



Lead and Cadmium Pollution: Implications for Health in Artisanal and Small Scale Gold Mining in Senegal and Kenya

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Abstract

Artisanal and Small-Scale Gold Mining (ASGM) is a prevalent activity, characterized by low-tech equipment and inadequate Occupational Health and Safety Standards (OHS). The ASGM is a significant source of Potentially Toxic Elements (PTEs), which can result in potential health risks to humans and the ecosystem. The interconnectedness between human and environmental health have gained global attention from scientific communities, public health and planetary health regarding human-environmental continuum's safety. This study aimed at assessing human and environmental health risks associated with mine pollution in Kedougou region of South Eastern Senegal and Kakamega region in Western Kenya. Purposive sampling was used to collect waste ores, agricultural soil, residential soils and surface water samples were taken from Kedougou region while secondary data on similar matrices were used from Kakamega region. Descriptive statistics, figures and tables were used to present the result. Health risks assessment were achieved using Enrichment Factors (EF), Index of Geo-accumulation (Igeo), Pollution Index (HPI), and Ecological Risk Assessment Indices (ERI); to ascertain the source and the burden of health risk as a result of contamination in the two regions. Distinct geological and mineralogical compositions contributed significantly to the difference in concentrations of these Pb and Cd across Eastern and Western Africa regions. Further, geographic variation in background concentrations contributed significantly to the natural Pb and Cd levels in environmental media between the different locales. This research concluded that ASGM is one of the contributors to human and ecosystem health risks associated with Pb and Cd pollution. There is urgent need for comprehensive Occupational Health and Safety Standards; implementation and training of miners to safeguard human health while maintaining the livelihood in ASGM operations as well as proper control of mine waste disposal and conservation measures around the ASGM areas.

Keywords: Lead, Cadmium, ASGM, Health risk, Kenya and Senegal

INTRODUCTION

Artisanal and Small Scale Gold Mining (ASGM) is characterized by low-tech equipment to exploit naturally occurring minerals and metal deposits [1, 2] and is usually undertaken by an individual, or as a family, community or a social group [3]. This sector is poverty-driven, poorly resourced, and comparatively inefficient in operation with inadequate occupational health and safety (OSH) standards [4-8] as well as weak regulations and concerns by the government and authorities [7].

Gold occurs in rocks containing varying sulphide concentrations of As- Arsenic, lead—Pb, cadmium —Cd, and other elements [7, 9]. In the process of rudimentary gold extraction, the



mining wastes, resulting from excavation and sluicing activities cause serious environmental and health risks, due to sulphuric acid release and other toxic complexes that compose the tailings [7, 9, 10]. Mine tailings produced from ASGM are composed of different toxic materials [11, 12], and are considered wastes as they do not attract any economic benefit [11]. Other forms of pollution are related to dust exposure, and mass transfer of harmful pollutants from the point of release to other environmental matrices like water, residential areas and agricultural land [5, 13]. Generally, ASGM is predominantly in developing countries [14, 15]. It provides wide range of informal employment and income to large population of miners in these countries [6, 8, 15] thereby contributing to 20–30% of the world's output [16] and this supports several populations from lower social-economic backgrounds [7, 14].

In Eastern Africa, Artisanal & Small-scale Gold Mining is a sustenance option to many homesteads [4, 15, 17]. An estimate of more than 40,000 families in Kenya are involved in ASGM [4]. Similarly, in Western Africa, many peasant farmers have adopted livelihood diversification to sustain their lives [18]. In Senegal alone more than 60,000 persons were involved in artisanal gold mining activities by 2009 [19] and this number has increased adding to migrants who find alternative livelihoods within the mine rich areas from agriculture [18, 20].

Kenya and Senegal have similar approach to ASGM with unique characteristics of arrangements and operations influenced by local contexts, culture, and believes [7, 9, 19, 21].

Legally, both countries have established frameworks—Kenya through the 2016 Mining Act [22] and Senegal through the 2003 Mining Code [23] to regulate and recognize ASGM. However, the regulations, just like in other developing countries, have faced challenges in implementation and adherence [4, 6]. Danger is looming on health risks associated with ASGM in developing countries as a result of safety concerns, resource conflicts, income fluctuations and environmental concerns associated with degradation of nature's life support systems that is human driven [24, 25]. In ASGM operations, gold is always found in small quantities [16], while operations coverage is wide with significant human health concern [26, 27].

