

Research Article

# Concentration Levels of Heavy Metals in Tailings, Water and Sweet Potatoes in Artisanal Gold Mining Areas of Kuria West Sub-county, Kenya

**John Gichimu Mbaka<sup>1,\*</sup> , Julius Kioko Nzeve<sup>1</sup> , Consolate Awuor Okoth<sup>2</sup> , Alexander Gori<sup>1</sup>**

<sup>1</sup>Department of Environmental Sciences, Machakos University, Machakos, Kenya

<sup>2</sup>Department of Health Sciences, Machakos University, Machakos, Kenya

## Abstract

Artisanal gold mining is an important economic activity in many regions of the world. However, mining activities can lead to the production of large quantities of heavy metal laden wastes which can result to widespread contamination of the environment. This study investigated the levels of heavy metals (Cr, Cu, Zn, As, Cd and Pb) in gold mine tailings, panning pond water, river water and sweet potatoes obtained from Kuria West Sub-County, Kenya and evaluated potential health risks among local residents. One-way analysis of variance (ANOVA) was used to test significant difference ( $p < 0.05$ ) of heavy metal concentrations across the different sampling sites. The mean concentrations for heavy metals such as chromium, copper, arsenic, cadmium and lead differed significantly ( $p < 0.05$ ) among the study sites for tailings. With regard to river water all the heavy metals differed significantly among the study sites ( $p < 0.05$ ). For sweet potatoes, there was no significant difference recorded ( $p > 0.05$ ) between the study sites. Results showed that tailings had the highest heavy metal mean concentrations (mg/kg) of As (946.45 – 2789.88), Pb (31.71 – 366.21), Zn (54.17 – 118.07), Cr (34.14 – 87.42), Cu (16.97 – 55.52) and Cd (0.32 – 1.85). Heavy metal concentrations in panning ponds water were comparatively lower (i.e.,  $< 2\text{mg/l}$ ) and were within the same range (0.0001 – 1.26mg/l). Heavy metal concentrations in river water (mg/l) recorded were Cr (0.031 – 0.184), Cu (0.063 – 4.058), Zn (0.097 – 0.824), As (0.002 – 0.666), Cd (0.0001 – 0.0036) and Pb (0.008 – 0.009). The concentrations of heavy metals recorded at the downstream sampling site except Zn exceeded World Health Organization (WHO) set limit for drinking water. The average concentrations for heavy metals in sweet potatoes such as chromium (3.32mg/kg), zinc (12.02mg/kg), Pb (0.44mg/kg) and As (0.31mg/kg) exceeded WHO set limit while Cu (7.57mg/kg) and Cd (0.08mg/kg) were within the recommended levels. The presence of heavy metals (Cr, Zn, Pb, and As) in higher concentrations than WHO set limits for sweet potatoes poses a health risk to the residents of Kuria west. In conclusion, it is recommended that mining activities should be regulated and licensed by relevant government agencies. Tailings and waste waters emanating from mining activities should be kept safely before treatment and disposal. Continuous monitoring of heavy metals should be undertaken to determine heavy metal concentrations in areas close to gold mines and further tests should be undertaken to determine heavy metal concentrations in soil, other crops, air and ground water.

## Keywords

Contamination, Mining, Artisanal Mining, Livelihood, Environment

\*Corresponding author: mbakagichimu@gmail.com (John Gichimu Mbaka)

**Received:** 28 July 2025; **Accepted:** 6 August 2025; **Published:** 2 September 2025



## 1. Introduction

The African continent has rich reserves of mineral resources and globally, it is ranked second in terms of quantity of minerals such as phosphorite, bauxite, uranium, cobalt, diamond, zirconium and platinum among many others [1, 2]. Although mining of mineral resources is an important economic activity, it is one of the major sources of heavy metals in the environment [3, 4]. Heavy metals refer to metals and metalloids having densities that exceed  $5\text{g/cm}^3$  [5]. Although certain heavy metals are important for plant growth, crops that are grown in soils contaminated with heavy metals can accumulate toxicants in levels above permissible limits. For example, cadmium, lead, arsenic and mercury are not vital for plant growth because they do not perform any functions in plants. However, metals such as iron, copper and zinc are important elements required for the growth of plants, although these metals can easily cause pollution if their concentrations exceed the permissible limits [6].

Artisanal gold mining is a profitable economic activity that serves as a source of income and livelihood for millions of people around the world [7]. In many developing countries, artisanal gold mining is increasing due to increase in the price of gold and poverty [8]. It is estimated that approximately 15 million people engage in artisanal gold mining activities as miners and many more people directly or indirectly depend on artisanal gold mining as their source of livelihood [9]. The benefits of artisanal gold mining include creation of job opportunities for local communities, development of infrastructure and contribution to a country's economy [7]. Despite these benefits, artisanal gold mining has deleterious effects on the environment and human health [10-12]. Artisanal gold mining operations are largely unregulated and the miners have less skills and knowledge to manage the various environmental and health related challenges that may emanate from mining operations [13, 14].

