in Tchivouba village. For Cu, the values varied from 0.34 in Mboukou to 3.53 in Tchivouba, with the contamination level being low in Mboukou village, moderate in Siala and Louceri villages, and very high in Tchivouba village. Finally, for As, C_f values varied between 0.53 (Louceri) and 2.38 (Tchivouba), reflecting a low contamination level in Siala village and moderate contamination levels in Mboukou and Tchivouba villages.

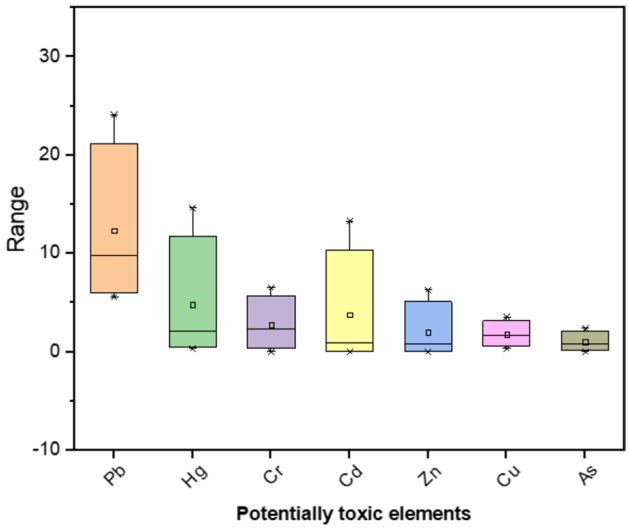

Fig. 3 Contamination factors for the PTEs in the study area

The pollution load indices (PLI) were determined for the present study area, and the results of this are illustrated

Table 4 Summary of the measured PTE concentrations in the soil samples from a prospective mining area in Hinda district (mg/kg) alongside background values from the UCC and reported concentrations in other studies

Country	Cr	Pb	Zn	Cu	As	Cd	Hg	Reference
European soils	94.8	32	68.1	17.3	11.6	–	–	[44]
Turkish Soil Pollution Control Regulation	100	300	300	140	–	–	–	[45]
Turkey, Bursa city	125	81	477	40	–	–	–	[46]
Turkey, Thrace region	173	33	45	20	8	–	–	[47]
China, Shenyang	67.9	116.76	234.8	92.45	–	1.1	–	[42]
China, Shanghai	107.9	70.69	301.4	59.25	–	0.52	–	[48]
Republic of the Congo, Hinda district	500	434	440	113	10.48	1.05	0.18	Present study
UCC	80	18	70	32	4.4	0.079	0.012	[27]

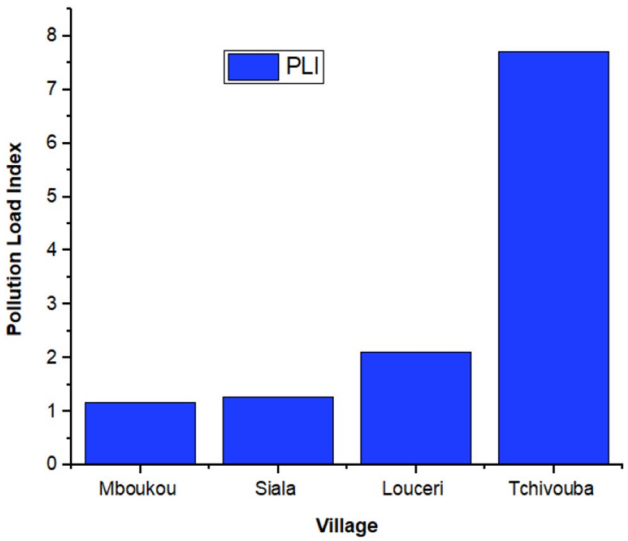

Fig. 4 Pollution load indices for the study area

in Fig. 4. These show that the whole study area was polluted to varying degrees.

Human health risk assessment

A human health risk assessment was carried out for all the potentially toxic elements investigated in the present study, and the results obtained for the four (4) villages are presented in Fig. 5.

The mean carcinogenic risk levels were Cr (6.90×10^{-3}) > Zn (6.41×10^{-3}) > Pb (5.17×10^{-3}) > Cu (1.33×10^{-3}) > As (1.41×10^{-4}) > Cd (9.25×10^{-6}) > Hg (1.38×10^{-6}) for children and Cr (3.45×10^{-3}) > Zn (3.21×10^{-3}) > Pb (2.59×10^{-3}) > Cu (6.65×10^{-4}) > As (7.16×10^{-5}) > Cd (4.63×10^{-6}) > Hg (6.91×10^{-7}) for adults. The carcinogenic risk levels therefore followed the same trend for both children and adults in the study area.