Lead and Cadmium from mining operations, at low concentrations cause acute or chronic related illnesses in humans as well as effects on agricultural soil balance leading to yield effects [17, 28–30]. High blood Lead and Cadmium levels and blood pressure fluctuations among other chronic health burdens, [31, 32] have been associated with drinking lead contaminated water, as well as airborne dust due to ASGM activities in Africa [6, 33]. There is a global concern over public health, the health of miners, the community and the biodiversity [4, 5, 34, 35] in most regions with such operations [36]. This has triggered global players, scientific community, socioeconomic practitioners, public health, planetary health and environmental policy makers to developed scientific interest of finding sustainable solutions related to ASGM operations while maintaining livelihood [1–3]. This study compared the human and environmental health risks burden of lead and cadmium from Artisanal and Small Scale Gold Mining to agriculture, water and residential areas in Kedougou, Eastern Senegal and Kakamega, western Kenya. Total elemental concentration for the Kakamega ASGM results for Lead and Cadmium were obtained from the recent analysis by [21] in 2022, while analysis for the Kedougou ASGM were conducted between February to July 2023 at Laboratoire de traitement des eaux usées, Institut fondamental d'Afrique noire, Université Cheikh Anta Diop. Total elemental concentrations in different matrices, and contamination indices; enrichment factor (EF), geo-accumulation index (Igeo), pollution index (HPI) and Ecological health risk assessment index (ERI) were utilized to ascertain the health risk burdens in the two regions [7, 21, 37].



MATERIALS AND METHODS

The study area

The study was based on ASGM areas in Western Kenya and Kedougou region in Senegal.

Geographical location of Senegal and Kenya

Figure 1.0 is a map of Africa, showing position of Kenya and Senegal, with a slim latitude differences in the North South direction. Nairobi, Kenya's latitude is -1.283333 and its longitude is 39.816667 . Dakar, Senegal's latitude is 14.692778 and its longitude is -17.446667 . with a distance difference of $6,544$ km.

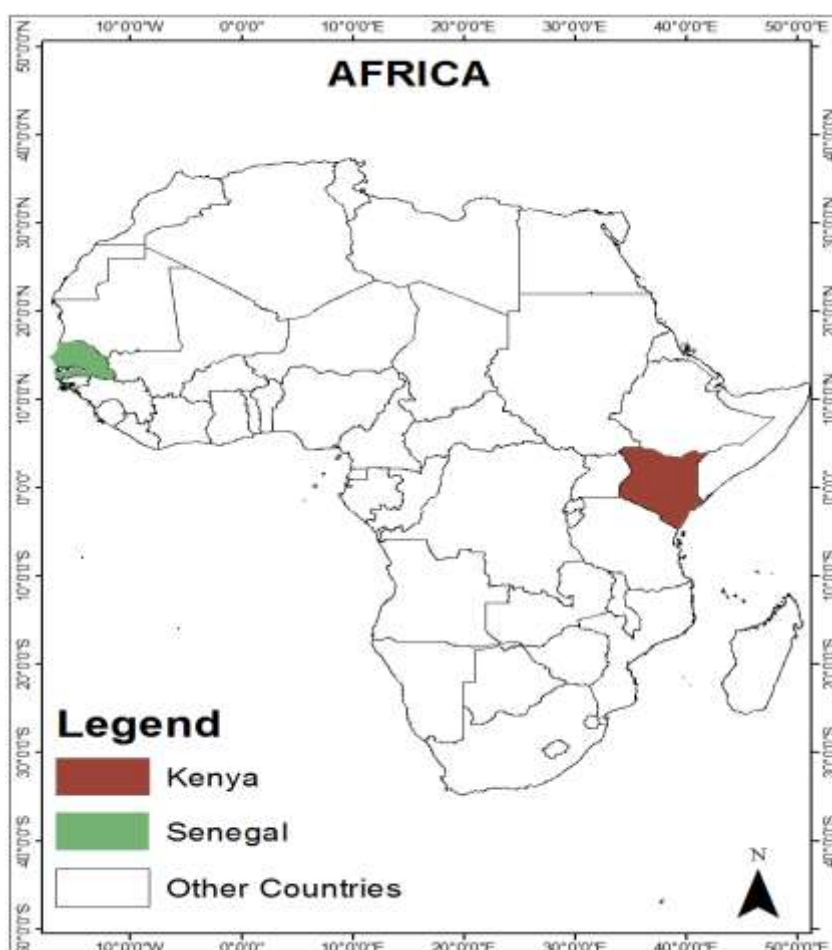


Figure 1.0. Map of *Africa* showing locations of Kenya and Senega

Kedougou region, Senegal

Kedougou region (Figure 2.0) covers around $16,896$ km² in the south-eastern part of Senegal, approximately 700 km from the Senegal's capital city, Dakar. The area is bound by Latitudes



12.762053° N and Longitudes 12.224414° W at an elevation of 123m above sea level. This region borders Mali to the eastern part and Guinea Bissau to the south. It is characterized by two major periods of thermal regime: a period of mild temperatures, from July to February, with most cool temperature in the months of December and January (19 °C to 34 °C) and a period of high temperatures (34 °C to 42 °C) between March and June. The region has rainy season of 5 months (June to October) and rainfall of at least 1,300 mm/year, it is one of the most rain fed regions in Senegal. With a population of 172,482 inhabitants by 2017, Kedougou region is essentially rural and is considered as one of the poorest in the country [18].

