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Geochemical Characterisation of Mine Wastes from Kuchiko Artisanal Gold Mining Areas, Part of Abuja Sheet 186SW North-West Nigeria

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Abstract: *Gold mining is a major environmental concern due to the significant amount of waste it generates. This waste can cause environmental damage and pose a potential threat to the ecosystem and human health. This study therefore aims to characterize the mineralogy and geochemistry of tailings and waste rocks from artisanal gold mining in Kuchiko area, north-central Nigeria using X-ray diffraction (XRD), X-ray fluorescence (XRF) and Atomic Absorption Spectrometry (AAS). Field observations revealed that mining operations had significant physical environmental impacts such as soil erosion and land degradation. The pH values of the samples were in the range of 5.1 to 6.7. Results of XRD analysis identified kaolinite, orthoclase, muscovite and quartz as the dominant minerals in the mine wastes. Result of the laboratory analyses showed the mean concentrations of some potentially toxic elements in mine wastes and tailings to be; Pb (256.86 ppm), As (0.445 ppm), Cu (87.31 ppm). Others are Zn (67.89 ppm), Ni (39.67 ppm), Th (9.723ppm), Ce (325.8 ppm), and Cr (221.63 ppm). Chemical analyses also revealed the mean concentration of Hg to be 8.4 (ppm). The presence of these elements in soils of this area may lead to uptake and accumulation in plants and animals; ultimately making their way into the human diet. Similarly, these elements can also contaminate surface and groundwater in the area, rendering it unsafe for human consumption. Exposure to these elements may result in stunted plant growth, as well as respiratory issues and potential liver and kidney damage in humans.*

Keywords: *Mining, Pollution, Contamination, Trace Elements, Environmental, Health*

1. INTRODUCTION

Mining involves the extraction of mineral deposits from either the Earth's surface or its interior (Obaje *et al.*, 2005; Ako *et al.*, 2014). It is restricted to areas where minerals are both present and economically viable. Worldwide, the mining sector offer jobs to approximately 45 million individuals and indirectly supports an additional 200 to 250 million people, including relatives of employees (Azapagic, 2004). Countless rural families in developing countries depend on artisanal mining to survive. When compared to industrial mining, which employs roughly 7 million people worldwide, artisanal mining supports nearly 100 million people inclusive of labourers and their families (World Bank, 2013).

More than 10 million people are employed globally by artisanal mining, notably for gold, which also has significant negative effects on the surrounding and human health (Hilson, 2006). In Nigeria, a wide range of individuals and mining businesses engage in a variety of mining activities. In Nigeria and by expansion Niger State, the majority of mining operations are conducted by artisanal and small-scale miners who employ uncomplicated and rudimentary technology. Artisanal and small-scale mining activities are currently underway in approximately sixteen (16) out of the twenty-five (25) local government areas within the state (Idris-Nda *et al.*, 2018).

Historical and contemporary mining activities have had a harmful influence on human populations all over the world due to the emission of metals and metalloids (Plumlee and Morman, 2011; Schwarzenbach *et al.*, 2010). This is primarily because regions near active or previous mining operations often contain elevated levels of potentially toxic elements (PTEs) that greatly surpass established human health standards. (Lim *et al.*, 2008; Meza-Figueroa *et al.*, 2009; Taylor *et al.*, 2010). Water, air and soil play crucial roles as pathways for human interaction to PTEs in regions impacted by mining, consequently making them the focus of numerous research investigations (Pearce *et al.*, 2010; Protonotarios *et al.*, 2002).

Gold exploitation by artisans is a frequent occurrence in the Kuchiko regions and many other areas in Nigeria. During gold mining operations, substantial quantities of waste materials are generated, with over 99 percent of the extracted ore in gold mining being discharged into the surrounding environment as waste, predominantly in the form of heavy metals (Adler and Rascher, 2007).

Tailings and waste rocks represent the two most prevalent forms of mining waste (Karen Hudson-Edwards *et al.*, 2011; Lindsay *et al.*, 2015; Parbhakar-Fox and Lottermoser, 2015; Sutthirat, 2011). When the ores are crushed and milled as part of the mineral extraction and processing processes, mine dumps known as tailings are created. They consist of a combination of pulverized rock and processing liquids produced in mills and washeries during the removal and processing of minerals (Karen Hudson-Edwards *et al.*, 2001; Kossoff *et al.*, 2014). Conversely, waste rocks are generated during the unearthing and mining of the ores. Furthermore, the issues of Acid Mine Drainage, which can have significant implications for both human health and ecological deterioration, are often associated with the mining of particular minerals, including copper, zinc, and nickel (Akcil and Koldas, 2006).