Artisanal gold mining industry experiences environmental challenges since its operations utilizes chemicals such as mercury during extraction of gold [14, 15]. Additionally, the ore from which gold is obtained may naturally contain heavy metals such as cadmium, lead, copper, arsenic and lead which contaminate the environment [16]. Once the extraction of gold from ore is complete, the solid (e.g., tailings) and liquid (e.g., panning ponds water) wastes emanating from the mining process are discarded into the environment. The heavy metals contained in these mining wastes contaminate environmental media such as soil, sediments, water and air and accumulate in living organisms and humans, causing various health effects [17-19]. For example, Palapa and Maramis [17] evaluated heavy metals in water of a stream flowing near gold amalgamation tailing ponds in Indonesia and found that the mean concentrations for heavy metals such as arsenic, chromium, and lead were relatively high and exceeded the world's average content of heavy metals in river water. Another study assessed

the effect of artisanal gold mining activities on heavy metals pollution in soil, stream sediments, well water and plant samples in Ghana [18]. The study found that both well and river water samples were contaminated with heavy metals and were unsuitable for consumption because of high levels of lead, cadmium and mercury. Additionally, heavy metals enrichment factors indicated that soil and sediments were contaminated with cadmium and mercury. The soil had about two times more mercury than river sediments and the concentration of heavy metals in corn exceeded the maximum limits permitted by the Food and Agricultural Organization and WHO standards. A study conducted in Kenya evaluated the effect of artisanal gold mining on heavy metal levels in fish, maize, cabbages, mangoes, potatoes and human hair to establish potential health risks posed to miners and local communities who obtain food resources from the area located near the gold mines [20]. The study found that the concentration levels of lead, cadmium, zinc and nickel in soil was higher than the maximum limits for agricultural soil. Additionally, the concentration levels of heavy metals in fish exceeded the maximum allowable concentrations for consumption. With regard to food crops, maize had the highest mean mercury concentrations followed by cabbages and potatoes and human hair had elevated nickel and zinc concentrations.

Heavy metals cause various health challenges in humans such as kidney diseases, impairment of intellectual ability, gastrointestinal problems, cancer, nervous system disorders, cardiovascular disorders and subsequent death [21-23]. Apart from humans, heavy metals modify plant growth by affecting physico-chemical and biochemical functions such as nutrient uptake and translocation and photosynthetic activity [23, 24]. In soil, heavy metals have an impact on chemical and biological processes, such as impairment of microbial activities [25]. Water resources such as rivers, lakes and ground water which acts as sources of water and habitat for animals may become degraded [26].

In Kenya, artisanal gold mining is an important economic activity. However, gold mining has potential effects on environment and human health. The objectives of this study were to: (i) determine and compare the concentration levels of heavy metals in tailings, panning ponds water, river water and sweet potatoes collected from different areas in Kuria West sub-county, Kenya, and (ii) recommend strategies which can be used to reduce the impact of artisanal gold mining on the environment.

## 2. Materials and Methods

### 2.1. Description of Study Area and Sites

The study was conducted in Kuria West sub-county, Migori County, Kenya. The Migori County is found in the

Lake Victoria basin which is volcanic in nature and has rich deposits of metals such as gold [10]. In addition to Kuria West sub-county, the Migori gold belt covers other sub-counties such as Suna West, Nyatike, Rongo and Kuria East. With the exception of mining, other economic activities in the Kuria West region include agricultural activities. Many families own gold mines and shafts and depend on it as a source of livelihood. They also participate in gold processing activities within the region. Families also participate in agricultural activities and plant crops such as tobacco, maize, beans and sweet potatoes. Area residents also engage in micro-enterprise and trade activities as mechanics, tailors, welders, masons, carpenters and traders. The area has two main rainfall seasons, with long rains falling between March and May and short rains falling between October and December. The annual rainfall amount ranges between 1000 mm and 2600 mm and temperature ranges between 24 °C and 31 °C [27]. Soil in the area is mainly composed of silty clay and loamy soils. The main rivers in the area include Nyakwana, Nyangoto, Hibwa, Ragana and Tebesi.

Three key mines where gold mining takes place in Kuria West sub-county were selected for study. They include Karosi gold mine (latitude: 1°11'0''S, longitude: 34°37'16''E), stadium gold mine (latitude: 1°11'25''S, longitude: 34°37'7''E) and Nyangoto gold mine (latitude: 1°9'10''S, longitude: 34°36'23''E). Other study sites were selected at the upstream (latitude: 1°14'28''S, longitude: 34°35'25''E), midstream (latitude: 1°10'53''S, longitude: 34°35'57''E) and downstream (latitude: 1°9'11''S, longitude: 34°36'25''E) areas of the Nyangoto River, to evaluate the potential effect of gold mining activities on heavy metal concentrations in river water. Gold mining activities are mainly concentrated at the mid-stream and downstream areas whereas there are minimal gold mining activities in the upstream zones of the river. For example, the Nyangoto gold mine is located about 20 meters from the river at the downstream reaches.

## 2.2. Collection of Samples and Processing

The first sampling occasion was undertaken during February 2021. During this time, one ore sample was collected from each mine for analysis of heavy metals. Ten heavy metals were analyzed in the ore to determine heavy metal concentrations before gold is processed. These heavy metals include chromium (Cr), cobalt (Co), copper (Cu), zinc (Zn), arsenic (As), cadmium (Cd), mercury (Hg), lead (Pb), Selenium (Se) and magnesium (Mg). The concentration of heavy metals in the ore are presented in Table 1. Based on the concentrations of heavy metals in the ore and potential toxicity, six heavy metals with potential negative effects to human health and environment were purposively selected for study (Table 2). These heavy metals include Cr, Cu, Zn, As, Cd and Pb.

Subsequently, sampling was conducted during September 2021 and January, April and July 2022. From each mine,

tailings were taken in triplicates of about 500 g and placed in labeled zip-lock plastic bags. Panning ponds water was collected from the mines using 1 liter plastic bottles. Additionally, triplicate water samples were collected from the three Nyangoto River study sites using labeled 1 liter plastic bottles. Concentrated nitric acid (5ml) was added to the water samples in-situ to prevent adsorption of dissolved elements onto the walls of the plastic bottles and to minimize the activity of microbes [28].

