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Evaluation of trace metal element contamination in kaolin and health risks associated with geophagy: A case study of Kimbanseke Commune, Democratic Republic of the Congo

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ABSTRACT

Introduction
In Kinshasa, kaolin consumption is a deeply rooted cultural practice, particularly among women. However, it represents a major exposure pathway for chemical contaminants, while the toxicological risks associated with trace metal elements (TMEs) remain poorly documented.

Purpose
This study evaluated health hazards associated with kaolin consumption. The overall objective was to assess health exposure risks among women in Kimbanseke to TMEs (lead, cadmium, and arsenic) resulting from geophagy. Specifically, the study aimed to (a) identify consumers and assess their level of exposure; (b) measure total concentrations of Pb, Cd, and As; (c) determine their in vitro bioaccessible fractions (gastric and intestinal phases) to calculate the Average Daily Dose (ADD), Hazard Quotient (HQ), and Hazard Index (HI); and (d) propose a decision-making tool.

Methods
A cross-sectional survey was conducted among 100 respondents in Kimbanseke. Physicochemical characterization was performed using X-ray fluorescence (XRF) to determine total metal concentrations. In vitro digestion simulation was conducted using a bioaccessibility model mimicking the gastric phase (pH 1.5) and intestinal phase (pH 7.0).

Results
XRF analyses revealed alarming total concentrations at Site 1 (Pb: 32.7 mg/kg; Cd: 11.1 mg/kg; As: 4.1 mg/kg) and Site 2 (Pb: 22.0 mg/kg; Cd: 1.8 mg/kg). These concentrations exceeded permissible limits set by WHO/FAO, notably the 2.0 mg/kg safety threshold for lead (Food and Agriculture Organization of the United Nations & World Health Organization, 2011) and 0.1 mg/kg for cadmium and arsenic. Bioaccessibility tests showed substantial release in the intestinal digestate (Pb: 0.90 mg/L; Cd: 0.16 mg/L; As: 0.13 mg/L). Risk assessment based on a daily consumption of 115 g over 15 years indicated potential health concern. However, inconsistencies were identified between reported bioaccessibility values and hazard indices, requiring recalculation for final risk classification.

Conclusion
Kaolin consumed in Kimbanseke contains TMEs above international guideline limits. The intestinal solubilization of metals indicates potential absorption and systemic toxicity. Public health intervention is required to regulate kaolin exploitation and raise awareness among consumers.

INTRODUCTION

Kaolin is a naturally occurring white clay that represents a paradox between its industrial utility and potential health implications (Charrié, 2007). Although its adsorbent properties are widely exploited for water purification, its direct consumption—known as *geophagy*—raises major concerns due to possible contamination by trace metal elements (TMEs). In sub-Saharan Africa, this practice is deeply rooted and is often linked to physiological and sociocultural motivations, such as relieving nausea during pregnancy or fulfilling ritual practices (Hunter-Adams, 2016; Mbayo et al., 2022). However, unlike essential nutrients, heavy metals such as lead (Pb), cadmium (Cd), and arsenic (As) have no physiological function and may cause systemic toxicity even at low doses (Traoré, 2023).

In the Kimbanseke commune of Kinshasa, rapid urbanization and environmental degradation are transforming this cultural habit into a major pathway of toxic exposure. The accumulation of anthropogenic pollutants in soils may contaminate kaolin deposits and products sold in local markets, increasing the risk of lead poisoning (plumbism), particularly among women and children (Musibono et al., 2010). This study applies quantitative exposure modeling to estimate hazard using the Average Daily Dose (ADD), Hazard Quotient (HQ), and Hazard Index (HI). Such modeling is essential because the clay matrix may influence metal bioavailability during gastrointestinal transit, thereby affecting the absorbed toxic burden (Traoré, 2023).