In order to gauge the environmental impact of gold mining activities, particularly in regions where unprofessional mining methods are predominant, it is essential to evaluate the characteristics of the generated waste. This assessment should consider factors such as their mineral and chemical composition, levels of heavy metals, their connection to soil, water, and human exposure as well as the degree of pollution they induce. The possible harm that mine waste and drainage could inflict on aquatic ecosystems, drinking water sources and human well-being will be evaluated based on mineral composition, chemical concentrations, acid generation, and the likelihood of metals leaching from mine waste and soils. Sani *et al.*, *(*2021), carried out a study to access trace and heavy metal contamination status of soil and water in artisanal gold mining areas of Kuchiko. The concentration levels of the investigated parameters from the samples collected were compared with World Health Organization (WHO) standard and these parameters were mostly within the permissible levels. In this study, results from the parameter analyzed will be compared with the US Environmental Protection Agency (USEPA) and continental crust by Taylor and Mc Lennan. Also, sample analysis will not only be limited to AAS, but will also include XRD and XRF. Additional methodology will also include environmental pollution Indices and element mobility.

Hence, the specific aim of this study is centred on achieving a comprehensive geochemical characterisation as complete as possible by establishing the composition of waste rock piles and tailings and assessing the acid generating potential, as this is key for any project proposal involving effective measures to mitigate environmental impact and concern.

2. METHODOLOGY

2.1 The Study Area

The research region is part of Suleja town, a significant satellite town situated in proximity to the Federal Capital Territory. It can be accessed through the Suleja-Dikko road. The research region is positioned within Longitudes 7° 10′ E to 7° 11′ 30″ E and Latitudes 9° 15′ N to 9° 18′ N (Fig. 1).

The study site is situated within Abuja sheet 186SW and the geological formations in this region belong to the Basement Complex, encompassing the Migmatite-Gneiss Complex, a Low-Grade Schist Belt and Older Granite. The terrain exhibits a moderately rugged topography, featuring elevated areas exceeding 2000 feet or 600 meters above sea level.

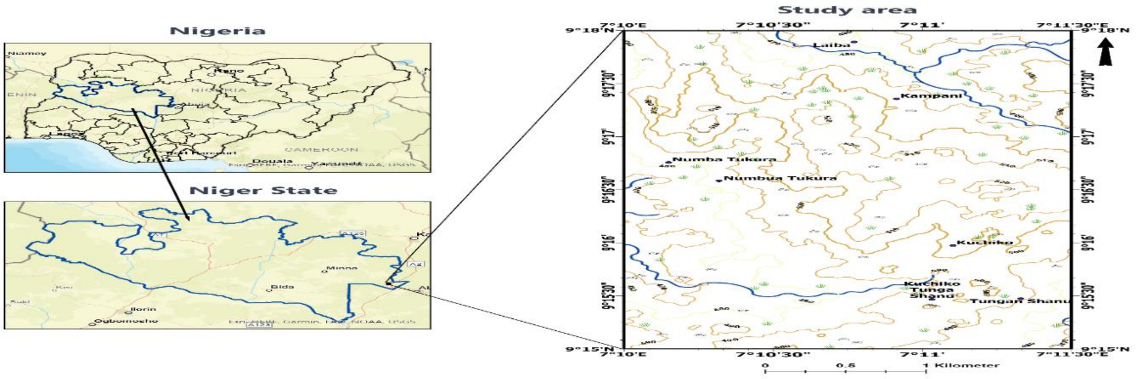

Fig1: *Location of Kuchiko artisanal mining area*

The study area experiences a tropical climate consisting of distinct dry and wet seasons. It has a yearly mean temperature of 26.3°C, and an average annual rainfall of 1405 mm. December stands as the driest month, while the peak precipitation occurs in September, with a mean of 272 mm. March emerges as the warmest month of the year, with a mean temperature of 30°C, whereas the lowest mean temperature is recorded in August at 24.5°C (Aminu et al., 2013), attributed to the frequency of rainfall. The vegetation primarily consists of savannah, characterized by shrubs, grasses and sparse tree coverage of moderate height and size.

2.2 Fieldwork and Sampling

This study involved geological mapping of the study area on a scale of 1:12,500 using a topographic map as the base map. After an in-depth study of the subject matter was done, sampling was carried out based on field observations.

Tailings, waste rocks and surrounding soils were collected in plastic bags and stored properly prior to analysis. The soils adjacent or surrounding mine locations may be contaminated from various sources such as tailings and ponds, along with different pathways like wind erosion and water flows, affecting various receptors including humans and agricultural soils among others. Therefore, it was important to collect soil samples from these areas, as this step is essential for comparing the levels of potentially hazardous elements with the concentrations found in the mines. A total of 21 samples were collected (Table 1), with 16 samples (soils, tailings, waste rock, pulverized rocks from the processing plant and stream sediment) from the mining sites and 5 rock samples from the outcrop locations. All samples were carefully collected, properly stored and then transported to the National Geo-Science Research Laboratory (NGRL) of the Nigerian Geological Survey Agency (NGSA) Kaduna and Centre for Dryland Agriculture, Kano for analysis.