Sweet potatoes (*Ipomoea batatas*), a major food crop in the area, were bought from major markets (i.e., Masaba and Kehancha) that are located near the gold mines and placed in labeled Ziplock plastic bags. All samples were placed in cool boxes and transported to the Kenya Plant Health and Inspectorate Service (KEPHIS) laboratory for analysis.

Tailings and sweet potatoes were dried and ground into particles utilizing mortar and pestle. About 0.5 g of each sample were utilized during digestion. River water and panning ponds water samples measuring 45ml were utilized during the digestion process. Samples were placed into digestion tubes and mixed with 9ml nitric acid to disintegrate the heavy metals. 4ml perchloric acid was utilized as an oxidizing agent during digestion. The samples were placed into a microwave digestion system for 50 minutes at 200 °C. Afterwards, the samples were cooled for about 20 minutes. After the digestion process was complete, the samples were placed into volumetric flasks and mixed with deionized water (250ml) prior to analysis of heavy metals using an Inductively Coupled Plasma Mass Spectrometer (ICPMS). The samples were analyzed at the KEPHIS analytical laboratory, Nairobi.

## 2.3. Data Analysis

Data analysis was undertaken using R [29]. ANOVA was used test significance difference ( $p \leq 0.05$ ) of heavy metal concentrations in river water, panning pond water and gold mine tailings among the different sampling sites. The Tukey test was utilized for post-hoc evaluations. On the other hand, significant differences in heavy metal concentrations in sweet potatoes collected from Masaba and Kehancha markets was evaluated using Independent Samples t-test. The heavy metal concentrations in river water and sweet potatoes were compared with WHO set limits.

## 3. Results

### 3.1. Ore Samples

In the ore samples, magnesium (4386.88mg/kg) had the highest average concentration followed by copper (112.76mg/kg), arsenic (58.53mg/kg) and zinc (46.71mg/kg). Selenium was below the limits of detection (BDL) (Table 1).

**Table 1.** Concentrations (mg/kg) of selected heavy metals in ore samples collected from the study sites on 8th February, 2021. Cr, Co, Cu, Zn, As, Cd, Hg, Pb, Se,mg refers to chromium, cobalt, copper, zinc, arsenic, cadmium, mercury, lead, selenium and magnesium.

| Sample type | Cr    | Co    | Cu     | Zn    | As    | Cd   | Hg   | Pb   | Se  | Mg      |
|-------------|-------|-------|--------|-------|-------|------|------|------|-----|---------|
| Ore         | 31.32 | 21.90 | 112.76 | 46.71 | 58.53 | 0.09 | 0.38 | 5.05 | BDL | 4386.88 |

### 3.2. Tailings

Across the study sites, arsenic had the highest mean concentration (2000.01mg/kg) in the tailing samples followed by lead (173.33mg/kg), zinc (83.74mg/kg), chromium (52.91mg/kg), and copper (31.19mg/kg). The concentrations of heavy metals in the tailings varied between and within the study sites. For example, the Nyangoto study site had the highest mean concentrations for arsenic, zinc, cadmium and

lead compared to the Stadium and Karosi study sites. On the other hand, the Stadium study site had the highest mean concentrations for copper and chromium (Table 2). Apart from copper, all the other heavy metals had higher mean concentrations in tailings than in the ore samples. The mean concentrations for heavy metals such as chromium, copper, arsenic, cadmium and lead differed significantly ( $p < 0.05$ ) among the study sites (Table 2). However, zinc did not differ significantly ( $p = 0.063$ ) among the study sites.

**Table 2.** Mean ( $\pm$ SE) heavy metal concentrations (mg/kg) in gold mine tailings.

| Study sites | Cr                  | Cu                 | Zn                   | As                     | Cd                | Pb                    |
|-------------|---------------------|--------------------|----------------------|------------------------|-------------------|-----------------------|
| Nyangoto    | 34.14 $\pm$ (1.91)  | 16.97 $\pm$ (1.45) | 118.07 $\pm$ (27.56) | 2789.88 $\pm$ (482.54) | 1.85 $\pm$ (0.53) | 366.21 $\pm$ (119.82) |
| Stadium     | 87.42 $\pm$ (11.84) | 55.53 $\pm$ (8.69) | 54.17 $\pm$ (9.79)   | 946.45 $\pm$ (170.15)  | 0.32 $\pm$ (0.08) | 31.71 $\pm$ (7.29)    |
| Karosi      | 37.15 $\pm$ (3.45)  | 21.10 $\pm$ (1.45) | 78.99 $\pm$ (13.42)  | 2263.71 $\pm$ (317.29) | 0.81 $\pm$ (0.14) | 122.06 $\pm$ (40.16)  |
| F (2, 33)   | 17.26               | 16.85              | 3.01                 | 7.46                   | 6.02              | 5.61                  |
| p-value     | 0.006               | 0.006              | 0.063                | 0.02                   | 0.006             | 0.008                 |