Health risk assessment is based on compliance with tolerable daily intakes and reference doses. For lead, although no safe exposure threshold exists, a reference dose of 0.0035 mg/kg/day is commonly used for modeling purposes. Cadmium has a reference dose of 0.0010 mg/kg/day, while inorganic arsenic is often evaluated using a reference dose of 0.0003 mg/kg/day (World Health Organization [WHO], 2011; U.S. EPA IRIS). International guideline concentrations recommended by WHO/FAO suggest maximum levels of 2 mg/kg for lead and 0.1–0.5 mg/kg for cadmium in mineral products (WHO & FAO, 2021).

TMEs detected in kaolin may originate from natural geochemical background or anthropogenic inputs linked to urban activities and artisanal processing methods, notably smoking/fumigation (Naili et al., 2016). These practices may also reinforce dependence mechanisms, making cessation difficult even when consumers are aware of the risks (Pains et al., 2016). This research therefore aims to provide quantitative evidence to support public health policy.

The general objective of this study was to evaluate health exposure risks among women in Kimbanseke to TMEs (Pb, Cd, and As) resulting from geophagy. Specifically, the study aimed to:

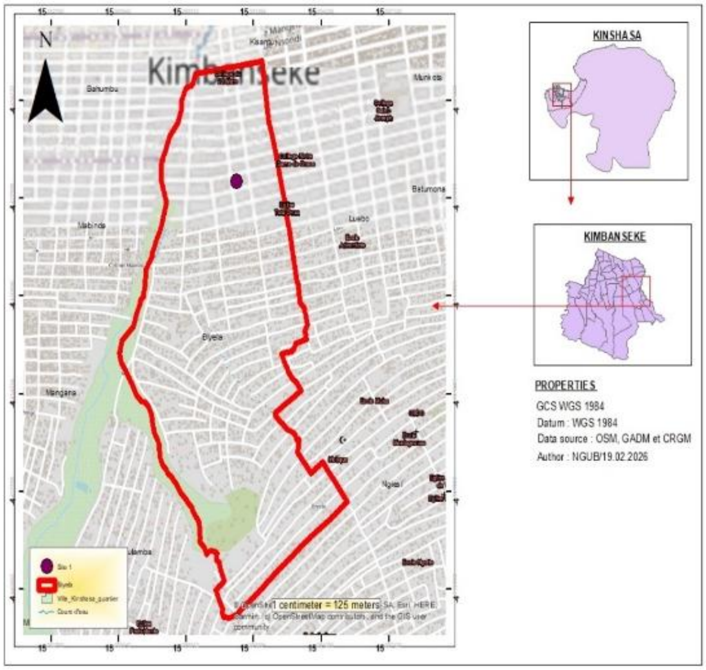
- identify consumers and assess their degree of exposure;
- measure total Pb, Cd, and As concentrations in raw and smoked kaolin;
- determine gastric and intestinal bioaccessible fractions to calculate ADD, HQ, and HI; and
- propose a decision-making tool for health authorities.

METHODS

Study Area and Sampling

The study was conducted in the Kimbanseke commune (Kinshasa, Democratic Republic of the Congo; see **Map 1 & 2**). Kaolin samples were collected from two sites: Site 1 (S1), Boma District, and Site 2 (S2), Biyela District. Three types of samples were collected per site: raw kaolin, processed (molded) kaolin, and smoked kaolin (*n* = 6). Geographic coordinates were recorded using a Garmin GPS receiver (S1: 4°25′37.19″S, 15°23′26.35″E; S2: 4°25′17.37″S, 15°23′18.56″E).

Map 1:
Geographic location of kaolin sampling sites in Kimbanseke (Biyela district)



Map 2:
Geographic location of kaolin sampling sites in Kimbanseke (Boma district)