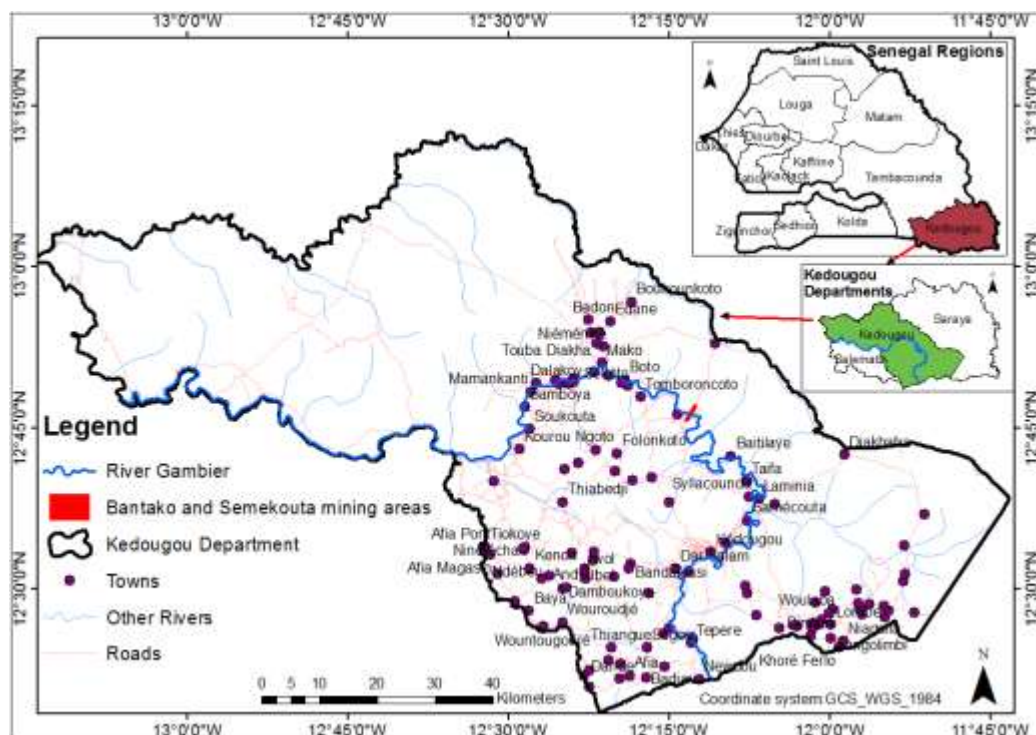


Figure 2.0. Map of **Senegal** showing Kedougou region and the mining areas

Geological features

Kedougou region can be referred back geologically to Kedougou-Kénieba inlier [19] which forms part of Precambrian basement (volcanic, volcano sedimentary and sedimentary formations) [19]. The major tectonic zones that are attributed to the preces of gold in Kedougou region are: the Main Transcurrent Zone and the Senegalo–Malian Shear Zone which are major regional controls of gold mineralisation [18]. Gold in this area has been shown to occur in two types; alluvial gold, associated with the hydrographic network and the gold-bearing quartz veins hosted by shear zones.

Kakamega Region

Kakamega (Fig 3.0.) region is bound by Latitudes 0.257010°N and Longitudes 34.722092° E at an elevation of 1472m above sea level in an area of 3224.9 km² with an estimated population of 1,867,579 as of 2019 (Kenya national bureau of statistics, 2019). Kakamega typically receives



about 1395 millimeters (54.9 inches) per year of precipitation. The County is found in the former Western Province of Kenya and borders Vihiga County to the South, Siaya County to the West, Bungoma and Trans Nzoia Counties to the North and Nandi and Uasin Gishu Counties to the East. Kakamega gold rush occurred in the early 1930s, fueled partly by the reports of the geologist Albert Ernest Kitson [38, 39].