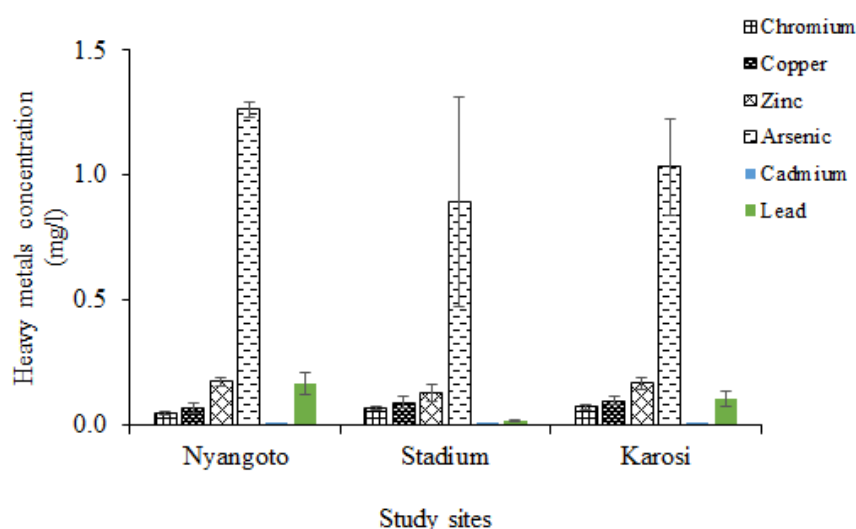
### 3.3. Panning Ponds Water

The mean concentrations of heavy metals in the panning ponds water were substantially lower ( $< 2\text{mg/l}$ ) than in the tailings (Figure 1). Across the study sites, arsenic had the highest mean concentration (1.06mg/l) in the panning ponds water followed by zinc (0.16mg/l), lead (0.09mg/l), and copper (0.08mg/l). The Nyangoto study site had relatively higher mean concentrations for arsenic ( $1.26 \pm 0.03\text{mg/l}$ ), zinc ( $0.17 \pm 0.02\text{mg/l}$ ), lead ( $0.17 \pm 0.04\text{mg/l}$ ) and cadmium ( $0.001 \pm 0.0001\text{mg/l}$ ) when compared to the other study sites. On the other hand, the Karosi study site had slightly higher mean values for copper ( $0.09 \pm 0.01\text{mg/l}$ ) and chromium ( $0.07 \pm 0.01\text{mg/l}$ ) than the other study sites. The mean concentrations for heavy metals such as chromium ( $F_{2, 33} = 3.04$ ,  $p = 0.061$ ), copper ( $F_{2, 33} = 0.64$ ,  $p = 0.534$ ), zinc ( $F_{2, 33} = 0.96$ ,  $p = 0.393$ ) and arsenic ( $F_{2, 33} = 0.49$ ,  $p = 0.617$ ) did not differ significantly among the study sites. However, the concentrations for cadmium ( $F_{2, 33} = 9.46$ ,  $p = 0.001$ ) and lead

( $F_{2, 33} = 5.95$ ,  $p = 0.006$ ) differed significantly among the study sites. Post Hoc Tukey test showed that Cd concentrations for Nyagoto site differed significantly with those of Stadium and Karosi sites ( $p < 0.05$ ), while Pb concentrations for Nyagoto site differed significantly with Pb levels recorded at Stadium ( $p = 0.004$ ).

### 3.4. River Water

The mean concentrations of heavy metals in the river water and in the panning ponds water were within the same range ( $0.0002 - 4\text{mg/l}$ ). The downstream study site of river Nyangoto had the highest mean concentrations for all heavy metals (Table 3). In particular, copper ( $4.06\text{mg/l}$ ), zinc ( $0.82\text{mg/l}$ ) and arsenic ( $0.67\text{mg/l}$ ) had higher mean values at the downstream site. Across the study sites, copper ( $1.40\text{mg/l}$ ), zinc ( $0.34\text{mg/l}$ ) and arsenic ( $0.22\text{mg/l}$ ) had the highest mean values when compared to the other metals. There was significant difference in the concentration of heavy metals among the study sites (all  $p < 0.05$ ).

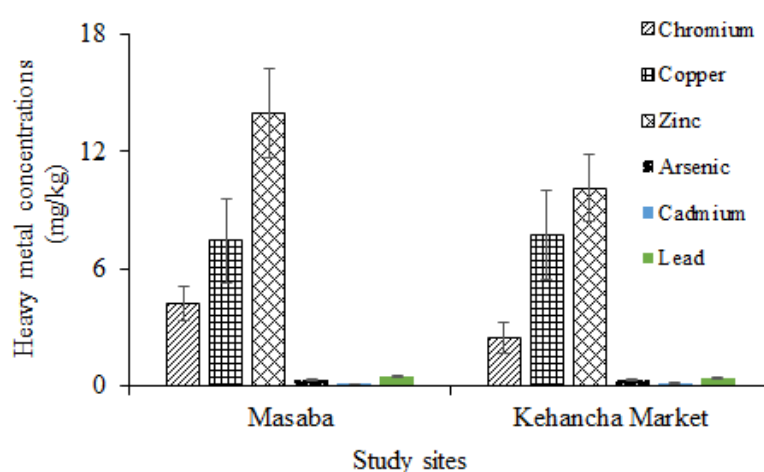


**Figure 1.** Mean heavy metal concentrations (mg/l) in panning ponds water collected from the study sites. Vertical bars represent  $\pm$ SE.