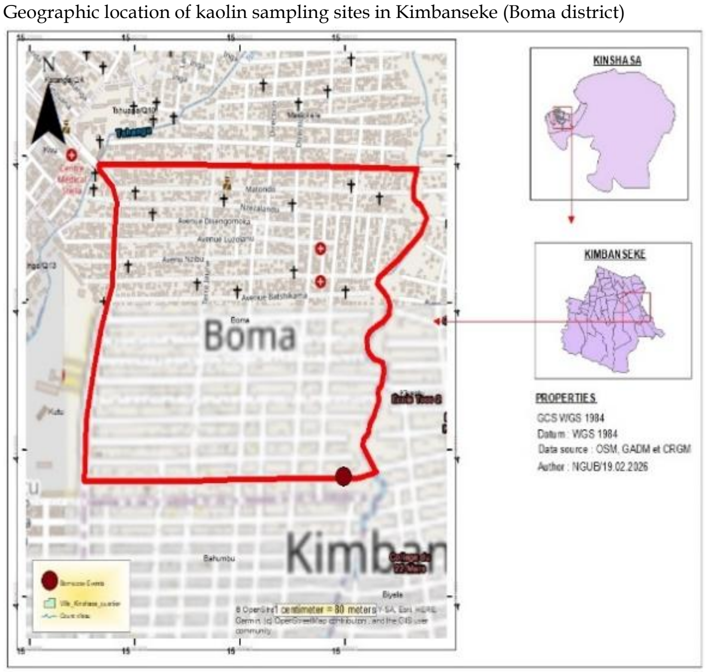


Photo 1:
Raw kaolin

Photo 2:
Molded kaolin

Photo 3:
Smoked (fumigated) kaolin

Consumption Survey and Ethical Considerations

A cross-sectional survey was conducted using a convenience sample of 100 voluntary female kaolin consumers. A structured questionnaire was administered to determine ingestion rate (IR), exposure frequency (EF), and exposure duration (ED). The study was conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained where possible; oral consent was obtained for illiterate participants. Confidentiality and anonymity were ensured.

Physicochemical Analysis by X-Ray Fluorescence (XRF)

Kaolin samples were oven-dried at 105°C for 24 h until constant weight. Mass measurements were taken using a Jinnuo JT2003B analytical balance. Samples were ground and sieved to 60 µm using a Retsch sifter. Pellets were prepared using a hydraulic press with Fluxana binder.

XRF analysis was conducted using a CGEA/CREN-K X-ray fluorescence spectrometer equipped with four secondary targets (Mo, Al_2O_3, Co, and HOPG Bragg). External calibration was performed by normalizing intensities relative to coherent and incoherent scattering peaks. The limit of detection (LOD) was established according to laboratory standards for Pb, Cd, and As. Results were reported with 95% confidence intervals using Student's *t*-test.

In Vitro Bioaccessibility Assessment (UBM Protocol)

The fraction of metals released in the gastrointestinal tract was evaluated using the Unified Bioaccessibility Method (UBM) protocol (Wragg et al., 2011).

Gastric phase

One gram of kaolin was mixed with 100 mL gastric solution (NaCl + HCl, pH 1.5) and stirred at 37°C for 1 h.

Intestinal phase

The pH was adjusted to 7.0 using $NaHCO_3$. Pancreatin and bile salts were added, followed by incubation at 37°C for 2 h.

Photo 4:
pH adjustment

Photo 5:
Measurement of kaolin sample weights

Bioaccessibility was calculated as:

$$B(\%) = \frac{c\ libere \times v\ suc}{M\ echantillon \times c\ total} \times 100$$

Quantitative Health Risk Modeling

Risk was assessed using the U.S. EPA exposure model (U.S. Environmental Protection Agency, 1989), incorporating the bioaccessibility coefficient (*B*):

$$\mathrm{ADD} = \frac{\mathrm{C} \times \mathrm{IR} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT}}$$

$$\mathrm{ADD\ (bio)} = \frac{\mathrm{C} \times \mathrm{IR} \times \mathrm{B} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT}}$$

where

- *C* is the total concentration (mg/kg),
- *IR* is ingestion rate (kg/day),
- *B* is bioaccessibility fraction,
- *EF* is exposure frequency (days/year),
- *ED* is exposure duration (years),
- *BW* is body weight (kg), and
- *AT* is averaging time (days).

Hazard quotient was calculated as:

$$HQ = \frac{ADD}{RfD}$$

Hazard index was calculated as:

HI = HQ(Pb) + HQ(Cd) + HQ(As)

Reference doses were Pb = 0.0035 mg/kg/day, Cd = 0.0010 mg/kg/day, and As = 0.0003 mg/kg/day (WHO, 2011; U.S. EPA IRIS).