We found the cancer risk levels to be greater than 1×10^{-4} for both children and adults, with Cr, Zn, Pb, Cu, and As contributing greatly to cancer risk in the present study area. Urgent remediation action is therefore required in this area, especially as Fig. 5 clearly shows that children are more exposed to risk than adults [16].

The potential pathways by which the PTEs in the soil of the prospective phosphate mining area of Hinda district contaminate the local population through ingestion and dermal contact are clearly illustrated in Fig. 6.

PTEs can be directly absorbed by ingesting locally grown food. In addition, during rainfall, they can leach away from soils and pollute the water supply, such as rivers.

The population of the study area can be acutely or chronically exposed to high levels of PTEs, and this can result in severe disorders and extreme damage from the oxidative stress due to free radical formation [49]. More specifically, the central nervous and immune systems of children and adults in the study area can be affected by high exposure to lead (Pb) through ingestion or dermal contact. In addition, the high exposure to chromium (Cr) through ingestion or dermal contact can lead to an increased risk of respiratory issues. Arsenic (As) can cause skin and neurological issues, as well as diabetes, while a high exposure to cadmium (Cd) can affect the endocrine system, lungs, and so on [50].

Another potential pathway for contamination relates to how children often like to play on the ground and in agricultural fields, leading to them being directly contaminated through dermal contact with the contaminated soils of the study area. This pathway is all the more important given that children in the area spend most of their time barefoot, whether it be in the house or outside, such as in their parent's agricultural fields. This explains why they are more exposed to PTEs than adults in the present study area (Fig. 5).

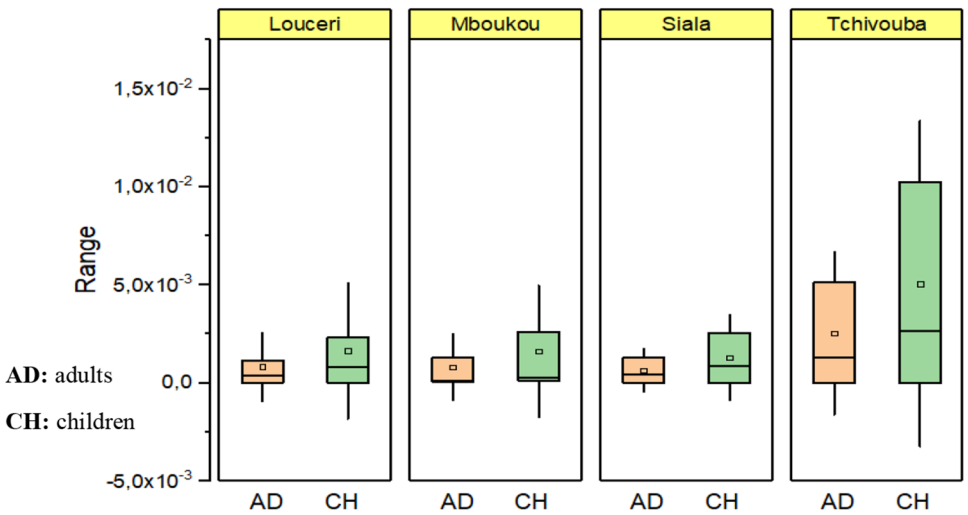

Fig. 5 Carcinogenic risk levels due to PTEs in soil samples from a prospective phosphate mining area in Hinda district