**Table 3.** Mean ( $\pm$ SE) heavy metal concentrations (mg/l) in river water and WHO set guidelines.

| Study sites | Cr                  | Cu                  | Zn                  | As                   | Cd                     | Pb                  |
|-------------|---------------------|---------------------|---------------------|----------------------|------------------------|---------------------|
| Upstream    | 0.031 $\pm$ (0.004) | 0.064 $\pm$ (0.018) | 0.098 $\pm$ (0.024) | 0.005 $\pm$ (0.001)  | 0.0002 $\pm$ (0.000)   | 0.009 $\pm$ (0.002) |
| Midstream   | 0.043 $\pm$ (0.007) | 0.064 $\pm$ (0.015) | 0.105 $\pm$ (0.030) | 0.002 $\pm$ (0.0006) | 0.0002 $\pm$ (0.00002) | 0.008 $\pm$ (0.003) |
| Downstream  | 0.184 $\pm$ (0.079) | 4.058 $\pm$ (2.104) | 0.824 $\pm$ (0.369) | 0.666 $\pm$ (0.339)  | 0.004 $\pm$ (0.001)    | 0.098 $\pm$ (0.04)  |
| WHO limit   | 0.05                | 2.0                 | 3.0                 |                      | 0.003                  | 0.01                |
| F2, 33      | 3.45                | 3.60                | 3.78                | 3.79                 | 3.85                   | 3.78                |
| p-value     | 0.047               | 0.038               | 0.033               | 0.033                | 0.031                  | 0.033               |

### 3.5. Sweet Potatoes



**Figure 2.** Mean heavy metal concentrations (mg/kg) in sweet potatoes obtained from Masaba and Kehancha markets in Kuria west sub-county. Vertical bars represent  $\pm$ SE.

The average concentrations for heavy metals such as chromium (3.32mg/kg), copper (7.57mg/kg) and zinc (12.02mg/kg) were higher in sweet potatoes than in river water and panning ponds water. However, tailing samples



had higher average heavy metal concentrations than sweet potatoes. Zinc and copper had the highest ( $>7\text{mg/kg}$ ) mean concentrations in sweet potatoes in the two sampling sites (Figure 2). The other heavy metals recorded had slightly lower concentration levels as follows; Arsenic ( $0.31\text{mg/kg}$ ), Cadmium ( $0.08\text{mg/kg}$ ) and lead ( $0.44\text{mg/kg}$ ). The heavy metal concentrations did not differ significantly between the sites ( $p > 0.05$ ).

## 4. Discussion

Arsenic had the highest mean concentration ( $2000.01\text{mg/kg}$ ) in tailings when compared to the other heavy metals. Arsenic is a typical element in the environment and is often a significant constituent in gold deposits [30]. Despite the fact that gold can be found in gold nuggets, it is usually bound within minerals such as iron and arsenic-containing minerals. These minerals are important in the formation of gold deposits and play a key role in concentration and accessibility of gold in natural deposits [31-33]. This may explain why high arsenic concentrations were recorded in the tailings samples when compared to other heavy metals.

The mean concentrations for heavy metals such as arsenic ( $946.45\text{--}2789.88\text{mg/kg}$ ), zinc ( $54.17\text{--}118.07\text{mg/kg}$ ), lead ( $31.71\text{--}366.21\text{mg/kg}$ ), cadmium ( $0.32\text{--}1.85\text{mg/kg}$ ), chromium ( $34.14\text{--}87.42\text{mg/kg}$ ) and copper ( $16.97\text{--}55.53\text{mg/kg}$ ) in the current study are within the range reported by other studies in other regions of the world. For example, Bempah et al. [34] evaluated the concentrations of heavy metals in gold mine tailings in Ghana and found that the mean concentrations of arsenic, copper and zinc were  $1752\text{mg/kg}$ ,  $92.17\text{mg/kg}$  and  $177.6\text{mg/kg}$ , respectively. Another study by Enkhzaya et al. [35] evaluated heavy metals in gold mines tailings in Mongolia and found that arsenic had the highest mean concentration in tailing samples. The study also found that arsenic and lead concentrations ranged between  $1346\text{--}2970\text{mg/kg}$  and  $115\text{--}685\text{mg/kg}$ , respectively. Another study conducted in Nigeria evaluated heavy metals in artisanal gold mine tailings and found that the mean values for lead, chromium and copper were  $1733.03\text{mg/kg}$ ,  $2.27\text{mg/kg}$  and  $45.90\text{mg/kg}$ . The study also found that the mean values for lead exceeded the United States Environmental Protection Agency (USEPA) guidelines acceptable for lead in the soil (i.e.,  $200\text{mg/kg}$ ) [36]. Mean lead concentrations in one of the study sites (i.e., Nyangoto  $366.21\text{mg/kg}$ ) in the current study also exceeded the USEPA values. The concentrations for heavy metals such as chromium and arsenic also exceeded the guidelines acceptable (i.e.,  $0.1\text{mg/kg}$  and  $20\text{mg/kg}$ , respectively) for agricultural soil by the WHO. This indicates that disposal of artisanal gold mines tailings into the environment may lead to contamination of the soil as demonstrated for other areas of the world such as Singida Region, Tanzania [37].

The mean concentrations for heavy metals such as lead,

cadmium, zinc and arsenic were higher in tailings than in the ore samples. Gold ore samples contain minerals such as sulphosalts, sulphides and arsenides [38]. After weathering of rocks during processing of gold ore these minerals are released and may lower the pH of nearby environments. This leads to increased mobilization of heavy metals such as lead, cadmium and zinc [30, 39]. This may explain why high heavy metal concentrations were recorded in tailings than in the unprocessed ore.

The concentrations of heavy metals in panning ponds water were lower ( $<2\text{mg/l}$ ) than in tailings. This finding indicates that tailings have higher heavy metal concentrations and could potentially have a higher capacity to pollute the environment than panning ponds water. Other studies have also recorded lower heavy metal concentrations in artisanal gold mine waste waters. For example, Muhammad et al. [40] evaluated heavy metals concentration in artisanal gold mine waste waters and tailings and found that the mean concentrations for lead, cadmium, chromium and copper ranged between  $0.0001\text{--}0.83\text{mg/l}$  in the waste waters. On the other hand, the mean concentrations for the four heavy metals ranged between  $0.005\text{--}1733.03\text{mg/kg}$  in the tailings. The concentrations of heavy metals exceeded the WHO and USEPA guidelines for heavy metals in drinking water and agricultural soil.