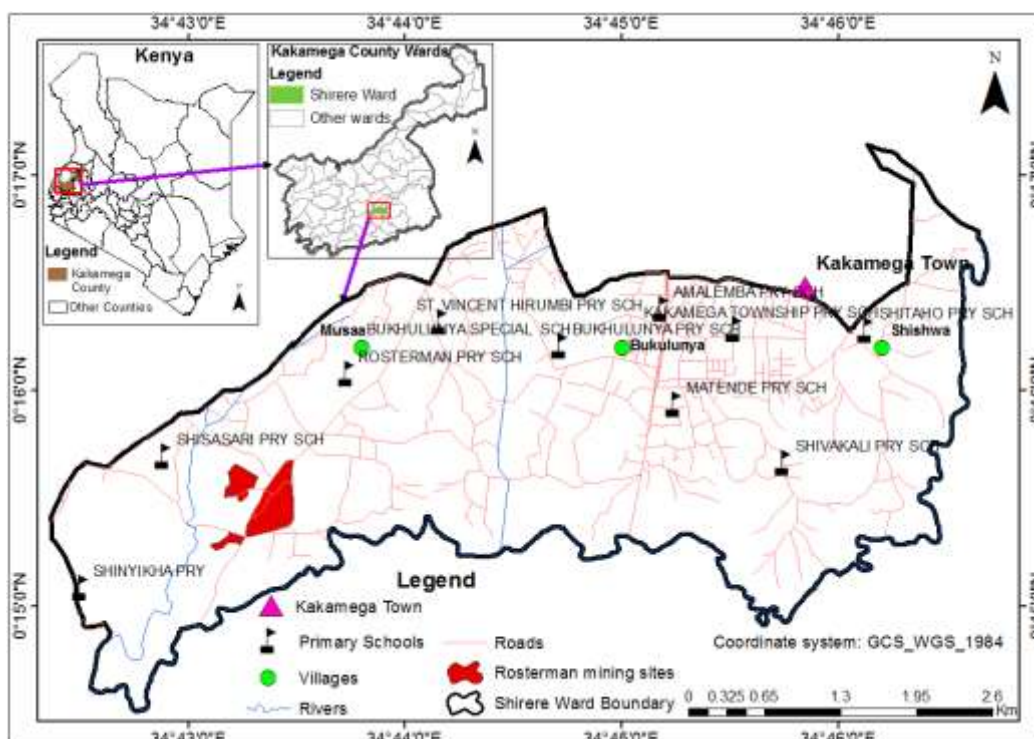


Figure 3.0. Map of Kenya (inset) showing Kakamega region and the mining areas

Geological features

The general geology of the county has formation belonging to the Nyanzian volcanic and the Kavirondian sediments. The Nyanzian System is associated with gold bearing auriferous quartz veins and placer deposits. At the Rosterman Gold Mine in Kakamega, the gold bearing quartz veins occur mainly from the underground geology. The veins occur in a series of marginal tension cracks along the diorites [40].

Southern part of the county is hilly and made of granites which raises it 1950m above sea level. Nandi Escarpment is a key feature on the eastern border of the county with steep cliffs rising from 1700m to 2000m.

Samples Collection and Preparation

Soil samples

Waste ores within the mining sites, the agricultural and residential soils in proximity to the mining areas processing sites were sampled.



Five points sampling criteria was used with 5×5 m grid at the twenty one purposively identified sampling points based on accessibility. The soil from the four corners and the centre, were homogenized using quartering method after which 200g were labelled appropriately into a Kraft bag until transportation to the laboratory.

Soil preparation and analysis

Fifty (50) soil samples collected in Kedougou ASGM region were transported to Université Cheikh Anta Diop, *Laboratoire de traitement des eaux usées, Institut fondamental d'Afrique* laboratory for analysis with similar procedures described for the Kakamega samples in [21].

The soil samples were air dry, ground, and sieved to <2 mm, at the *Laboratoire de traitement des eaux usées, Institut fondamental d'Afrique noire* laboratory in Université Cheikh Anta Diop and further oven-dried at 40°C after sieving.

Twenty grams (20 g) sub-sample of each dried sample were dissolved in a mixed acid solution (HCl: 10 mL/ HNO_3 :10 mL/ H_2O_2 :10 mL), heated and further stirred until cooling. The analytes were filtered using grade one (G1) whatman paper into a 500 mL flask and topped up to the gauge line from which the digest was used for analysis in AAS (*Thermo iCE 3000 with acetylene air flame*) at the *Laboratoire de traitement des eaux usées, Institut fondamental d'Afrique noire*. Lead and Cadmium levels were quantified in mg/kg

Water sample

Duplicate river water samples were collected from River Gambier from two directly opposite sides of the river that were accessible within the proximity of the mining site. Two hundred millilitres (200 ml) of the samples were appropriately labelled into 200ml sampling bottles and stored below 4°C until transportation to the laboratory at Université Cheikh Anta Diop for analysis. The procedures for preservation and digestion for analysis followed the same description for River Isiukhu water samples associated with ASGM in Kakamega [21].

Water preparation for analysis

Twenty (20) water samples from River Gambier were sieved through 0.45 micrometre filters, 0.5% v/v HCl and 1% v/v HNO_3 were added to 10 ml of the water sample for complete digestion. Total metal concentrations were then determined by AAS (*Thermo iCE 3000 with acetylene air flame*) the *Laboratoire de traitement des eaux usées, Institut fondamental d'Afrique noire*. Lead and Cadmium levels were quantified in mg/l; this procedure followed similar steps used for Kakamega samples, except for analysis that used Inductively Coupled Plasma Mass Spectrometry (ICP-MS, Agilent 8900 ICP-QQQ) at the British Geological Survey Laboratory.

Quality control

Quality control was achieved by using standardized sampling protocols to ensure consistency, replicates, and properly label all samples in appropriate sampling materials. Further, subjecting the machine to a series of measurements with a range of standards which made it possible to obtain a straight line calibration. Blank sample and a standard were analyzed. All the used



glassware were thoroughly cleaned in nitric acid solution and rinsed with distilled water. The data was validation and verification using statistical analysis as well as using validated literatures.