RESULTS

Survey Results

Table 1:
Distribution of respondents by sociodemographic characteristics (n = 100)

Variable	Category	N	%
Spatial distribution	Biyela	50	50.0
	Boma	50	50.0
	Total	100	100.0
Age (years)	18–27	37	37.0
	28–37	42	42.0
	38–47	13	13.0
	48–57	5	5.0
	≥ 58	3	3.0
	Total	100	100.0
Occupation	Trader/merchant	41	41.0
	Housewife	29	29.0
	Student	16	16.0
	Teacher/education	4	4.0
	Health sector	2	2.0
	Technical sector	3	3.0
	Other	5	5.0
	Total	100	100.0
Education level	Secondary	55	55.0
	Higher/university	42	42.0
	Primary	2	2.0
	None	1	1.0
	Total	100	100.0

Table 2:
Distribution of respondents by kaolin consumption characteristics (n = 100)

Variable	Category	n	%
Physiological status	Non-pregnant/non-breastfeeding	81	81.0
	Breastfeeding	11	11.0
	Pregnant	8	8.0
	Total	100	100.0
Body weight	45–59 kg	15	15.0
	60–74 kg	52	52.0
	75–89 kg	32	32.0
	≥ 90 kg	1	1.0
	Total	100	100.0
Duration of consumption	0–9 years	33	33.0
	10–19 years	43	43.0
	20–29 years	16	16.0
	30–39 years	7	7.0
	≥ 40 years	1	1.0
	Total	100	100.0
Frequency	Daily	57	57.0
	A few times/week	18	18.0
	Rarely	25	25.0

Variable	Category	n	%
	Total	100	100.0
Daily quantity	Low (½ stick)	42	42.0
	Moderate (1 stick)	44	44.0
	High (2–3 sticks)	14	14.0
	Total	100	100.0
Motivation	Taste/craving (pica)	78	78.0
	Relief of nausea	14	14.0
	Tradition/culture	6	6.0
	Other	2	2.0
	Total	100	100.0
Supply source	Street vendor	76	76.0
	Market	24	24.0
	Total	100	100.0
Risk awareness	Aware	69	69.0
	Unaware	31	31.0
	Total	100	100.0
Reported effects	Constipation	49	49.0
	Stomach pain	6	6.0
	Fatigue	1	1.0
	None	44	44.0
	Total	100	100.0

The sample was evenly distributed between Biyela and Boma. Most respondents (79%) were between 18 and 37 years old. Traders (41%) and housewives (29%) represented the largest groups. Education level was high, with 97% reporting secondary or university education. Consumption patterns indicate chronic exposure, with 43% consuming kaolin for 10–19 years and 57% reporting daily ingestion. Most women obtained kaolin from street vendors (76%), indicating minimal regulatory oversight.

Total Concentrations of TMEs

Table 3:
Total concentrations of TMEs in kaolin samples (mg/kg)

Sample	Pb	Cd	As	Product status
Boma raw	29.5	31.5	5.0	Raw (quarry)
Boma smoked	32.7	11.1	4.1	Finished product (stick)
Boma molded	15.2	4.8	< 0.1	Sun-dried
Biyela raw	28.8	16.5	5.0	Raw (quarry)
Biyela smoked	22.0	< 1.9	1.5	Finished product (stick)
Biyela molded	24.4	4.4	2.0	Sun-dried
WHO/FAO guideline	2.0	0.1	0.1	—

Total concentrations exceeded WHO/FAO guideline limits at both sites.