Table1: *Sample location, sample ID and description*

LATITUDE (N)	LONGITUDE (E)	ID	TYPE	DESCRIPTION
9^{0} 15’ 47’’	7^{0} 10’ 46’’	CM 01	rock	Waste rock from mine pit
		CM 02	Sand	Waste sand from mine pit
		CM 03	soil	Soil from farmland
9^{0} 16’ 59’’	7^{0} 10’ 34’’	CM 04	rock	Waste rock from mine pit
		CM 05	rock	Host rock from the mine pit
		CM 06	sand	Waste sand from the mine pit
		CM 07	soil	Soil from farmland
9^{0} 16’ 19’’	7^{0} 11’ 10’’	CM 08	Rock	Waste rock from mine pit
		CM 09	sand	Waste sand from mine pit
9^{0} 16’ 13’’	7^{0} 11’ 11’’	CM 12	sediment	Stream sediment 1
		CM 14	sediment	Stream sediment 2
9^{0} 16’ 13’’	7^{0} 11’ 09’’	CM 10	tailing	Tailing from the processing plant
		CM 11	soil	Soil from farmland beside the plant
		CM 13	powder	Pulverized rocks from the processing plant
9^{0} 17’ 38’’	7^{0} 11’ 06’’	CM 15	tailing	Tailing from the mine site
		CM 16	soil	Soil from farmland

2.3 Laboratory Work

2.3.1 Sample preparation

This stage involves sample preparation for paste pH, mineralogical and geochemical analysis. Solid samples (soils and tailings) were air dried at room temperature for about 2-3 days, sieved through a 2mm sieve and kept in polythene bags at room temperature before analysis. Samples were analyzed for their elemental and mineralogical composition using X-ray fluorescence (XRF) X-ray diffraction (XRD) methods respectively at the National Geo-Science Research Laboratory (NGRL), Kaduna.

2.3.2 X-ray diffraction (XRD) Analysis

The NGRL utilizes the Empyrean diffractometer equipped with a copper anode material manufactured by PANalytical. It operates in conjunction with various other components, including a water chiller responsible for cooling the X-ray tube and maintaining a consistent temperature. The material under examination underwent a thorough process of fine grinding and homogenization to establish its average bulk composition. The analysis of the sample was conducted utilizing the reflection-transmission spinner stage, employing the Theta-Theta configuration. The Two-Theta starting position was set at 5 degrees, concluding at 80 degrees, with a Two-Theta step increment of 0.026261 and each step lasting 30 seconds. The tube current was maintained at 40mA, with a voltage of 45VA applied. Additionally, a Programmable Divergent Slit with a 5mm Width Mask was employed and the Goniometer Scan feature was activated.

2.3.3 X-ray fluorescence (XRF) Analysis

The analysis was conducted using an Energy Dispersive X-ray Fluorescence (EDXRF) spectrometer specifically the "Epsilon 4" model from PANalytical. The samples were crushed (reduced to fine powder) employing the Retsch PM 400 planetary ball mill. Care was taken to ensure that the ground samples passed through 150-micro mesh sieves. Subsequently, the powdered samples were appropriately packaged and labelled, all set for the analysis.

For each analysis, 20g of the prepared samples were precisely weighed into individual sample cups. The choice of filters was based on a specific periodic table utilized for elemental analysis. The measurement duration for each sample was 100 seconds and air was used as the medium throughout. LOI was determined gravimetrically by heating 1g of the powdered sample in a cleaned weighed crucible at 1000oc. After which the crucible and the content was weighed to get the difference in weight before and after heating.

2.3.4 Atomic Absorption Spectrometry (AAS) Analysis

The extraction of trace metals from the soil samples was conducted following the procedure originally outlined by Crock et al. (1983) with slight modifications. Approximately 2.5g of sieved sample was subjected to a multi-acid digestion process, which involved dissolution in hot nitric acid (HNO3) 7ml, followed by a combination of 2 ml hydrogen peroxide (H2O2) and 1 ml perchloric acid (HCLO4). The samples were subsequently digested on a hot plate at a temperature of 150°C for a duration of 1 hour. Following this, the solution was allowed to cool and filtered through Whatman No. 40 filter paper before being adjusted to the 50 ml mark with distilled water. Procedural blanks were also prepared and aspirated alongside the analytical samples to correct for background absorption. The detection limit for the metal was 0.001ppm while that of the blank was 0.00ppm. Values for precision expressed as RSD% were less than 5% for most elements except for mercury.