Health risks Assessment:

Enrichment Factor

The Enrichment Factor (EF) was used to identify the actual origin of elements [41]. Calculation of EF was based on the equation introduced by Chester and Stoner [41-43] as follows:

$$EF = \left(\frac{\frac{Cx}{C_{ref-sample}}}{\frac{Cx}{C_{ref-background}}} \right)$$

with C_x representing the concentration of element under determination (Lead and Cadmium) and C_{ref} represents the concentration of a reference element (Iron)

Geo-accumulation index

The geo-accumulation index (IGeo) adopted from Müller, 1969 [44, 45], was used to quantify accumulation of lead and cadmium in soils. The assessment of Lead and Cadmium pollution level was achieved using the ratio between the content of the element in sample and the background content of the element.

$$I_{geo} = \log_2 \left(\frac{Cx}{1.5Cb} \right)$$

where C_x is the concentration of the elements (Pb and Cd) and C_b is geochemical background value of the elements (Pb and Cd). Factor 1.5 is the background matrix correlation factor due to the lithological effects.

The IGeo values, classified in seven numerical ranges, was used to determine pollution levels of each element [45].

Pollution Index (PI)

Pollution index was used to assess water quality, with respect to potentially toxic elements pollution from the ASGM [46]. The PI represent total quality of water with respect to each PTE in consideration. The suitability of water for drinking purpose is determined by its PI quality with respect to specific elements under consideration [46, 47].

PI Calculation

As described in [46, 47], the PI was calculated by:

Calculation of weightage of i th parameter, then calculation of the *quality rating* for each element and finally the summation of these sub-indices in the overall index

The weightage of i th parameter

$$w_i = k/S_i \quad (1)$$

where W_i is the unit weightage and S_i the recommended standard for i th parameter, while k is the constant of proportionality.

Individual quality rating is given by the expression

$$Q_i = 100 V_i/S_i \quad (2)$$

where Q_i is the sub index of i th parameter, V_i is the monitored value of the i th parameter in $\mu\text{g/l}$ and S_i the permissible limit for the i th parameter.



The formula for calculation is thus as follows.

$$PI = \sum_{i=1}^n (Q_i W_i) / \sum_{i=1}^n W_i \quad (3)$$

where Q_i is the sub index of i th parameter. W_i is the unit weightage for i th parameter, n is the number of parameters considered. The critical pollution index value is 100.

Ecological Risk Assessment of Soil in ASGM in Kedougou and Kakamega Regions

During computation of ERA index, Contamination factor (Cf), the degree of contamination (Cd), and the Pollution Load Index (PLI) were considered for individual element (Pb and Cd) [48]
The formular below was adopted:

$$Cf = \sum_{i=1}^n \left\{ \frac{Ci}{Bi} - 1 \right\} \quad (1)$$

$$Cd = \sum_{i=1}^n (Cf) \quad (2)$$

$$PLI = \sqrt[n]{Cf1 \times Cf2 \times Cf3 \times \dots \times Cfn} \quad (3)$$

$$PERI = \sum_{i=1}^n Eri = \sum_{i=1}^n Cf_i \times Tri \quad (4)$$

where C_i is the concentrations of Lead and Cadmium in (mg/kg) and B_i is the background value of Lead and Cadmium (mg/kg). Values in [49, 50] were used for background concentrations. The Cf categories were used to show the level of contamination [51].

RESULTS AND DISCUSSIONS

Waste ores, agricultural soils and residential soils were analysed for total Cd and Pb and the mean concentrations taken in mg/kg (Table 1) for Kedougou region. Secondary data from Kakamega regions were used (Table 1)

Table 1: Mean concentrations of Lead-Pb and Cadmium-Cd levels in waste ore, Agriculture and Residential soil samples in Kedougou and Kakamega regions

Element	Areas where soils were sampled					
	Waste Ore		Agricultural		Residential	
	Kedougou	Kakamega	Kedougou	Kakamega	Kedougou	Kakamega
Lead (mg/Kg)	9.58	74.80	13.86	31.27	12.82	40.30
Cadmium (mg/Kg)	1.34	0.34	1.12	0.21	1.26	0.23

From Table 1 above, total Lead concentration were higher for waste ores, Agricultural and Residential areas in Kakamega compared to Kedougou region; $78.80 > 9.58$, $31.27 > 13.86$, $40.30 > 12.82$, respectively, while Cadmium concentrations were higher in Kedougou in the same matrices compared to Kakamega results; $1.34 > 0.34$, $1.12 > 0.21$, $1.26 > 0.23$, respectively. Further analysis of variance of mean soil lead concentration in Kakamega and Kedougou region at 0.05 confidence levels, the f-ratio value was 18.9356 and the p-value 0.0014. This indicated that there is significant variation in concentration of soil lead cross the two regions. Similarly, analysis of variance of mean soil Cadmium concentration in Kakamega and Kedougou region at 0.05



confidence level showed a significant variation in concentrations across the region and across the different matrices of consideration at $p < 0.05$.

Globally, there is direct association between PTEs levels in the environment and anthropogenic sources like mining, atmospheric deposition of combustion emissions, and the use of fertilizers [52].

Table 2: Mean concentrations of Lead-Pb and Cadmium-Cd levels in water samples from Kedougou and Kakamega regions

Element	Regions of interest	
	Kedougou	Kakamega
Lead-Pb (mg/l)	0.0374	0.285
Cadmium-Cd (mg/l)	0.060	0.075

Lead-Pb and Cadmium-Cd levels in water had a mean concentration of 0.0374 mg/l and 0.060 mg/l, respectively, in Kedougou while in Kakamega, the mean concentration were 0.285 mg/l and 0.075 mg/l, respectively.