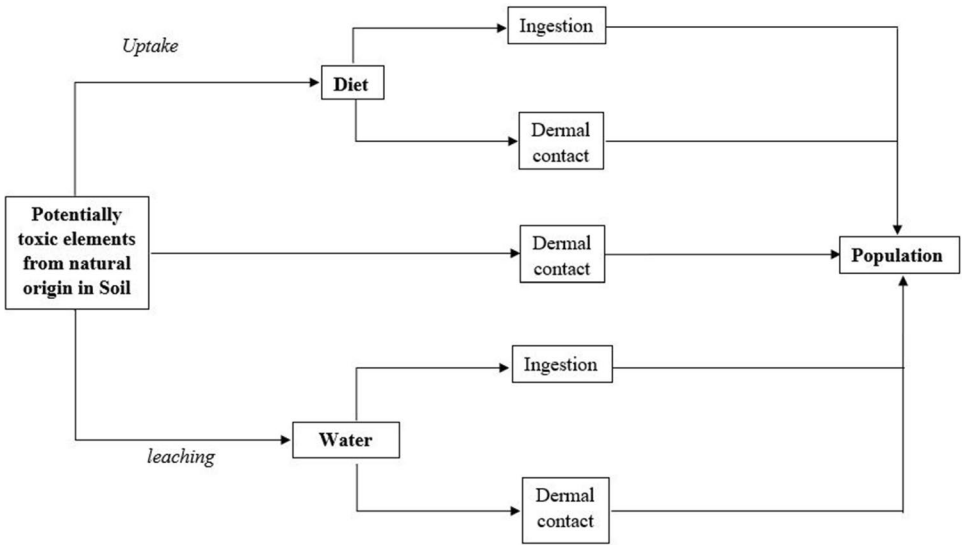

Fig. 6 Environmental pathways by which PTEs in the soil of Hinda district contaminate the local population

Conclusion

This study determined PTE concentrations through ICP-MS for different soil samples that were collected from a prospective phosphate mining area in Hinda district. The contamination levels were alarmingly high, with these being principally influenced by the phosphate rocks that were present everywhere in the study area. Indeed, the mean concentrations were found to be above those for the upper continental crust (UCC), and compared with other studies around the world, the PTE concentrations determined in the present study were higher than those reported by other studies. Ecological indices were also determined for the study area, with the results showing that the study area was polluted with a pollution load index above one (PLI > 1). The carcinogenic risks were also evaluated, and the alarming results were above the recommended level of 1×10^{-4} for both children and adults. In addition, children were found to be more susceptible to the carcinogenic health effects of PTEs, leading to an increased risk of cancer. The environmental pathways for PTEs were also described, with this showing the contamination of children and adults in the study area through ingestion and dermal contact. Overall, this provides evidence that local residents in the considered study area are at an increased risk of cancer due to exposure to potentially toxic elements.

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Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

References

1. N'Guessan YM, Probst JL, Bur T, Probst A (2009) Trace elements in stream bed sediments from agricultural catchments (Gascogne region, S-W France): where do they come from? Sci Total Environ 407:2939–2952
2. Salvarredy-Aranguren MM, Probst A, Roulet M, Isaure MP (2008) Contamination of surface waters by mining wastes in the Milluni Valley (Cordillera Real, Bolivia): mineralogical and hydrological influences. Appl Geochem 23:1299–1324
3. Hutchinson SM, Rothwell JJ (2007) Mobilisation of sediment-associated metals from historical Pb working sites on the River Sheaf, Sheffield, UK. Environ Pollut. https://doi.org/10.1016/j.2007.10.033
4. Mazurek R, Kowalska J, Gasiorek M, Zadrozny P, Jozefowska A, Zaleski T, Kepka W, Tymczuk M, Orlowska K (2017) Assessment of heavy metals contamination in surface layers of Roztocze National Park Forest soils (SE Poland) by indices of pollution. Chemosphere 168:839–850
5. Marchand C, Allenbach M, Lallier-Verges E (2011) Relationships between heavy metals distribution and organic matter cycling in mangrove sediments (Conception Bay, New Caledonia). Geoderma 160:444–456
6. Li F, Zhang J, Jiang W, Liu C, Zhang Z, Zhang C, Zeng G (2017) Spatial health risk assessment and hierarchical risk management for mercury in soils from a typical contaminated site, China. Environ Geochem Health 39:923–934
7. Yang Q, Li Z, Lu X, Duan Q, Huang L, Bi J (2018) A review of soil heavy metal pollution from industrial and agricultural regions in China: pollution and risk assessment. Sci Total Environ 642:690–700
8. Islam MS, Ahmed MK, Habibullah-Al-Mamun M (2016) Apportionment of heavy metals in soil and vegetables and associated health risks assessment. Stoch Environ Res Risk Assess 30:365–377
9. Jia Z, Li S, Li W (2018) Assessment of soil heavy metals for eco-environment and human health in a rapidly urbanization area of the upper Yangtze Basin. Sci Rep 8:3256
10. Chen H, Teng Y, Lu S, Wang Y, Wang J (2015) Contamination features and health risk of soil heavy metals in China. Sci Total Environ 512–513:143–153