2.3.5 Paste pH

Paste pH is a static technique used in soil science. The pH values of the samples were promptly assessed following collection, employing the Hanna HI 9811-5 portable pH meter. Ten grams of soil material were weighed into a beaker and combined with distilled water in a solid-to-solution ratio of 1:1, adhering to the guidelines recommended for use in metal mining studies in British Columbia as described by Price (1997). Ten millilitres of distilled water were quantified using a plastic graduated cylinder and introduced into the sample. Likewise, the electrical conductivity of the samples was determined using the same meter.

3. RESULTS AND DISCUSSION

3.1 Geology

The geologic mapping of Kuchiko area revealed that the region is outcropped by Migmatite, Gneiss, Low-Grade Schist and Granite (Fig 3). Within the granite and gneiss members lies the quartz vein that miners excavate and explore in search of gold. Gneiss members are more prevalent than granite, covering about 45 % of the study area (Plate I). These formations are typically found at lower elevations and exhibit a mix of light and dark colours, characterized by a medium to coarse grain texture. The rock's mineral composition primarily consists of quartz, feldspar, and mica. The schist exhibits slight weathering and foliation, characterized by a medium to coarse-grained texture. The granites are light in colour and texturally, they are fine to medium grained.

PlateI: *Gneiss outcrop in the study area*

9° 16′ 50″ 7° 10′ 44″

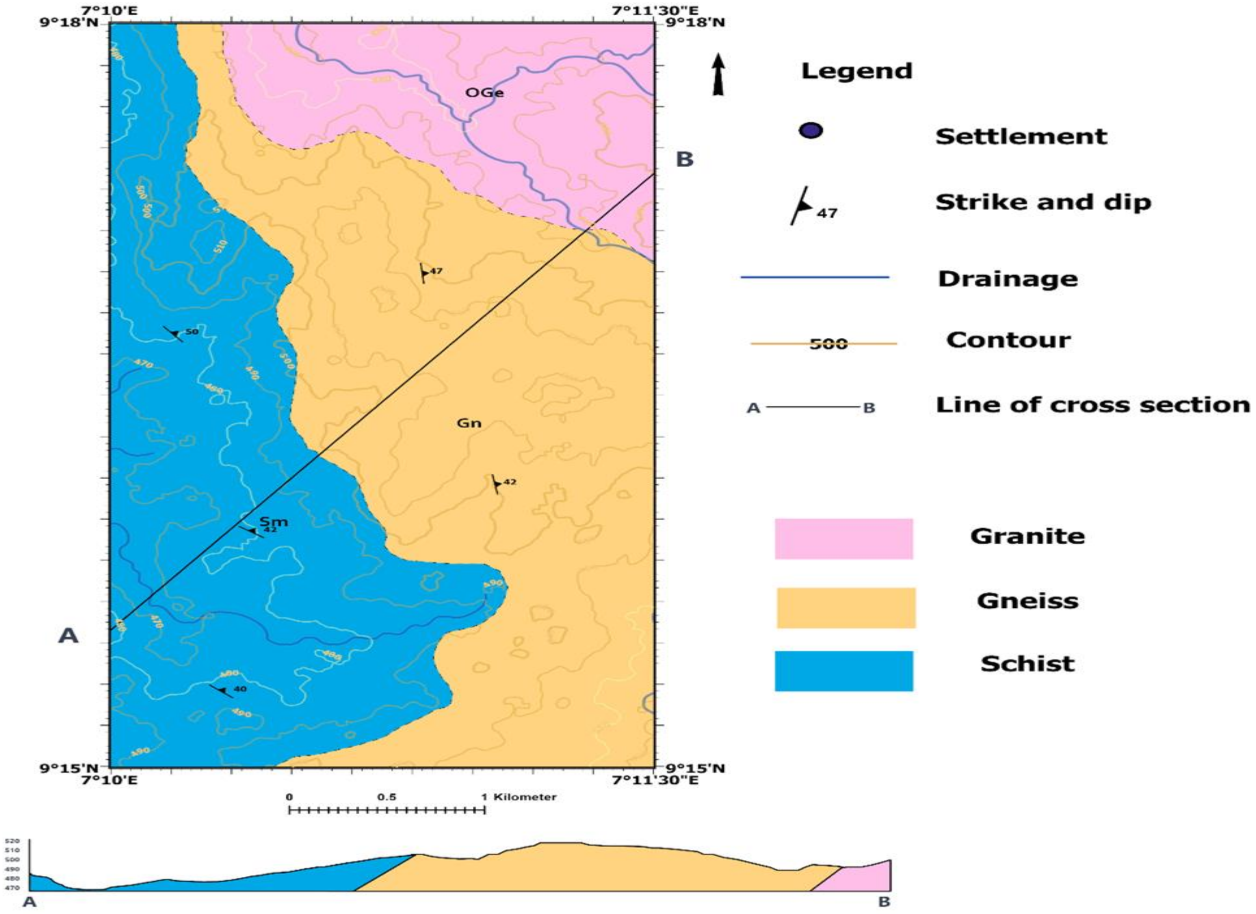

Fig3: *Geology of Kuchiko area, NW Nigeria*

3.2 Laboratory Results

3.2.1 Physical Parameters

The electrical conductivity (EC) and pH results of the soil samples showed substantial variations. The EC values varied approximately from 30 µs/cm to 380 µs/cm (**Table 2**). The lowest and highest EC values were measured in sample CM02 and CM13 respectively. The pH values of the samples were in the range of 5.1 to 6.7. The lowest pH value was measured in sample (CM07) while the highest pH value was also observed in sample (CM02).