Distinct geological and mineralogical compositions are the major influence in the difference in concentrations of these PTEs across the two regions. This has been exacerbated by further environmental destructions due to mining activities [53].

In Kakamega region, the higher lead concentrations is attributed to its geological setting within Lake Victoria Greenstone Belts, which are known for complex mineral deposits [54]. These deposits often include lead-bearing minerals, a result of the region's unique geological history and processes. The mineralization within these Greenstone Belts, influenced by complex Precambrian Metamorphic Geology and hydrothermal activity, which favors the accumulation of lead [39]. Further pollution in different environmental matrices are aided by extraction and processing of lead ores, significantly contribute to environmental contamination, releasing lead particulates during ore crushing and grinding and erosion of the mine tailings [55].

Conversely, Cadmium in Kédougou region is associated with mineralization processes, potentially including those that favor cadmium enrichment, such as associations with zinc. Cadmium is commonly found as a byproduct in zinc ores, and the geochemical conditions in Kédougou is more conducive to concentrating cadmium compared to Kakamega [56, 57]. Additionally, the geological diversity, being part of the ancient West African Craton, which includes cadmium-bearing sulfide ores releases cadmium to the environment [56].



Assessment of PTEs pollution in previous studies indicated that lead in six different sampling sites within Kakamega were higher in concentration than cadmium [40]. Further, The Pollution indices which are computed from the total concentration of different PTEs in Kakamega and Vihiga, indicated significant enrichment and pollution of soils, sediment and water in decreasing order of $As > \dots > Pb > Cd$ [21]. In other areas, intensification of human agricultural activities, the growing industrialization, and the rapid urbanization have been shown to influence concentration levels of Lead and Cadmium Kenya [30].

Contamination from ASGM areas to different environmental matrices has been significant compared to other non mining areas in Africa. Along the Senegal River Basin, intensified irrigation has been done using water from River Senegal. Analysis of lead and cadmium were below $12 \mu\text{g/g}$ at 20cm depth [58] indicating low health risk levels. Similarly, bioaccumulation of lead and cadmium from two fish species (African catfish - *Clarias gariepinus*) and (Tilapia fish - *Oreochromis niloticus*) from the right north bank of Senegal River in Mauritania (Rosso, Boghé, and Kaédi) indicated low levels of lead and cadmium [59].

Other studies conducted in association to ASGM in different part of Africa, show related trend of high contamination by lead and cadmium to the soil and related matrices as demonstrated in Table 5. These have significantly affected water quality in their proximities [60, 61].

Health risk assessment: Determination of contamination levels

Contamination levels were determined using different contamination indices including enrichment factor, Index of geoaccumulation (Igeo), Pollution Index (HPI), and Ecological Risk Assessment Indices (ERI). [45, 50].

Enrichment Factor

Different EF score categories describe soil quality based on PTE's under consideration. Table 3 shows the EF classification criteria described by Taylor [50]. Table 4 shows the EF class scores for different sites, both in Kedugou and Kakamega.

Table 3: The Enrichment Factor Classification [50]

EF Category	EF Class	EF Description (Soil quality)
$EF \leq 1$	1	Background concentration
EF 1-2	2	Deficiency to minimal enrichment
EF 2-5	3	Moderate enrichment
EF 5-20	4	Significant enrichment
EF 20 – 40	5	Very high enrichment
EF > 40	6	Extremely high enrichment

Table 4: Enrichment Factor results for Kedougou region (Senegal) and Kakamega (Kenya) regions



Region	Site	Element	Enrichment Factor Score	Class	Description (Soil quality)
Kedougou	S1	Lead-Pb	0.503371	1	Background concentration
		Cadmium-Cd	9.469808	4	Significant enrichment
	S2	Lead-Pb	0.728771	1	Background concentration
		Cadmium-Cd	7.926154	4	Significant enrichment
	S3	Lead-Pb	0.673703	1	Background concentration
		Cadmium-Cd	8.925769	4	Significant enrichment
Kakamega	S1	Lead-Pb	3.932343	3	Moderate enrichment
		Cadmium-Cd	2.406154	3	Moderate enrichment
	S2	Lead-Pb	1.643909	2	Deficiency to minimal enrichment
		Cadmium-Cd	1.486154	2	Deficiency to minimal enrichment
	S3	Lead-Pb	2.118629	3	Moderate enrichment
		Cadmium-Cd	1.627692	2	Deficiency to minimal enrichment

Lead and Cadmium concentration from Kedougou and Kakamega, showed different levels of enrichment, these scores translates to different levels of health and environmental risks.

The levels of enrichment for lead were higher in Kakamega region, compared to background concentration score recorded in Kedougou region. Lead risk levels- 'deficiency to minimal enrichment' to 'Moderate enrichment' indicating that the levels in soil are slightly above natural background [43, 50]. This levels are of health concern since lead is a potent environmental toxin with no known safe exposure level. Even small increases of lead concentration in soil can have adverse health effects, especially over prolonged periods, affecting both children and adults [28].