The concentrations of heavy metals in panning ponds water and river water were within the same range ( $0.0002\text{--}4\text{mg/l}$ ). Similarity in heavy metal concentrations between panning ponds water and river water could be due to the fact that panning ponds water was obtained from the nearby river (i.e., river Nyangoto). The downstream site of River Nyangoto had the highest heavy metal concentrations and this could be due to the close proximity ( $\sim 20\text{m}$ ) of the mine to the river. Tailings were piled near the river and this could have led to contamination of the river water by heavy metals. Tailings can be carried into water ways, such as rivers, by wind and run off. The recorded concentrations of heavy metals in river water in the current study are similar to those recorded by other previous studies. For example, Ning et al. [41] evaluated the concentrations of heavy metals such as lead, cadmium, zinc, copper, chromium and arsenic in a gold mining area in China and found that the concentrations ranged between  $0.01\text{--}1.64\text{mg/l}$ . The results showed that the surface water of the gold mining area was highly polluted by mercury, zinc and cadmium and the concentrations of heavy metals depended on the distance from the pollution source.

The mean concentrations for heavy metals such as chromium, copper and zinc were higher in sweet potatoes than in panning ponds water or river water. This indicates that the sweet potatoes had higher mean heavy metal concentrations than environmental media. The possible reason for the relatively high heavy metal concentrations in sweet potatoes could be due to accumulation of heavy metals in plant tissue from the environment. Previous studies have also reported accumulation of heavy metals in plants growing in gold min-

ing areas. For example, Mkumbo et al. [42] evaluated heavy metals in indigenous plants growing in a gold mining area in Tanzania and found that plants growing in polluted soils accumulated heavy metals such as zinc, lead and copper. Another study conducted in Nigeria found that artisanal gold mining operations discharged heavy metals into the environment and contaminated drinking water sources and food crops such as spinach, onions and sweet potatoes [43]. Therefore, contamination of the environment with heavy metals in artisanal gold mining areas can lead to accumulation of potentially harmful elements in plants growing in polluted soil.

## 5. Conclusions and Recommendations

In conclusion, tailings had the highest heavy metal concentrations compared to panning ponds water and river water. Sweet potatoes had lower heavy metal concentrations than tailings. However, sweet potatoes had higher heavy metal concentrations than river water or panning ponds water.

To minimize contamination of the environment with heavy metals from gold mining operations, the following recommendations are suggested:

- 1) Taking into account the reality of economic conditions in Kuria West Sub-County, halting gold mining operations without alternative sources of livelihood is not realistic. Therefore, attention should alternatively be placed on educating the miners about environmentally friendly mining practices.
- 2) There is need for designation of specific areas where gold mining processes can be undertaken without posing significant threats to the environment and human health.
- 3) Tailings and waste waters (i.e., panning ponds water) can be safely kept in containment ponds which minimize the spread of potentially harmful elements into the environment. The tailings and panning ponds water should be treated before disposal.
- 4) Former ore processing sites should be rehabilitated and should not be utilized as farmlands after mining operations have ceased.
- 5) Measures should be undertaken by relevant government agencies to prevent processing of gold near sensitive areas such as drinking water sources and farmlands.
- 6) Mining activities should be licensed and regulated by relevant government agencies.
- 7) Continuous monitoring should be undertaken to determine heavy metal concentrations in areas close to gold mining sites. Additionally, further tests should be conducted to ascertain the levels of heavy metals in soil and other plants grown in the area.
- 8) Various regulations governing mining operations and environmental management should be implemented.
- 9) All polluted mining sites should be remediated to prevent further contamination of the environment.

## Abbreviations

|        |                                               |
|--------|-----------------------------------------------|
| ANOVA  | One-way Analysis of Variance                  |
| BDL    | Below the Limits of Detection                 |
| ICPMS  | Inductively Coupled Plasma Mass Spectrometer  |
| KEPHIS | Kenya Plant Health and Inspectorate Services  |
| USEPA  | United States Environmental Protection Agency |
| WHO    | World Health Organization                     |

## Author Contributions

**John Gichimu Mbaka:** Resources, Validation, Visualization

**Julius Kioko Nzeve:** Resources, Software, Supervision, Validation, Visualization

**Consolate Awuor Okoth:** Conceptualization, Data curation, Formal Analysis, Resources, Software, Supervision, Validation, Visualization, Writing – original draft

**Alexander Gori:** Conceptualization, Data curation, Funding acquisition, Investigation, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing

## Funding

This work was supported and financed through an internal research grant by Machakos University, Grant number FY2019/2020.

## Conflicts of Interest

The authors declare no conflicts of interest.

## References

- [1] Ndlovu, S. (2008). Biohydrometallurgy for sustainable development in the African minerals industry. *Hydrometallurgy* 91, 20-27. <https://doi.org/10.1016/j.hydromet.2007.11.007>
- [2] Cust, J. and Zeufack, A. (2023). Africa's resource future: harnessing natural resources for economic transformation during the low-carbon transition, World Bank Publications. 270 pages. ISBN-10: 146481743x. <https://openknowledge.worldbank.org/handle/10986/39599>
- [3] Alengebaw, A., Abdelkhalek S. T., Qureshi, S. R., and Wang, M. (2021). Heavy metals and pesticides toxicity in agricultural soils and plants: ecological risks and human health implications. *Toxics* 9, 42. <https://doi.org/10.3390/toxics9030042>
- [4] Xiong, H., Yin, Y., Cui, X., Dai, W., Dong, J., Wang, X., and Duan, G. (2025). The effects of coal mining on heavy metal concentrations and microbial composition in surrounding soils. *J. Environ. Sci.* <https://doi.org/10.1016/j.jes.2025.05.060>