Table2: *pH, EC and TDS data in soils and mine wastes from Kuchiko area*

Samples	pH	EC (µs/cm)	TDS(mg/l)
CM 02	6.7	30	10
CM 06	6.1	40	10
CM 07	5.1	170	80
CM 09	5.6	50	20
CM 10	6.2	40	10
CM 11	6.4	250	110
CM 12	6.0	90	40
CM 13	6.2	380	140
CM 15	6.0	40	10
CM 16	5.5	190	90

It is also important to highlight that the generation and persistence of acidity are predominantly influenced by the type of sulfide mineral undergoing oxidation, the reaction mechanism, and the presence of minerals that can neutralize acid, such as carbonates and aluminosilicates. Silicate minerals, which constitute the majority of minerals present in the Earth's crust, serve as the primary reservoir for buffering capacity within the environment (Lottermoser, 2010). The dissolution of silicate minerals like quartz, orthoclase, and plagioclase feldspars can also act to counterbalance acidity (Lapakko, 2002). However, their dissolving rates and the subsequent acid neutralization are comparatively slower when compared to carbonate minerals.

3.2.2 Mineralogy

The waste materials and soils from Kuchiko were studied using the XRD technique. The chosen samples for the mineralogical analysis were two samples of the waste rock (CM01 and CM04), two samples of the tailing (CM10 and CM15) and the pulverized powder from the processing plant (CM13). The powdered samples were analyzed using an Empyrean diffractometer. The mine waste exhibits a largely similar mineralogical composition, mainly comprising primary minerals derived from igneous or metamorphic host rocks: quartz (12-77 wt%), albite (3-7 wt%), muscovite (3-23 wt%) and feldspar (6-16 wt%) (**Table 3**). Minor minerals are visible in principal amounts in some of the areas in Kuchiko. Traces of other minerals like anorthite, anthophyllite, biotite and potassium aluminium silicate were also detected. Quartz, muscovite and orthoclase were present in all samples, were as anthophyllite and potassium aluminium silicate are present only in the pulverized rocks gotten from the processing plant. Kaolinite and biotite are present only in the sample CM15 (tailing).

Table 3: *Mineralogical composition (w%) of the studied samples from Kuchiko*

Minerals	Formula	CM O1	CM 04	CM 10	CM 13	CM 15
Quartz	SiO_2	47	77	53	12.2	44
Muscovite	$KF_2(Al_2O_3)_3(SiO_2)_6$	3	4.9	23	4	2.4
Orthoclase	$KAlSi_3O_8$	14	13.7	16.4	6	10.6
Albite	$NaAlSi_3O_8$	3	4	7.3	-	-
Biotite	$K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$	-	-	-	-	7.1
Anorthite	$CaAl_2Si_2O_8$	33	-	-	-	-
Kaolinite	$Al_2Si_2O_5(OH)_4$	-	-	-	-	36
Anthophyllite	$(Fe,Mg)_7Si_8O_2(OH)_2$	-	-	-	24	-
Potassium Al. silicate	$KAlSiO_4$	-	-	-	54	-
Sum		100	99.6	99.7	100.2	100.1

3.2.3 Major and Trace Element Geochemistry

The findings show that for the Kuchiko area **(Table 4),** the mean (± std. dev) concentrations (wt %) of SiO_2, TiO_2, Al_2O_3 and Fe_2O_3 are 69.0 ± 11.7, 0.7± 0.4, 15.7 ± 5.9 and 5.5± 3.4 respectively. The results for MgO, CaO, K_2O and Na_2O are 1 ± 1.4, 0.9 ± 1.6, 3.0 ± 1.6 and 6.4 ± 0, while MnO and LOI give 0.06 ± 0.03 and 3.4 ± 2.1 respectively. From these results, it can be observed that the silica, alumina and iron contents are high, while there was a decrease in some of the alkalis compared to their published crustal average values (Taylor and McLennan, 1985, 1995). The high SiO_2 content can directly be linked to the silicate mineral phases in the samples (quartz and aluminosilicates), while the Fe_2o_3 can be linked with Fe presence in clay minerals more evident in sample CM15. Likewise, the soils in this region typically exhibit a low organic matter property, as evidenced by the low mean percentage of loss on ignition, LOI %.