11. Dong R, Jia Z, Li S (2018) Risk assessment and sources identification of soil heavy metals in a typical county of Chongqing Municipality. Southwest China Process Saf Environ 113:275–281
12. Ni M, Mao R, Jia Z, Dong R, Li S (2018) Heavy metals in soils of Hechuan County in the upper Yangtze (SW China): comparative pollution assessment using multiple indices with high-spatial resolution sampling. Ecotoxicol Environ Saf 148:644–651
13. Dartan G, Taşpınar F, Toröz İ (2015) Assessment of heavy metals in agricultural soils and their source apportionment: a Turkish district survey. Environ Monit Assess 187:99
14. Cai L, Xu Z, Bao P, He M, Dou L, Chen L, Zhou Y, Zhu YG (2015) Multivariate and geostatistical analyses of the spatial distribution and source of arsenic and heavy metals in the agricultural soils in Shunde, Southeast China. J Geochem Explor 148:189–195
15. Kumar V, Sharma A, Kumar R, Bhardwaj R, Kumar TA, Rodrigo-Comino J (2018) Assessment of heavy-metal pollution in three different Indian water bodies by combination of multivariate analysis and water pollution indices. Hum Ecol Risk Assess 26:1–16. https://doi.org/10.1080/10807039.2018.1497946
16. Singh UK, Kumar B (2017) Pathways of heavy metals contamination and associated human health risk in Ajay River basin, India. Chemosphere 174:183–199
17. Environmental Protection Agency (EPA) (2007) United States. Ionizing radiation Fact book. EPA. Office of Radiation and Indoor Air. EPA-402-F-06-061
18. International Commission on Radiological Protection (ICRP) (1991) 1990 recommendation of the International Commission on radiological protection. Oxford: Pergamon Press. ICRP publication 60, Annal of the ICRP 210-3
19. Moubakou Diahou RRC, Bounouira H, Dallou GB, Cherkaoui El Moursli R, Bouka Biona C (2021) Environmental radioactivity measurement in soils of an abandoned potash deposit at Holle, Republic of Congo. E3S Web Conf 336(4):00030. https://doi.org/10.1051/e3sconf/202233600030
20. USEPA (1989) Risk assessment guidance for Superfund. Volume I: human health evaluation manual (Part A). Interim Final. Office of Emergency and Remedial Response. EPA/540/1-89/002
21. Moubakou Diahou R, Bounouira H, Dallou G et al (2023) Kayzero-standardization method of neutron activation analysis study for major and minor elements determined in soils and phosphate rocks of the prospective phosphate mining area in the Hinda district, Republic of Congo. J Radioanal Nucl Chem. https://doi.org/10.1007/s10967-023-08795-7
22. Doležalová Weissmannová H, Mihočová S, Chovanec P, Pavlovský J (2019) Potential ecological risk and human health risk assessment of heavy metal pollution in industrial affected soils by coal mining and metallurgy in Ostrava, Czech Republic. Int J Environ Res Public Health. https://doi.org/10.3390/ijerph16224495
23. Akolawole JS, Okoye PA, Omokpariola DO (2022) Effect of storage on the levels of sodium benzoate in soft drinks sold in some Nigerian market with exposure and health risk assessment. Environ Anal Health Toxicol. https://doi.org/10.5620/eaht.2022030
24. Grigoratos T, Martini G (2015) Brake wear particle emissions: a review. Environ Sci Pollut Res Int 22(4):2491–2504. https://doi.org/10.1007/s11356-014-3696-8
25. Tang X, Li B, Lu J et al (2020) Gold determination in soil by ICP-MS: comparison of sample pretreatment methods. J Anal Sci Technol 11:45. https://doi.org/10.1186/s40543-020-00245-3
26. Mao, Jingchun and Liu, Xinyue and Chen, Bao and Luo, Famei and Wu, Xudong and Jiang, Donghua and Luo, Zhenggang. 2017. Determination of heavy metals in soil by inductively coupled plasma mass spectrometry (ICP-MS) with internal standard method. Electronics Science Technology and Application. https://doi.org/10.18686/esta.v4i1.36.
27. Gao Y, de Brauwere A, Elskens M, Croes K, Baeyens W, Leermakers M (1998) Evolution of trace metal and organic pollutant concentrations in the Scheldt River Basin and the Belgian Coastal Zone over the last three decades. J Mar Syst 128:52–61
28. Antoniadis V, Golia EE, Shaheen SM, Rinklebe J (2017) Bioavailability and health risk assessment of potentially toxic elements in Thriasio plain, near Athens, Greece. Environ Geochem Health 39:319–330
29. Antoniadis V, Golia EE, Liu Y, Wang S, Shaheen SM, Rinklebe J (2019) Soil and maize contamination by trace elements and associated health risk assessment in the industrial area of Volos. Greece Environ Int 124:79–88
30. Islam MS, Ahmed MK, Al-Mamun MH (2015) Metal speciation in soil and health risk due to vegetables consumption in Bangladesh. Environ Monit Assess 187:288–303
31. Shaheen SM, Shams MS, Khalifa MR, El-Daly MA, Rinklebe J (2017) Various soil amendments and wastes affect the (im) mobilization and phytoavailability of potentially toxic elements in a sewage effluent irrigated sandy soil. Ecotoxicol Environ Saf 142:375–387
32. Saha S, Hazra GC, Saha B, Mandal B (2015) Assessment of heavy metals contamination in different crops grown in long-term sewage-irrigated areas of Kolkata, West Bengal. India Environ Monit Assess 187:4087
33. Shaheen SM, Abdelrazek MAS, Elthoth M, Moghanm FS, Mohamed R, Hamza A, El-Habashi N, Wang J, Rinklebe J (2019) Potentially toxic elements in saltmarsh sediments and common reed (Phragmites australis) of Burullus coastal lagoon at North Nile Delta, Egypt: a survey and risk assessment. Sci Total Environ 649:1237–1249
34. Tomlinson DC, Wilson JG, Harris CR, Jeffrey DW (1980) Problems in the assessment of heavy metals in estuaries and the formation pollution index. Helgol Mar Res 33:566–575
35. De Miguel E, Iribarren I, Chacon E, Ordonez A, Charlesworth S (2007) Risk-based evaluation of the exposure of children to trace elements in playgrounds in Madrid (Spain). Chemosphere 66(3):505–513. https://doi.org/10.1016/j.chemosphere.2006.05.065
36. Zhang ZY, Yang XD, Simay Z, Mohammed A (2018) Health risk evaluation of heavy metals in green land soils from urban parks in Urumqi, northwest China. Environ Sci Pollut 25(5):4459–4473. https://doi.org/10.1007/s11356-017-0737-0
37. Hu X, Zhang Y, Ding Z, Wang T, Lian H, Sun Y, Wu J (2012) Bioaccessibility and health risk of arsenic and heavy metals (Cd Co, Cr, Cu, Ni, Pb, Zn and Mn) in TSP and PM2. 5 in Nanjing, China. Atmos Environ 57:146–152
38. Luo XS, Ding J, Xu B, Wang YJ, Li HB, Yu S (2012) Incorporating bioaccessibility into human health risk assessments of heavy metals in urban park soils. Sci Total Environ 424:88–96. https://doi.org/10.1016/j.scitotenv.2012.02.053
39. USEPA (2011) Exposure factors handbook 2011 edition. National Center for Environmental Assessment, Office of Research and Development. Washington D.C.
40. USEPA (2002) Supplemental guidance for developing soil screening levels for superfund sites. OSWER 9355.4-24.
41. USEPA (2020) Regional screening level (RSL) resident soil table (TR=1E-06, HQ=1) May 2020 (corrected). US Environmental Protection Agency, 2020. Available at: https://semspub.epa.gov/work/HQ/200047.pdf. Accessed 09 October 2020
42. Li XY et al (2013) Heavy metal contamination of urban soil in an old industrial city (Shenyang) in Northeast China. Geoderma 192:50–58
43. Moubakou RRC, Dallou GB, Bounouira H, Cherkaoui R, Bouka C (2022) Baseline data of radioactivity and radon mass exhalation rate in soils and phosphate rocks of a prospective phosphate mining area in Hinda district, Republic of Congo. Arab J Geosci