- [5] Zhang, X., Yan, L., Liu, J., Zhang, Z., and Tan, C. (2019). Removal of different kinds of heavy metals by novel PPG-nZVI beads and their application in simulated stormwater infiltration facility. *Appl. Sci.* 9, 4213. <https://doi.org/10.3390/app9204213>
- [6] Vatansever, R., Ozyigit, I., and Filiz, E. (2017). Essential and beneficial trace elements in plants and their transport in roots: a review. *Appl. Biochem. Biotechnol.* 181, 464-482. <https://doi.org/10.1007/s12010-016-2224-3>
- [7] Hilson, G. (2002). Small-scale mining and its socio-economic impact in developing countries. *Nat. Resour. Forum.* 26, 3-13. <https://doi.org/10.1111/1477-8947.00002>
- [8] Cartier, L. E. and Bürge, M. (2011). Agriculture and artisanal gold mining in Sierra Leone: alternatives or complements? *J. Int. Dev.* 23, 1080-1099. <https://doi.org/10.1002/jid.1833>
- [9] Hinton, J. J., Veiga, M. M. and Veiga, A. T. C. (2003). Clean artisanal gold mining: a utopian approach. *J. Clean. Prod.* 11, 99-115. [https://doi.org/10.1016/S0959-6526\(02\)00031-8](https://doi.org/10.1016/S0959-6526(02)00031-8)
- [10] Ogola, J. S., Mitullah, W. V. and Omulo, M. A. (2002). Impact of gold mining on the environment and human health: a case study in the Migori gold belt, Kenya. *Environ. Geochem. Health.* 24, 141-157. <https://doi.org/10.1023/A:1014207832471>
- [11] Veiga, M. M., Maxson, P. A., and Hylander, L. D. (2006). Origin and consumption of mercury in small-scale gold mining. *J. Clean. Prod.* 14, 436-447. <https://doi.org/10.1016/j.jclepro.2004.08.010>
- [12] Arifin, Y. I., Sakakibara, M. and Sera, K. (2015). Impacts of artisanal and small-scale gold mining on environment and human health of Gorontalo Utara Regency, Gorontalo Province, Indonesia. *Geosci.* 5, 160-176. <https://doi.org/10.3390/geosciences5020160>
- [13] Maconachie, R. and Hilson, G. (2011). Safeguarding livelihoods or exacerbating poverty? Artisanal mining and formalization in West Africa. *Nat. Resour. Forum.* 35, 293-303. <https://doi.org/10.1111/j.1477-8947.2011.01407.x>
- [14] Esdaile, L. J. and Chalker, J. M. (2018). The mercury problem in artisanal and small-scale gold mining. *Chem. Eur. J.* 24, 6905-6916. <https://doi.org/10.1002/chem.201704840>
- [15] Bugmann, A., Brugger, F., Zongo, T. and Merwe, A. (2022). "Doing ASGM without mercury is like trying to make omelets without eggs". Understanding the persistence of mercury use among artisanal gold miners in Burkina Faso. *Env. Sci. Pol.* 133, 87-97. <https://doi.org/10.1016/j.envsci.2022.03.009>
- [16] Tampushi, L. L., Onyari, J. M., and Muthama, N. J. (2022). Environmental distribution and risk of exposure of heavy metal pollutants from Lolgorian artisanal gold mining in Kenya. *Bull. Environ. Contam. Toxicol.* 109, 310-316. <https://doi.org/10.1007/s00128-022-03575-7>
- [17] Palapa, T. M. and Maramis, A. A. (2015). Heavy metals in water of stream near an amalgamation tailing ponds in Talawaan-Tatelu Gold mining, North Salewesi, Indonesia. *Procedia Chem.* 14, 428-436. <https://doi.org/10.1016/j.proche.2015.03.058>
- [18] Amoakwah, E., Ahsan, S., Rahman, M. A., Asamoah, E., Es-sumang, D. K., Ali, M., and Islam, K. R. (2020). Assessment of heavy metal pollution of soil-water-vegetative ecosystems associated with artisanal gold mining. *Soil Sediment Contam.* 29, 788-803. <https://doi.org/10.1080/15320383.2020.1777936>
- [19] Afriyie, R. Z., Arthur, E. K., Gikunoo, E., and Baah, D. S. (2023). Potential health risk of heavy metals in some selected vegetable crops at an artisanal gold mining site: a case study at Moseaso in the Wassa Amenfi West District of Ghana. *J. Trace Elem. Minerals.* 4, 100075. <https://doi.org/10.1016/j.jtemin.2023.100075>
- [20] Ngure, V. and Kinuthia, G. (2020). Health risk implications of lead, cadmium, zinc and nickel for consumers of food items in Migori gold mines, Kenya. *J. Geochem. Explor.* 209, 106430. <https://doi.org/10.1016/j.gexplo.2019.106430>
- [21] Singh, R., Gautaru, N., Mishra, A. and Gupta, R. (2011). Heavy metals and living systems: an overview. *Indian J. Pharmacol.* 43, 246-253. <https://doi.org/10.4103/0253-7613.81505>
- [22] Sankhla, M. S., Kumani, M., Nandan, M., Kumar, R., and Agrawal, P. (2016). Heavy metals contamination in water and their hazardous effect on human health - a review. *Int. J. Curr. Microbiol. Appl. Sci.* 5, 759-766. <https://dx.doi.org/10.20546/ijcmas.2016.510.082>
- [23] Bharti, K. R. and Sharma, R. (2022). Effect of heavy metals: an overview. *Mater. Today Proc.* 51, 880-885. <https://doi.org/10.1016/j.matpr.2021.06.278>
- [24] Dias, M. C., Monteiro, C., Moutinho-Pereira, J., Correia, C., Goncalves, B., and Santos, C. (2013). Cadmium toxicity affects photosynthesis and plant growth at different levels. *Acta Physiol. Plant.* 35, 1281-1289. <https://doi.org/10.1007/s11738-012-1167-8>
- [25] Chu D. (2018). Effects of heavy metals on soil microbial community. *IOP Conf. Ser. Earth Environ. Sci.* 113, 012009. <https://doi.org/10.1088/1755-1315/113/1/012009>
- [26] Akhtar, N., Ishak, M. I. S., Bhawani, S. A. and Umar, K. (2021). Various natural and anthropogenic factors responsible for water quality degradation: a review. *Water* 13, 2660. <https://doi.org/10.3390/w13192660>
- [27] Nyamohanga, P. W. (2017). Factors influencing maize crop production among small-scale farmers in Kuria East Sub-county, Migori County, Kenya, MSc Thesis, Egerton University. 108 pages. <http://172.16.31.117:4000/handle/123456789/1492>
- [28] Smith, R. (1983). A laboratory manual for the determination of metals in water and waste water by atomic absorption spectrophotometry, National Institute for Water Research. Council for Scientific and Industrial Research Technical Guide K63. PP 1- 29. ISBN 0798824824.
- [29] R Development Core Team (2015): R: a language and environment for statistical computing. Vienna: R Foundation for Statistical Computing, Vienna, Austria. <http://www.r-project.org/>



