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Reclamation after Gold Mining: implication of Reclamation Practices on Soil Physicochemical Properties and Heavy Metal Concentration

Eric Darko[1], **Charles Afriyie-Debrah***[2], **Alexander Anning**[3], **Bernard Fei-Baffoe**[1], **Jonathan Nartey Hogarh**[1], **Kwasi Adu Obirikorang**[4], **Daniel Osei-Twumasi**[1], **and Agbesi Kwadzo Keteku**[2]

[1]*Department of Environmental Science, Faculty of Biosciences, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana*
[2]*CSIR-Crops Research Institute, Cereals Division, Environmental and Biosafety, P. O. Box 3785, Kumasi-Ashanti, Ghana*
[3]*Department of Theoretical and Applied Biology, Faculty of Biosciences, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana*
[4]*Department of Fisheries and Watershed Management, Faculty of Renewable Natural Resources, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana*

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Corresponding Author: **Charles Afriyie-Debrah** | E-Mail: **(degreatdebrahgh@gmail.com)**

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ABSTRACT

Post-mining land reclamation, involving techniques such as re-contouring, back-filling, slope stabilization, and drainage management, has become a cornerstone of sustainable mining operations, particularly in Ghana, where environmental awareness and the need to mitigate mining impacts are growing. This study assessed the effectiveness of reclamation practices implemented by three major mining firms, focusing on changes in soil physicochemical properties and heavy metal concentrations. The investigation was conducted at three distinct mine sites, designated as Site 1, Site 2, and Site 3, with adjacent undisturbed areas within each mining concession serving as reference sites for baseline comparison. Soil sampling was systematically carried out within designated plots on both reclaimed and reference sites. At each plot, five composite soil cores were collected at two depths (0–20 cm and 20–40 cm) to evaluate variations in surface and subsurface soil conditions. Analytical results revealed consistently elevated concentrations of heavy metals, including mercury, cadmium, and copper, in reclaimed sites compared to their corresponding reference areas across both depths. Geo-accumulation indices indicated moderate contamination levels in specific reclaimed zones, underscoring persistent environmental challenges. Effect size analysis further confirmed that reclamation interventions have not yet fully restored soil quality to pre-mining conditions, despite evidence of progressive remediation efforts aimed at improving soil health and reducing contamination over time. These findings highlight that while current reclamation strategies contribute positively to environmental recovery, significant gaps remain in achieving full restoration of soil health to baseline conditions. The persistence of elevated heavy metal concentrations emphasizes the need for enhanced reclamation approaches, including long-term monitoring, advanced soil amendment practices, and targeted remediation of contaminants. Such improvements are critical to ensuring that post-mining landscapes meet acceptable environmental standards and more closely align with pre-mining ecosystem characteristics. This study underscores the importance of refining reclamation programs to address these challenges effectively, thereby supporting sustainable environmental recovery and minimizing the long-term ecological footprint of mining activities in Ghana and similar mining regions globally.

Keywords: *Post-mining reclamation, physicochemical properties, heavy metal contamination, environmental restoration, geo-accumulation index, remediation strategies.*

1.0 INTRODUCTION

Mineral mining has historically played a significant role in driving global economic growth and development, particularly in sub-Saharan Africa [1]. In many African countries, especially those rich in gold, mineral exports are the primary source of revenue [1]. Ghana, for instance, is the second largest gold producer in Africa after South Africa and ranked eighth globally in 2018, with a production of 136.2 tons [2].

To contextualize Ghana's gold output, the country accounted for approximately 3.3% of global gold production in 2012, generating export revenues of approximately US$5.64 billion [3]. Mineral exploitation contributes significantly to Ghana's economy, representing approximately 45% of total export earnings and 9% of GDP [4]. Gold remains the most valuable mineral, comprising nearly 95% of Ghana's total mineral revenue [2].