The result of the XRF analysis from which the potentially toxic element was summarized in Table 4, along with published concentrations and guideline for soil concentrations, shows that the concentration of Pb, Cu, As, Cr and Zn in the Kuchiko samples ranges from 0.27 to 467.4 µg/g with a mean (± standard deviation) of 256.9 ± 146.3 µg/g; 37.2 to 334.1 with a mean of 87.3 ± 81.3 µg/g; 1.4 to 3.5 with a mean of 0.5 ± 1.1 µg/g; 46.4 to 554.6 with a mean of 221.6 ± 141.9 µg/g and 19.3 to 204 µg/g with a mean of 67.9 ± 64.9 µg/g respectively, while the concentration of Ni ranges from 2.1 to 208.4 µg/g with a mean of 39.7 ± 59.0 µg/g.

The results were compared with the guideline values for potential toxic elements in soils (USEPA) and this revealed that the concentration of Ni, Pb, Cu, Zn and Cr in the Kuchiko area is higher than the values set for soils by the United States Environmental Protection Agency (USEPA), The presence of these elements in soils and sediments at levels above the permitted maximums poses substantial risks to the environment and public health.

Table 4: *Summary of XRF data for major (wt. %) and trace elements (ppm) in soils and mine wastes from Kuchiko area, along with published concentrations and soil guideline values for some potentially toxic elements.*

Element	This work					Cont. Crust	Soils
	Min	Max	Mean	Med	Std. Dev.	A	B
Al_2O_3	1.3	28.0	15.7	16.2	5.9	15	
Si_2O_2	49.3	96.7	69.0	68.5	11.7	66	
P_2O_5	0.3	0.6	0.5	0.5	0.1	0.2	
SO_3	0.02	0.2	0.1	0.1	0.1	1.5	
K_2O	0.8	5.4	3.0	3.1	1.6	3.4	
CaO	0.1	4.9	0.9	0.4	1.6	4.2	
TiO_2	0.03	1.4	0.7	0.7	0.4	0.5	
Na_2O	6.4	6.4	6.4	6.4	0	3.9	
MgO	0.2	4.4	1.0	0.5	1.3	2.2	
MnO	0.0	0.1	0.1	0.1	0.0	0.1	
Fe_2O_3	0.4	10.1	5.5	5.6	3.4	5	
L.O.I	0.5	7.4	3.4	3.3	2.1		
pH	5.1	6.7	6.0	6.1	0.5		
V	23.7	339.7	206.6	278.6	128.6	60	
Cr	46.4	554.6	221.6	201.7	141.9	35	68
Ni	2.1	208.4	39.7	16.9	59.0	20	22
Cu	37.2	334.1	87.3	62.8	81.3	25	22
Zn	19.3	204.0	67.9	37.9	64.9	71	66
Zr	0.1	777.0	287.4	197.0	292.6	190	
Ga	11.0	47.2	20.9	16.1	11.5	17	
As	1.4	3.5	0.4	0.0	1.1	1.5	-
Rb	14.6	316.7	112.9	85.9	88.8	112	
Sr	26.3	762.3	390.5	328.8	237.1	350	
Y	10.0	54.9	26.0	21.9	16.0	22	
Nb	11.1	25.8	18.1	18.0	5.9	25	

Sn	50.4	225.5	159.5	171.4	59.7	5.5	
Sb	47.1	47.1	47.1	47.1	0.0	0.2	
W	71.6	71.6	71.6	71.6	0.0	2.0	
Te	41.2	68.4	57.8	60.8	12.0		
Ce	46.5	867.1	325.8	63.9	468.8	64	
Pb	0.3	467.4	256.9	316.5	146.3	20	30
Th	1.8	18.4	9.7	7.6	6.0	10.7	
Ba	48.8	933.5	427.8	453.1	285.6	550	

a: Upper continental crust, Taylor and McLennan, 1985, 1995; b: USEPA (1996) soil guideline values.

3.3 Contamination Indices

3.3.1 Enrichment ratio

Enrichment ratios as discussed by (Albright, 2004; Tijani *et al.*, 2006) were computed to evaluate the degree of enrichment or depletion of trace elements within the soils of Kuchiko area, with regards to their natural crustal levels. In this study, the Upper Continental Crust concentrations of these elements as established by Taylor and McLennan in 1995 was adopted as the baseline or reference values, and the enrichment ratio (ER) was determined using the equation:

ER= Cn/Bn

With C_n representing the concentration of an element as determined in a sample, and B_n signifies the background or baseline concentration, specifically referring to the upper crustal concentration of the element as outlined by Taylor and McLennan (1985, 1995). An enrichment ratio of 1 signifies that the soil or sediment demonstrates no enrichment or depletion of a specific element when compared to the average crustal concentration. Conversely, an ER greater than (>)1 or less than (<)1 serves as an indicator of either enrichment or depletion, respectively.