- [30] Straskraba, V. and Moran, R. E. (1990). Environmental occurrence and impacts of arsenic at gold mining sites in the Western United States. *Int. J. Mine Water* 9, 181- 191. <https://doi.org/10.1007/BF02503691>
- [31] Simon, G., Huang, H., Penner-Hahn, J. E., Kesler, S. E., and Kao, L. (1999). Oxidation state of gold and arsenic in gold-bearing arsenian pyrite. *Am. Min.* 84, 1071-1079. <https://doi.org/10.2138/am-1999-7-809>
- [32] Tounkara, F., Chen, J., Sidibe, M. and Soumare, O. (2021). Influence of copper and arsenic on gold recovery in the Yalea deposit, Western Mali. *Open J. Geol.* 11, 142-154. <https://doi.org/10.4236/ojg.2021.114008>
- [33] Costa, F. R., Nery, G. P., Carneiro, C. C., Kahn, H., and Ulsen, C. (2022). Mineral characterization of low-grade gold ore to support geometallurgy. *J. Mater. Res. Technol.* 21, 2841-2852. <https://doi.org/10.1016/j.jmrt.2022.10.085>
- [34] Bempah, C. K., Ewusi, A., Obiri-Yeboah, S., Asabere, S. B., Mensah, F., Boateng, J., and Voight, H. (2013). Distribution of arsenic and heavy metals from mine tailings dams at Obuasi municipality of Ghana. *Am. J. Eng. Res.* 2, 61-70.
- [35] Enkhzaya, S., Ohe, K., Shiomori, K., Oyunt Setseg, B., and Bayanjargal, O. (2016). Assessment of heavy metals in mining tailings around Boroo and Zuunkharaa gold mining areas of Mongolia, *JEST* 9 (2016) 379-389. <https://doi.org/10.3923/jest.2016.379.389>
- [36] USEPA, (2008). Unites States Environmental Protection Agency. Allowable limits for lead in soil.
- [37] Herman, A. and Kihampa, C. (2015). Heavy metals contamination in soils and water in the vicinity of small-scale gold mines at Londoni and Sambaru, Singida region, Tanzania. *IJEMA* 3, 397-403. <https://doi.org/10.1016/j.ijema.20150306.13>
- [38] Hammond, N. Q. and Tabata, H. (1997). Characteristics of ore minerals associated with gold at the Prestea mine, Ghana. *Minerological Mag.* 61, 879- 894. <https://doi.org/10.1016/10.1180/minmag.1997.061.409.10>
- [39] Calmano, W., Hong, J. and Forstner, U. (1993). Binding and mobilization of heavy metals in contaminated sediments affected by pH and redox potential. *Water Sci. Technol.* 28, 223-235. <https://doi.org/10.2166/wst.1993.0622>
- [40] Muhammad, I., Ashiru, S., Ibrahim, I., Salawu, K., Muhammad, D., and Muhammad, A. (2013). Determination of some heavy metal sin wastewater and sediment of artisanal gold local mining site of Abare area in Nigeria. *JETT* 1, 174-182.
- [41] Ning, L., Liyuan, Y., Jirui, D., and Xugui, P. (2011). Heavy metal pollution in surface water of Linglong gold mining area, China. *Procedia Environ. Sci.* 10, 914-917. <https://doi.org/10.1016/j.proenv.2011.09.146>
- [42] Mkumbo, S., Mwegoha, W., and Renman, G. (2012). Assessment of the phytoremediation potential for Pb, Zn and Cu of indigenous plants growing in a gold mining area in Tanzania. *Int. J. Environ. Sci.* 2, 2425-2434. <https://doi.org/10.6088/ijes.00202030123>
- [43] Lar, M., Ngozi-Chika, C. S., and Tsuwang, K. (2014). Environmental health impact of potentially harmful element discharges from mining operations in Nigeria. *Am. J. Environ. Prot.* 3, 14-18. <https://doi.org/10.11648/j.ajep.s.2014030602.12>