Despite its economic importance, mining poses serious environmental challenges at both the local and global scales [5]. Although this sector supplies critical raw materials to numerous industries, it is widely recognized as a major contributor to environmental degradation, affecting air quality, water resources, and soil health [6]. Mining land use is inherently temporary with widely varying lifespans. Mines are typically decommissioned and closed when resources are depleted, extraction becomes economically unviable, or due to high operational costs and fluctuating market prices [7]; [8] and [9].

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In a mining cycle, mine closures are the last phases that include the cessation of all operations, and instituting rehabilitation programmes to improve some of the negative environmental impacts [10] and [11]. Post-mining landscapes are characterized by significant geophysical changes, which makes them markedly different from surrounding undisturbed landscapes [12]. The direct impacts of mining disturbance to land surfaces are usually severe with the destruction of natural ecosystems, either through the removal of all previous soils, plants, and animals or their burial beneath waste disposal facilities [13]. The specific harmful environmental impacts of mining include severely eroded topsoil, heavy metal accumulation in soil, water or biota and acid mine drainage [14]. Surface mining is generally 2-11 times more damaging to the environment than underground mining [15].

After the Structural Adjustment Programme from the 1980s, Ghana has experienced an increase in resource extraction activities by international and transnational corporations [16], [17]. The downside of commercial, large-scale mining corporations is that very often, the local communities that host their mining operations are highly impacted environmentally and socially, especially in the post-mining periods [18]; [19] and [20]. This notwithstanding, there is a general lack of comprehensive efforts to assess the dynamics of environmental degradation and impacts on local livelihoods when mining expands into rural landscapes [21] and [17]. There is a common perception among non-governmental and community-based organizations and the host communities in Ghana that directly links mining to environmental degradation [22].

In Ghana, as in many other countries, mining regulations require mining companies to enter into a Reclamation Bond Agreement with the Environmental Protection Agency (EPA). This agreement typically takes the form of an insurance package or financial guarantee, intended to cover the costs of land reclamation or restoration should a company fail to adequately assess environmental impacts or fulfil its reclamation responsibilities in host communities. However, numerous reports indicate that some companies either fail to post the required bond or, despite signing the agreement, do not fully adhere to its conditions [23]. Moreover, in cases where mining firms undertake site reclamation with the intent of restoring pre-disturbance ecological functions, the environmental effectiveness and ecological outcomes of these techniques are often poorly understood or insufficiently documented [24].

To encourage sustainable mining practices, the EPA of Ghana sets colour-rated standards for mining companies relating to environmental standards and compliance with environmental laws in Ghana. The colour rating system ranks from best to worst as Gold to Red. It describes companies employing clean technology, waste minimization, and pollution prevention practices, and companies employing no pollution control effort and causing serious environmental damage [23]. The EPA has also established processes for publicly disclosing the performance of mining companies concerning the ratings. According to [25], public disclosure of environmental performance in developing countries is an effective way of ensuring compliance with environmental regulations.

Increased environmental awareness and the need to minimize the effects of mining have made post-mining reclamation of degraded land an integral feature of mining projects [26]. Reclamation is the process by which the productivity of derelict or highly degraded lands is improved to restore ecosystem functions. Thus, the revegetation of degraded sites, mostly using exotic tree species [27]. Long-term mining reclamation requires the establishment of stable nutrient cycles from plant growth and microbial processes [28], [29] and [30].

Globally, post-mining land reclamation often falls short of restoring the original biodiversity, even though certain ecological functions—such as soil stabilization, water regulation, and vegetation cover—can be re-established [31]. To enhance long-term sustainability, mining companies are encouraged to adopt reclamation strategies that balance productive land use with environmental and social protection. International best practices include two primary approaches: allowing spontaneous natural succession, where native species gradually recolonize the disturbed area, or actively planting selected species to accelerate restoration and achieve desired ecological outcomes. In Ghana, reclamation practices and success criteria vary across mining companies, as each firm tailors its efforts to specific post-mining land use goals. However, there is limited understanding of how these approaches impact soil quality and heavy metal accumulation. This study, therefore, aims to assess the effects of reclamation strategies implemented by three major mining companies in Ghana on soil physicochemical properties and heavy metal concentrations.