The level of enrichment by Cadmium from Kedougou region showed a significant enrichment score while Kakamega showed deficiency of enrichment to moderate enrichment. This reveals variations among the two PTEs tested, including the potential health risks that are associated with the two elements in the different regions.

"Significant enrichment" of Cadmium (Cd) in this test signified concentrations above natural background levels, which are the usual concentrations of Cadmium found without human interruptions[41, 50, 62]. This phenomenon is attributed to direct influence of Artisanal and Small-scale Gold Mining [41]. People living in or near ASGM areas, especially vulnerable groups like children, pregnant women, elderly and individuals with existing health conditions, face higher risk of adverse effects due to potential exposure to Cadmium through contaminated mediums [21, 63-65].

Index of geoaccumulation (Igeo)



Table 5 represents the Geo-accumulation index classification levels, given by [45]. Table 6 shows the Igeo Concentration for both sites in Kedougou (Senegal) and Kakamega (Kenya) regions.

Table 5: Classification of Index of geoaccumulation (Igeo) [45][45]

Igeo values	Igeo class	Soil quality
> 5	6	Extremely polluted
4-5	5	Highly polluted
3-4	4	Moderately to highly polluted
2-3	3	Moderately polluted
1-2	2	Unpolluted to moderately polluted
0-1	1	Unpolluted
0	0	Background concentration

Table 6: Index of geoaccumulation concentration in Kedougou (Senegal) and Kakamega (Kenya) regions

Region	Site	Element	Igeo	Igeo Class	Description (Soil quality)
Kedougou region	S1	Lead-Pb	-1.455	0	Background concentration
		Cadmium-Cd	2.779	3	Moderately polluted
	S2	Lead-Pb	-0.921	0	Background concentration
		Cadmium-Cd	2.522	3	Moderately polluted
	S3	Lead-Pb	-1.034	0	Background concentration
		Cadmium-Cd	2.693	3	Moderately polluted
Kakamega region	S1	Lead-Pb	1.511	2	Unpolluted to moderately polluted
		Cadmium-Cd	0.802	1	Unpolluted
	S2	Lead-Pb	0.252	1	Unpolluted
		Cadmium-Cd	0.107	1	Unpolluted
	S3	Lead-Pb	0.618	1	Unpolluted
		Cadmium-Cd	0.238	1	Unpolluted

From the Igeo computations, Kedougou region showed background level concentration for Pb in all the sites while from Kakamega region, the scores indicated moderate pollution for Pb. Similarly, Cd showed moderate pollution in Kedougou region while in Kakamega region, it showed unpolluted level score.

In areas impacted by Artisanal and Small-scale Gold Mining (ASGM), moderately polluted Igeo scores for Lead and Cadmium signify concentrations that are significantly higher than natural background level [45]. These have been attributed by geological differences, the natural composition of the soil and rock in each region, and the waste management strategies. Such



moderate pollution levels have been shown to pose considerable health risks, primarily due to accumulation in the body [66].

Heavy Metal Pollution Index (HPI) Calculation

Table 7: HPI evaluation table according to Majhi and Biswal [46]

HPI Value	Quality of water
0-25	Very good
26-50	Good
51-75	Poor
Above 100	Very poor (unsuitable for drinking)

Table 8: HPI Results for River Gambier water from Kedougou region

Element	vi	Si	Wi= 1/Si	vi/Si	100(vi/Si)	Qi	QiWi	HPI
Lead	0.0374	0.01	100	3.74	374	374	37400	86.30769
Cadmium	0.057	0.003	333.3	19.91	1991	1991	663611	1531
Sum			433.3				701011	1618
Score						HPI	1618	

Table 9: HPI Results for River Isikhu water, Kakamega region

Element	vi	Si	Wi= 1/Si	vi/Si	100(Mi/Si)	Qi	QiWi	HPI
Lead	0.18	0.01	100	18	1800	1800	180000	415
Cadmium	0.05	0.003	333.3	16.67	1666	1666	555555	1282
			433.3				735555	1697
						HPI	1697	

HPI, Heavy metal pollution index, as shown in Tables 8 and 9, indicated values above 100 from both sites, giving indication of contamination levels beyond recommendation for drinking purposes [46].

Heavy Metal Pollution Index (HPI) exceeding 100 in river water signifies a critical level of heavy metal contamination. The HPI takes into account several heavy metals, such as Lead, Cadmium, Mercury, Arsenic, and others. A high score indicates that multiple heavy metals are present in concentrations that are of concern from an environmental and health perspective. Some of the contributors to contamination in water bodies around the ASGM areas were associated to erosion and deposition from mine tailings, which often contain concentrated heavy metals. The presence of multiple heavy metals in high concentrations poses serious health risks to humans and wildlife, harm aquatic life, disrupt food chains, and decrease biodiversity [46, 48].