Based on the ER classification, elements such as Cu, Ni, Cr, Zn, and Pb were observed to be enriched in comparison to their natural crustal levels (Taylor and McLennan, 1985, 1995). It is worth noting that the enrichment ratio for Sb, Sn, and W significantly surpasses the average crustal concentration. Table 5 shows the summary of enrichment ratio for the elements.

Table 5: *Summary of enrichment ratios, ER for the samples from Kuchiko area*

Element	**Enrichment ratios, ER**		
	Kuchiko		
	Mini	**Maxi**	**Mean**
V	0.4	5.7	3.4
Cr	1.3	15.9	6.3
Ni	0.1	10.4	2.2
Cu	1.5	13.4	3.5
Zn	0.3	2.9	1.0
Zr	0.0	4.1	1.5
Ga	0.7	2.8	1.2
As	0.9	2.3	1.6
Rb	0.1	2.8	1.0
Sr	0.1	2.2	1.1
Y	0.5	2.5	1.2
Nb	0.4	1.0	0.7
Sn	9.2	41	29.0
Sb	235.5	235.5	235.5
W	35.8	35.8	35.8
Ce	0.7	13.6	5.1

Pb	0.0	23.4	12.8
Th	0.2	1.7	0.9
Ba	0.1	1.7	0.8

Mini: minimum; Maxi: maximum

3.3.2 Index of Geoaccumulation

One of the techniques employed for estimating the enrichment of an element's concentration above background or baseline levels involves the computation of the geoaccumulation index, *Igeo*, as proposed by Muller (1969). This approach serves as a means to gauge the extent of pollution through the utilization of seven enrichment classes, determined by an increase in the numerical values on the scale (**Table 6**)

Table6: Classes of the index of geoaccumulation, *Igeo* (Muller, 1969).

I_{geo} Value	I_{geo} class	Pollution intensity
>5	6	Extremely polluted
4-5	5	Strongly to extremely polluted
3-4	4	Strongly polluted
2-3	3	Moderately to strongly polluted
1-2	2	Moderately polluted
0-1	1	Unpolluted to moderately polluted
0	0	Unpolluted

The index of geoaccumulation, *Igeo* was computed for all the samples from the Kuchiko area according to the equation by (Muller, 1969):

I_{geo} = Log2(Cn/1.5Bn)

where C_n represents the concentration of the element measured in a given sample and B_n denotes its concentration in a reference sample or the background concentration, which, in this context is the average crustal value established by Taylor and McLennan (1985, 1995). Additionally, a constant value of 1.5 is introduced to minimize the influence of the variations of background values (Abrahim and Parker, 2008). A summary of the outcomes for Kuchiko area is provided in **Table 7**.

Table7: Summary of statistics of *Igeo* for the samples from Kuchiko area

Element	Indices of geoaccumulation, I_{geo}		
	Kuchiko		
	Min	**Max**	**Mean**
V	-1.9	1.9	0.7
Cr	-0.2	3.4	1.8
Ni	-3.8	2.8	-0.6
Cu	-0.0	3.2	0.9
Zn	-2.5	0.9	-1.2
Zr	-11.1	1.5	-3.1
Ga	-1.2	0.9	-0.4
As	-0.7	0.6	-0.0
Rb	-3.5	0.9	-1.0
Sr	-4.3	0.5	-0.9
Y	-1.7	0.7	-0.6
Nb	-1.8	-0.5	-1.1
Sn	2.6	4.8	4.1
Sb	7.3	7.3	7.3
W	4.6	4.6	4.6

Ce	-1.1	3.2	0.5
Pb	-6.8	4.0	2.2
Th	-3.2	0.2	-1.1
Ba	-4.1	0.2	-1.4

Min: minimum; Max: maximum

With regards to the *Igeo* classifications outlined in **Table 6**, the results of this study, as presented in **Table 7**, indicate potential contamination concerns for Sn and Pb in the Kuchiko area. With mean *Igeo* values of 4.1 and 2.2, these elements fall into class 5 and class 3, respectively, on the Muller 1969 scale. This suggests that the soils from the region are extremely polluted and strongly polluted with regards to the elements.

3.4 Element Mobility

Trace element contamination is caused by both natural environmental processes like weathering of rocks and anthropogenic activities (Sarkar *et al.*, 2014). The mobility of trace elements is dictated by their chemical form within the environment. Anthropogenic elements in ionic and carbonate forms exhibit the highest mobility, whereas elements bound to silicates and primary minerals, on the other hand display restricted mobility (Klink *et al.*, 2019; Morillo *et al.*, 2008). Because total trace element analysis does not give enough information to assess the hazards linked with mobility, procedures that allow for the determination of particular metal fractions are used.