2.0 MATERIALS AND METHODS

2.1 Study Area

The study was conducted at three commercial gold mines located in the Ashanti and Western North Regions of Ghana in 2023. For each reclaimed site, an undisturbed area within the concessions was chosen as a reference site to compare the reclamation success. The study locations were coded as Site 1, Site 2, and Site 3. The mines operate open-pit gold and underground mining. The reclaimed areas of the mining companies were formerly rock waste dumps of the mining companies. The process involved earthworks and slope battering to reduce steep slopes to gentler angles not exceeding 30°. Mine waste overburden and stockpiled soils with very low nutrients were used for the initial landscape contouring. For successful phyto-stabilization in the initial stages of the reclamation process, soil amendments were required to create optimum growing conditions for re-vegetation, immobilize accumulated heavy metals, and decrease their bioavailability to water sources or the food web. Biochar (625 kg) and composts (1,250 kg) per 25 m by 25 m were applied to improve soil properties at the three mines. Following the initial site preparations, seedlings of nitrogen-fixing *Acacia mangium*, *Gliricidia sepium*, *Leucaena leucocephala*, and *Senna siamea* were planted to expedite the process of succession.

2.2 Plot Selection and Distribution

Each mine site was stratified into two main strata (a reclaimed site and a reference site). Before the actual survey, a reconnaissance walk was taken through the entire site coverage of the two strata, zoning and plot demarcations, and an initial assessment of unique vegetation characteristics was done. In each stratum, five (5) plots measuring 25 x 25 m^2 were systematically demarcated. The first plot was mostly selected and the subsequent ones were systematically located at least 100 m from the first plot. This was to ensure a wider coverage of the area. The Geographical Positioning System (GPS) was used to navigate from the subsequent plots. A 100 m measuring tape and a prismatic compass were used to establish the plots.

2.3 Soil Sampling

Soil samples were collected within the subplots of each sampling plot on the reference and reclaimed sites of each mine. In each plot, five soil cores were collected at two depth ranges—0-20 cm and 20-40 cm—and placed in separate plastic zip-lock bags for analysis. The sampling points within each plot were spread out as much as possible to represent as much spatial homogeneity as possible.

2.4 Measurements of Soil Physicochemical Parameters

Soil pH and conductivity were measured using a pH electrode and a conductivity electrode, respectively by mixing the soil samples with water (1:2.5, soil: solution ratio, w/v). All the collected soil samples were analysed for the determination of organic matter content using the loss-on-ignition (LOI) procedure. Before the LOI analyses, the soil samples were air-dried and sieved through a 2 mm sieve. Following the air drying, the samples were oven-dried at 105 ºC for 24 hours to remove any residual moisture, cooled in a desiccator, and the dry weight was determined before samples were combusted in a muffle furnace at temperatures ranging from 300 to 550 ºC in 2 hours in a muffle furnace. After combustion, the samples were cooled in a desiccator and re-weighed to determine the soil organic matter content by the following equation (1):

$$\text{Soil organic matter } (\%) = \frac{\text{Oven dry soil weight (g)} - \text{Soil weight after combustion (g)}}{\text{Oven dry soil weight (g)}} \times 100\text{---------- Eq 1}$$

Soil samples were prepared for the determination of organic carbon using the same methods for the organic matter and combusted at 360 ºC for 2 h in a muffle furnace. Total C was presumed to equal organic C as no calcareous samples were analysed in this study. The soil organic carbon content was calculated by the equation (2) below:

$$\text{Soil organic carbon } (\%) = \frac{\text{Oven dry soil weight (g)} - \text{Soil weight after combustion (g)}}{\text{Oven dry soil weight (g)}} \times 100 \cdots\cdots\cdots\text{ Eq 2}$$

For phosphorus determination, soil samples were air-dried, ground, and sieved (2 mm). Sub-samples of the ground soil (2.5 g) were subjected to an extraction process using 50 ml of 0.5 M $NaHCO_3$ solution (pH adjusted to 8.5). The mixture was placed on an orbital shaker and subjected to shaking for 30 min and filtered through Whatman No. 40 filter paper. The phosphorus contents of the filtrates were analysed using the ascorbic acid colourimetric method. The Kjeldahl method was used to determine the total soil nitrogen content.