Water bodies are dynamic system and can receive continuous inputs of pollutants, combined with erosion, sedimentation, chemical use in mining, and the higher bioavailability of waterborne



pollutants, contributes to the higher pollution levels in rivers associated with ASGM compared to the surrounding soils [61]. From observation, Kedougou region has the worst gullies running from areas of mining down to the river Gambier which is surrounded by mining activities in the both sides. Coupled by high temperatures, climate change and high impacts of deforestation to make the mining tunnel walls can be serious health threat if the remedial actions are not put in place. Effects of ASGM activities on water quality in Gurara local government area, Niger state, Nigeria indicated a similar trend in pollution levels directly attributed to mining wastes [67].

Ecological Risk Assessment (ERA) of Soil in ASGM in Kedougou and Kakamega Regions Contamination factor classification

The Cf values is an important factor during ERA [51] it can be categorised to show different levels of contamination as in the Table below:

Table 10: Cf categories [68]

Cf Class	Quality
$Cf < 1$	Non contaminated
$1 < Cf < 3$	Low contamination level
$3 < Cf < 5$	Moderate contamination level
$Cf > 5$	high contamination level

The Cf, PLI and Ecological risk in soils around ASGM in Kedougou and Kakamega are shown in Tables 11 and 12 respectively.

Table 11. Computation of Cf, PLI and Ecological risk in soils around ASGM in Kedougou

Factors	Sites	Element	Ci	Bi	Ci/Bi	(Ci/Bi) - 1
Contamination Factors	S1	Lead	9.575	17.5	0.547143	-0.45286
		Cadmium	1.338125	0.13	10.29327	9.293269
	S2	Lead	13.8625	17.5	0.792143	-0.20786
		Cadmium	1.12	0.13	8.615385	7.615385
	S3	Lead	12.815	17.5	0.732286	-0.26771
		Cadmium	1.26125	0.13	9.701923	8.701923
					Cd	24.68215
			Cf, Pb	-0.928	PLI	-23.78
			Cf, Cd	25.61		23.78
						4.876



Potential Ecological Risks Index (PERI)

	Element	Cf	Tr	Cf*Tr
	Lead	-0.9284286	5	-4.64214
	Cadmium	25.6105769	30	768.3173
			PERI	763.68

Table 12. Computation of Cf, PLI and Ecological risk in soils around ASGM in Kakamega

Sites	Element	Ci	Bi	Ci/Bi	(Ci/Bi)-1
S1	Lead-Pb	74.8	17.5	4.274286	3.274286
	Cadmium-Cd	0.34	0.13	2.615385	1.615385
S2	Lead-Pb	31.27	17.5	1.786857	0.786857
	Cadmium-Cd	0.21	0.13	1.615385	0.615385
S3	Lead-Pb	40.3	17.5	2.302857	1.302857
	Cadmium-Cd	0.23	0.13	1.769231	0.769231
				Cd	8.364
		Cf, Pb	5.364	PLI	16.092
		Cf, Cd	3		16.092
					4.011

Element	Cf	Tr	Cf*Tr
Lead	5.364	5	26.82
Cadmuim	3	30	90
		PERI	116.82

The Elevated Potential Ecological Risk Index (PERI) scores in indicated severe soil and water contamination. The soil contamination compromises agricultural productivity and food security, impacting the livelihoods of local communities as well as endangering aquatic life and human health through exposure to polluted water and food sources. An assessment of PTEs pollution of soil-water-vegetative ecosystems associated with artisanal gold mining in Ghana showed a similar trend of high risk score of enrichments [69].

**Table 13. summary of Cf, PLI and Ecological risk (ERI) in soils around ASGM in Kedougou and in Kakamega Region.**

Region	Element	Cf	PLI	ERI	Contamination level
Kedougou	Lead-Pb	-0.928	4.877	763.67	noncontaminated
	Cadmium-Cd	25.61			high contamination level
Kakamega	Lead-Pb	5.364	4.011	116.82	high contamination level
	Cadmium-Cd	3			Low contamination level

CONCLUSIONS

The ASGM is a major human influence to the environment, significantly posing health risks to human and the ecosystem. Contamination indices indicates the actual burden of pollution associated with PTEs as was revealed in this study and are useful in making interventions to safeguard human and environmental health. Assessment of Lead and Cadmium levels in waste ores, agricultural soil, water and residential soils associated with ASGM in Kedougou region (Senegal, West Africa) and Kakamega region (Kenya, Eastern Africa) revealed presence of Lead-Pb and Cadmium-Cd levels that are of health concern. Cadmium levels and health risks were higher in Kedougou region as compared to Kakamega region. while lead levels from Kakamega were higher than from Kedougou region. Soil contaminatin indices further revealed the health risk burdens associated with individual PTE in the two regions.

RECOMMENDATIONS

Further studies on other PTE should be done, to determine their contamination levels for comparative study across the two regions. This will provide science based information on total PTE levels, contamination levels and their movements patterns across different environmental matrices within the two regions and health risks implications. Other environmental and geological factors that influence the total PTE, their mobility patters and health risk burdens should be assessed.

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