44. Kabata-Pendias A, Pendias H (1984) Trace elements in soils and plants. CRC Press, Florida, p 315
45. SPCR (2005) Soil pollution control regulation. Republic of Turkey Ministry of Environment and Forestry. Official Gazette No, 25831
46. Aydinalp C, Marinova S (2003) Distribution and forms of heavy metals in some agricultural soils. Pol J Environ Stud 12:629–633
47. Coşkun M, Steinnes E, Frontasyeva MV, Sjobakk TE, Demkina S (2006) Heavy metal pollution of surface soil in the Thrace region. Turkey Environ Monit Assess 119:545–556
48. Shi T, Ma J, Zhang Y, Liu C, Hu Y, Gong Y, Wu X, Ju T, Hou H, Zhao L (2019) Status of lead accumulation in agricultural soils across China (1979–2016). Environ Int 129:35–41
49. Jaishankar M, Tseten T, Anbalagan N, Mathew BB, Beeregowda KN (2014) Toxicity, mechanism and health effects of some heavy metals. Interdiscipl Toxicol 7:60–72. https://doi.org/10.2478/intox-2014-0009
50. White SJO, Shine JP (2016) Exposure potential and health impacts of indium and gallium, metals critical to emerging electronics and energy technologies. Curr Environ Health Rep 3(4):459–467