2.5 Determination of Heavy Metals

All soil samples used for heavy metal analysis were oven-dried, ground into a fine powder using a porcelain mortar and pestle, and subsequently subjected to acid digestion. About 0.5g of the ground soil samples were weighed into 50 ml digestion tubes, after which 1ml of distilled water, 2.0 ml perchloric acid (HNO_3-$HClO_4$) (1:1 vv) and 5.0 ml sulphuric acid (H_2SO_4) were added. The acid-soil mixtures were refluxed at 200ºC for 30 minutes in a clean fume chamber. The completely digested subsamples were allowed to cool at room temperature, after which the undigested sediment fractions were filtered off through a Whitman Glass Microfibre filter paper (GF/C) to obtain clear solutions that were diluted to 50 ml in volumetric flasks with deionised water. Concentrations of all heavy metals except for mercury and arsenic were determined using an Atomic Absorption Spectrophotometer and the results were expressed as total concentrations (µg/g dry weight (dw). Mercury and cadmium levels of the soil samples were determined using inductively coupled plasma mass spectrometry (ICP-MS).

2.6 Quality Assurance and Control

All the glassware used was soaked overnight with HNO_3 (10% v/v) and rinsed thoroughly with deionized water prior to use. Sample digestions and heavy metal analyses were performed in triplicate for each soil sample. Additionally, prepared blank solutions were used to correct the analytical values and continual calibration verification standards were run after every 50 samples to ensure that calibration curves were linear with regression coefficients, r2 > 0.995. Certified reference materials for soil were used for quality assurance and quality control procedures. The recovery for all elements ranged from 96.0% to 104.5%.

2.7 Calculation of Geoaccumulation Index (Igeo)

To ascertain the extent of heavy metal pollution in the sampled soils from the reclaimed and reference sites, Müller's geoaccumulation indices were calculated to measure the pollution intensities in the study areas [32]. The Igeo is associated with a qualitative scale of pollution and was calculated using the equation (3),

$$Igeo = Log_2\left[\frac{Cn}{1.5\ Bn}\right]\text{ ---Eq 3}$$

Where

Cn is the measured content of element "n", and Bn is the element's content in the "average shale" background concentration.

The calculated Igeo values were compared to the description of sediment quality in Igeo Classification Table (Table 1) to determine the heavy metal pollution intensities of the reclaimed mine sites and their respective reference sites.

Table 1: Description of sediment quality using the Igeo classification scale (Müller, 1979)

Igeo	Class	Pollution Intensity
<0	0	Unpolluted
0-1	1	Unpolluted to moderately polluted
1-2	2	Moderately polluted
2-3	3	Moderately to strongly polluted
3-4	4	Strongly polluted
4-5	5	Strongly to extremely polluted
>5	6	Extremely contaminated

2. 8 Statistical Analysis

Data are presented as mean ± SD. Normality and homoscedasticity were assessed using the Kolmogorov–Smirnov test and Bartlett's test, respectively. The data complied with the assumption of parametric tests a t-test was used to test for differences in the means of the different heavy metals from the reclaimed sites and their respective control sites. In instances where laboratory analyses were carried out on subsamples, data were not treated as pseudo-replicates but rather, statistical analyses were carried out on replications considered at sample levels.

Principal Component Analyses were performed on the heavy metal datasets from the reclaimed and control sites to extract a smaller number of independent factors (principal components) and find the associations between the assayed heavy metals and the different sites. The PCA analysis and biplots were executed using PAST ver. 4.03. All other graphs and statistical analyses were executed using SigmaPlot ver. 12.0 (Systat Software Inc, San Jose, CA, USA). In all cases, differences were considered significant at p < 0 .05.