Gastric and Intestinal Release

Table 4:
TME concentrations in gastric digestate (mg/L)

Site	Pb	Cd	As
Site 1 (Boma)	0.049 ± 0.034	0.084 ± 0.007	0.140 ± 0.220
Site 2 (Biyela)	0.012 ± 0.001	0.048 ± 0.013	0.138 ± 0.229

Table 5:
TME concentrations in intestinal digestate (mg/L)

Site	Pb	Cd	As
Site 1 (Boma)	0.900 ± 0.000	0.156 ± 0.208	0.100 ± 0.200
Site 2 (Biyela)	0.600 ± 0.500	0.032 ± 0.012	0.000 ± 0.000

Bioaccessibility

Table 6:
Bioaccessibility of TMEs in intestinal phase

Element	Site	Total concentration (mg/kg)	Released concentration (mg/L)	Bioaccessibility (%)
Pb	1	32.7	0.90	0.275
Pb	2	22.0	0.60	0.273
Cd	1	11.1	0.16	0.144
Cd	2	1.8	0.03	0.167
As	1	4.1	0.13	0.317
As	2	1.5	0.00	0.000

Note. Calculations assume a digestate volume of 0.1 L and sample mass of 1 g.

Bioaccessibility values were low (< 0.5%) for all elements, suggesting strong retention of metals within the kaolin matrix.

Average Daily Dose (ADD)

Table 7:
Average daily dose (ADD) of TMEs by site

Site	Element	Total C (mg/kg)	Bioaccessibility (%)	CbioC_{bio}Cbio (mg/kg)	ADD (mg/kg/day)
1	Pb	32.7	0.275	0.0899	1.59×10^{-4}
1	Cd	11.1	0.144	0.0160	2.83×10^{-5}
1	As	4.1	0.317	0.0130	2.30×10^{-5}
2	Pb	22.0	0.273	0.0601	1.06×10^{-4}
2	Cd	1.8	0.167	0.0030	5.30×10^{-6}
2	As	1.5	0.000	0.0000	0.00

Risk Assessment (HQ and HI)

Table 8
Hazard quotient (HQ) and hazard index (HI)

Site	Element	ADD (mg/kg/day)	RfD (mg/kg/day)	HQ
1	Pb	1.59×10^{-4}	0.0035	0.05
1	Cd	2.83×10^{-5}	0.0010	0.03
1	As	2.30×10^{-5}	0.0003	0.08
	HI (Site 1)			0.16
2	Pb	1.06×10^{-4}	0.0035	0.03
2	Cd	5.30×10^{-6}	0.0010	0.01
2	As	0.00	0.0003	0.00
	HI (Site 2)			0.04

Health Effects of TMEs

Table 9:
Target organs and health effects of Pb, Cd, and As exposure

Element	Target organs	Health effects in women	Health effects during pregnancy
Pb	Blood, bones, nervous system, kidneys	Anemia, hypertension, neurotoxicity, renal impairment, bone storage	Miscarriage risk, prematurity, fetal growth restriction, reduced cognitive development
Cd	Kidneys, bones, lungs	Chronic renal injury, osteomalacia, cancer risk	Placental accumulation, impaired fetal nutrient transfer, low birth weight
As	Skin, liver, cardiovascular system	Skin lesions, diabetes risk, neuropathy, cancers	Increased infant mortality, long-term chronic disease programming

DISCUSSION

The balanced sampling design (50% Biyela and 50% Boma) strengthens representativeness and supports the characterization of Kimbanseke as an artisanal kaolin processing center (Kinyua et al., 2016). Contrary to common assumptions associating geophagy with illiteracy, 97% of respondents had secondary or university education. This suggests that consumption is not driven by ignorance, but rather by cognitive dissonance, in which sensory satisfaction outweighs risk perception (Maitra, 2020). The predominance of traders (41%) further suggests that continuous availability reinforces habitual consumption (Kutalek et al., 2010).

XRF results revealed systematic exceedance of WHO/FAO guideline values (WHO & FAO, 2021), particularly for lead and cadmium. Lead concentrations reached 32.7 mg/kg, exceeding the guideline value of 2.0 mg/kg. Toxicologically, lead is considered a non-threshold contaminant because no exposure level is completely safe (Tuakuila, 2015). Chronic ingestion of 115 g/day, as observed in this study, may contribute to long-term skeletal accumulation, since lead can substitute for calcium in bone tissue (Needleman, 2004).