Table 8 shows the result of AAS analysis carried out on selected elements. From the trace elements analyzed, Hg, Cr, Pb, Cu, Cd, Ni, Fe and Zn were specifically selected due to their prevalence in the waste materials and their inclusion in the primacy contaminant lists of environmental protection agencies. The data shows high concentrations of Hg and Fe in the Kuchiko samples ranging from 0.6 to 10.3 with a mean (± standard deviation) of 8.4 ± 2.9 µg/g and 14.3 to 15.6 with a mean of 15.0 ± 0.5 µg/g, while the concentration for Cd is the least with values ranging from 0.0 to 0.1 and a mean of 0.1 ± 0.0 µg/g.

Table8: *Summary of AAS data for trace elements (ppm) in soils and mine wastes from Kuchiko area along with published concentrations.*

Element	This work								
	Min	**Max**	**Mean**	**Med**	**Std. Dev.**	**a***	**b***	**c***	**d***
Cd	0.0	0.1	0.1	0.1	0.0	0.1		0.1	
Cr	1.4	4.2	2.4	2.4	0.9	35		126	
Cu	0.5	3.9	1.6	1.3	1.1	25		14.3	
Hg	0.6	10.3	8.4	9.0	2.9	0.04	0.023	0.056	6.25
Ni	1.2	1.8	1.1	1.2	0.4	20		18.6	
Pb	1.0	4.7	2.2	2.0	1.1	20		17	
Zn	0.0	0.3	0.1	0.0	0.1	71		52	

Min: minimum; Max: maximum; Med: median; Std. Dev; standard deviation; a: Upper continental crust, Taylor and McLennan, 1985, 1995; USEPA (SSL) 1996 c: Wedepohl, 1995; d: Anka, Zamfara (Lar Uriah *et al.*, 2013).

The mean concentration of Hg obtained from the samples is higher than the published concentration. This outcome was predictable, given the utilization of mercury amalgamation methods in the processing of gold ore at the mining sites in Kuchiko. This level of Hg concentration calls for concern as exposure to high levels of mercury in any form has been found to be a contributive agent for various disorders (Odukoya *et al*., 2021).

With the result of the AAS analysis, it is possible to get the percentage of mobile trace element capable of leaching into the environment from the bulk geochemistry result. The leachable fraction was derived by dividing the average concentration of individual element from the AAS data by the average concentration of the elements from the bulk geochemical data (XRF) multiplied by 100. **Table 9** shows the percentage of elements that can be leached into the wider environment from each sample location.

Table9: *fraction of elements (%) that might be leached into the environment*

Element	CM 04	CM 06	CM 07	CM 09	CM 10	CM 11	CM 12	CM 13	CM 15
Cr	0.5	1.6	3.8	1.3	1.1	3.1	0.5	0.8	2.4
Cu	4.3	2.5	2.1	2.3	0.5	4.5	0.7	1.4	1.1
Fe	0.2	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.0
Ni	0.3	4.5	55.5	13.8	7.6	20.8	4.9	0.8	1.8
Pb	1.3	0.7	0.6	0.6	1561.3	0.6	0.4	0.7	0.4
Zn	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.3

From the calculation, it can be said that there is no risk related to the release of Zn into the wider environment as it has a very low mobile percentage rate. The mobile percentage rate of Pb, Cr and Cu are also low, while the rate is high for Ni in samples CM06, CM07, CM09, CM10, CM11 and CM12 (4.5 %, 56 %, 13 %, 7 %, 21 % and 5 % respectively). Surprisingly, the highest proportion of potential mobile fraction was found for Pb in sample CM10. The primary trace metals with leaching potential from the mine waste include Ni, Cu, Cr, and Pb.

4. CONCLUSION

Artisanal gold mining is a common source of income in the Kuchiko region. However, its operations are harmful and have exacerbated environmental and human health issues. To assess the potential environmental impact of both the mine wastes and the surrounding soils within the research area, samples were collected and analyses were performed.

Chemical study and summary statistics data show that the soils of Kuchiko and wastes have much higher concentration of Pb, Cu, Ni, Zn, Sn and Cr when compared to both USEPA guideline value for potentially toxic elements in soil and the upper continental crust value. This study demonstrates that the combined application of geochemical and mineralogical methodologies can provide an environmental characterization of active or closed mining sites, enabling for the evaluation of potential contamination and the extent of impacted zones. Nearly all of the studied samples clearly show the mineralogical and geochemical characteristics of the ore mineralization. Quartz, kaolinite, biotite, orthoclase, muscovite and anorthite are among the minerals that was identified by XRD. Significantly high contents of mercury were identified by the AAS analysis in the bulk of the soils and mine wastes, reflecting the related environmental hazards linked with the mine. Agricultural soil samples surrounding the mine areas show notable amounts of Pb, Fe, Hg and Sn but lower Arsenic content. The presence of these elements in soils and sediments at levels above the permitted maximums poses substantial risks to the environment and public health.

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