3.0 RESULTS

3.1 Granulometric Analysis

Granulometric analysis indicated that the soils of the 0-20 cm layer of the reclaimed sites had higher sand components compared to the reference site. Clay soils were generally associated with the deeper layers. The deeper layers also had higher moisture content compared to their respective upper layers. The bulk densities were similar irrespective of the depth. The results of the granulometric analysis and the soil textural classes are shown in Table 2.

Table 2: Granulometric analysis and textural class of soil samples from the reclaimed mine sites and their respective mine

Site	% Sand	% Silt	% Clay	% Moisture	Bulk Density (gcm^{-1})	Textural class
Site 1 $_{0-20}$*	57	31	12	0.80	1.06	Sandy Loam
Site 1 $_{0-20}$#	65	28	7	0.16	1.02	Sandy Loam
Site 2 $_{0-20}$*	26	62	12	0.12	1.06	Silty Loam
Site 2 $_{0-20}$#	44	45	11	0.32	1.01	Loam
Site 3 $_{0-20}$*	42	43	15	1.11	1.01	Loam
Site 3 $_{0-20}$#	67	28	5	0.33	1.08	Sandy Loam
Site 1 $_{20-40}$*	41	41	18	0.87	1.09	Loam
Site 1 $_{20-40}$#	35	48	17	0.40	1.05	Loam
Site 2 $_{20-40}$*	31	52	17	0.26	1.03	Silty Loam
Site 2 $_{20-40\#}$	43	24	33	1.04	1.08	Clay Loam
Site 3 $_{20-40}$*	39	38	23	1.02	1.07	Loam
Site 3 $_{20-40}$#	43	40	17	0.89	1.04	Loam

** Reference site*
 # Reclaimed site

3.1.1 Soil Physicochemical Characteristics

Soil pH for the reclaimed sites and their corresponding reference sites varied from 5.50 to 6.45. The highest and lowest soil electrical conductivity were 0.30 and 0.03 dsm-1, respectively for the 0-20 cm depth of Site 1 and the 20-40 cm depth of Site 3. The total and available soil phosphorus was high for all the monitored reclaimed sites, with Sites 1 and 2 recording higher levels than their reference sites. Soil nitrogen contents ranged from 39.80 to 51.80 mgkg-1. There was a general higher trend of total nitrogen levels in the soils sampled from the reference sites compared to the reclaimed sites. Soil organic matter and organic carbon contents were also higher for the reference sites compared to the reclaimed sites as shown in Table 3.

Table 3: The physicochemical parameters of soil samples from the reclaimed mine sites and their respective mine sites

Site	pH	EC (mS/cm)	TP (mgkg-1)	AP (mgkg-1)	TN (%)	OC (%)	OM (%)
Site 1 $_{0-20}$*	6.30±0.16	0.13±0.09	780.00±113.14	12.80±1.21	0.39±0.11	2.65±0.54	4.57±0.74
Site 1 $_{0-20}$#	6.30±0.32	0.30±0.29	1064.00±329.59	14.56±1.07	0.10±0.04	0.91±0.30	1.57±0.52
Site 2 $_{0-20}$*	5.60±0.16	0.09±0.02	1020.00±55.44	13.60±2.84	0.31±0.02	1.97±0.16	3.88±0.25
Site 2 $_{0-20}$#	6.10±0.50	0.13±0.11	800.00±26.46	14.30±1.55	0.27±0.04	1.90±0.23	3.27±0.39
Site 3 $_{0-20}$*	6.45±0.41	0.11±0.03	741.00±66.4	22.17±2.99	0.16±0.02	2.81±1.34	3.77±1.18
Site 3 $_{0-20}$#	5.58±0.13	0.05±0.02	554.00±136.67	26.76±8.58	0.20±0.08	2.23±0.98	3.86±1.70
Site 1 $_{20-40}$*	5.70±0.54	0.05±0.03	710.12±87.24	12.00±1.40	0.27±0.07	1.67±1.08	2.88±0.97
Site 1 $_{20-40}$#	6.32±0.15	0.24±0.25	720.00±98.23	12.54±3.14	0.07±0.03	0.68±0.36	1.18±0.62
Site 2 $_{20-40}$*	6.40±0.22	0.04±0.01	690.00±57.03	12.80±3.11	0.24±0.01	1.36±0.01	2.35±0.01
Site 2 $_{20-40}$#	6.43±0.38	0.07±0.05	710.00±80.00	13.00±2.03	0.22±0.03	1.48±0.21	2.57±0.38
Site 3 $_{20-40}$*	6.37±0.22	0.03±0.01	554.21±45.65	19.08±5.82	0.08±0.02	2.18±0.35	3.25±0.68
Site 3 $_{20-40}$#	5.50±0.10	0.05±0.01	438.00±82.28	24.84±9.18	0.12±0.04	1.21±0.54	2.08±0.93