Cadmium concentrations were extremely high, particularly in Boma (31.5 mg/kg), exceeding the guideline limit by more than 300-fold. Because cadmium has a biological half-life of several decades, it may accumulate in renal tissue and induce irreversible nephrotoxicity and bone demineralization (Satarug, 2010).

The presence of pregnant (8%) and breastfeeding women (11%) represents a critical concern, given that lead and arsenic can cross the placental barrier (WHO, 2021). In addition, kaolinitic clays may reduce the bioavailability of essential micronutrients such as iron and zinc, thereby aggravating iron-deficiency anemia and reducing the effectiveness of prenatal supplementation (Hooda et al., 2004).

Although many studies emphasize pregnancy-related effects, the predominance of non-pregnant women (81%) indicates that geophagy represents a broader toxicological concern. Long-term exposure may increase risks of renal impairment, bone fragility, hypertension, and endocrine disruption (Needleman, 2004; Satarug, 2010; Tuakuila, 2015).

However, despite high total concentrations, measured bioaccessibility values were below 0.5% for all TMEs, indicating strong retention by the kaolin matrix. This may limit acute toxicity, but long-term daily exposure may still represent a cumulative risk. Additional studies are required to confirm in vivo absorption and systemic biomonitoring outcomes.

Study Limitations

Although this study provides crucial data on the bioaccessibility of heavy metals in Kimbanseke kaolin, it has certain limitations. *First*, the risk assessment is based on an *in vitro* simulation which, while rigorous, does not replace an *in vivo* clinical study. *Second*, the absence of biological assays (blood lead levels, urinary cadmium, or arsenic hair analysis) in the consumers does not yet allow for a direct correlation between kaolin ingestion and actual body burden. Future research incorporating biological sampling is required to validate these predictive models.

CONCLUSION

This study evaluated health exposure risks associated with trace metal elements (TMEs)—lead, cadmium, and arsenic—resulting from geophagy among women in the Kimbanseke commune. The findings reveal that kaolin consumed in this area contains heavy metals at concentrations exceeding international guideline limits.

XRF analysis confirmed contamination levels exceeding WHO/FAO standards, with lead concentrations reaching 32.7 mg/kg and cadmium reaching 31.5 mg/kg. In vitro digestion experiments demonstrated measurable intestinal release of metals, indicating potential gastrointestinal solubilization and absorption. Although bioaccessibility values were low, the high daily consumption rate (115 g/day) suggests that chronic exposure may still contribute to cumulative toxic burden.

Given the vulnerability of pregnant and breastfeeding women and the potential for chronic renal, neurological, and cardiovascular effects, public health authorities should implement regulatory and preventive measures. Geophagy in Kimbanseke can no longer be viewed solely as a cultural practice, but must be recognized as a potential route of hazardous chemical exposure.

Recommendations and Regulatory Framework

Recommendations for political and health authorities

- Implement awareness campaigns emphasizing that artisanal kaolin may represent a health hazard.
- Regulate commercialization by imposing standardized packaging weights and consumer advisories.
- Inspect extraction sites and monitor anthropogenic contamination sources.
- Promote soil stabilization and remediation strategies, including phytoremediation.
- Establish a regulatory body for mineral products intended for food, medicinal, and cosmetic use.

Recommendations for the medical community (antenatal care services)

- Integrate blood lead level testing and urinary cadmium screening for women reporting pica or geophagy.
- Train health personnel to identify chronic constipation and treatment-resistant anemia as possible indicators of kaolin ingestion.
- Recognize geophagy as a factor reducing effectiveness of iron supplementation.

Recommendations for researchers

- Extend research to in vivo biomonitoring by analyzing blood, urine, and breast milk samples.
- Develop national mapping of kaolin deposits to identify lower-risk areas.

Recommendations for manufacturers and consumers

- Encourage safer fumigation processes and reduce contamination during processing.
- Promote industrial rather than dietary use of kaolin.
- Inform consumers that chronic consumption may result in long-term toxicity.

Ethical Approval: The study protocol was approved by the Faculty of Science and Technology, University of Kinshasa, Kinshasa, Democratic Republic of the Congo on 5 January 2025.

Conflicts of Interest: None declared.

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