** Reference site*
 # Reclaimed site
EC: Electrical conductivity; TP: Total phosphorus; AP: Available phosphorus; TN: Total nitrogen; OC: Organic carbon; OM: Organic matter.

3.1.2 Heavy Metal Levels in Soils from Reclaimed and Reference Sites

There was a general trend of higher levels of heavy metals in the soils from the reclaimed sites compared to their respective reference sites in the top 20 cm depth. At Site 1, the soils of the reclaimed site had significantly higher arsenic levels than the reference site (p = 0.0003). The soils from the reclaimed site at Site 2 also had significantly elevated arsenic levels (p = 0.0044) compared to its reference site. Similarly, the arsenic levels in the sampled soils from Site 3 were also significantly higher (p = 0.0005) than its reference site (Figure 1 A). Cadmium and copper levels in the soils from the reclaimed and reference sites of all three sites were not statistically distinguishable from each other (p > 0.05), although the reclaimed sites had slightly higher levels. Lead levels were consistently significantly higher in the soils of the reclaimed sites at Site 1 (p = 0.0407) and Site 3 (p = 0.0489) relative to their reference plots, but there was no significant difference between the levels recorded for the reference and reclaimed sites at Site 2 (p > 0.05). Mercury levels were significantly higher in the reclaimed plots of Site 1 (p < 0.0007) and Site 3 (p < 0.0001) than their respective reference plots but there were no significant differences in the levels for the reclaimed and reference plots at Site 2 (p = 0.2965). The plots of heavy metal levels in the reclaimed and reference sites are shown in Figure 1 (A-H).

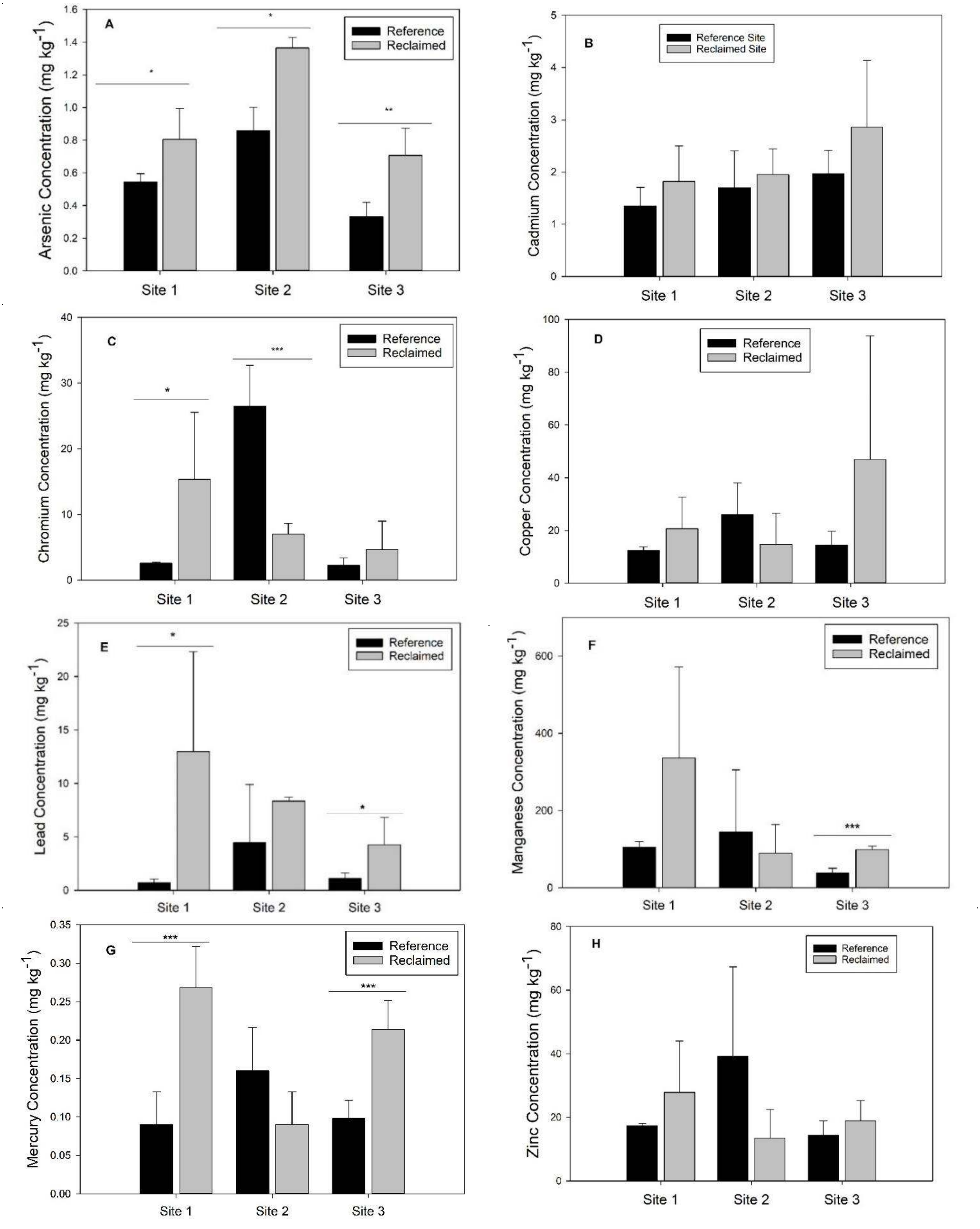

Figure 1 (A-H): Heavy metal levels in the reclaimed gold mining sites and reference sites at 0-20 cm depths.

In the 20-40 cm depth, the trends in the heavy metal levels in the reclaimed and reference sites were fairly similar to the top 20 cm. For arsenic and cadmium, significant differences in the levels recorded for the reclaimed and reference sites were only recorded for Site 2 and Site 3, respectively.

There were no significant differences ($p > 0.05$) in copper and mercury between reference and reclaimed sites at all the three mining sites. Except for Site 3, which recorded a significant difference ($p = 0.0105$) in cadmium levels, there were no significant differences ($p > 0.05$) in the cadmium levels for Sites 1 and 2 (Figure 2). A similar trend was recorded for chromium. Except for the Site 2, Site 1 ($p = 0.043$) and Site 2 (0.0101) recorded significantly higher zinc levels in the reclaimed sites than their respective reference sites.

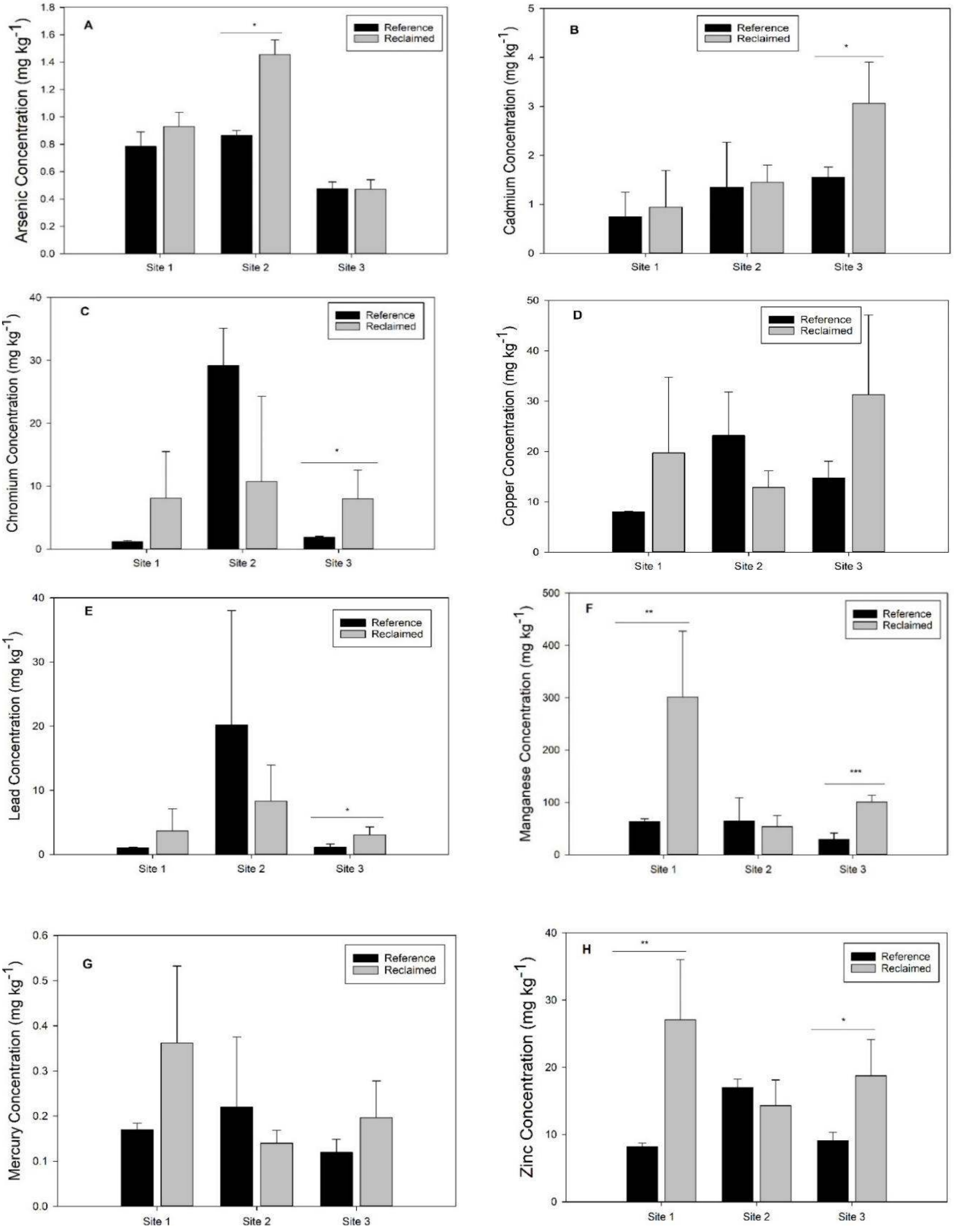

Figure 2 (A-H): Heavy metal levels in the reclaimed gold mining sites and reference sites at 20-40 cm depths.

3.1.3 Effects of Mining on Soil Chemical Properties and Heavy Metal Contamination

The effect size analyses indicated that the reclamation activities at the three sites had not yet restored the mine sites to their pre-mining states. The effect size of the investigated soil chemical properties was negative for all but five parameters in the 0-20 cm depth. Except for potassium and total phosphorus, all the other parameters had moderate to large negative effect size weights. All forms of nitrogenous nutrients had significantly reduced levels in the top 20 cm profiles of the reclaimed sites compared to the reference sites, as evidenced by their significant negative weights. Organic matter and organic carbon levels had also been significantly impacted negatively by mining activities. The trends of the soil chemical properties of the 20-40 cm depth were very similar to the top 20 cm (Figure 3A and B). There were, however, significant positive weights for most of the assayed heavy metals in the two soil levels. Except for chromium and zinc in the 0-20 cm level, and arsenic in the lower profile, all the other metals had positive weights, with cadmium and mercury having large positive effect sizes (Figure 3C and D).

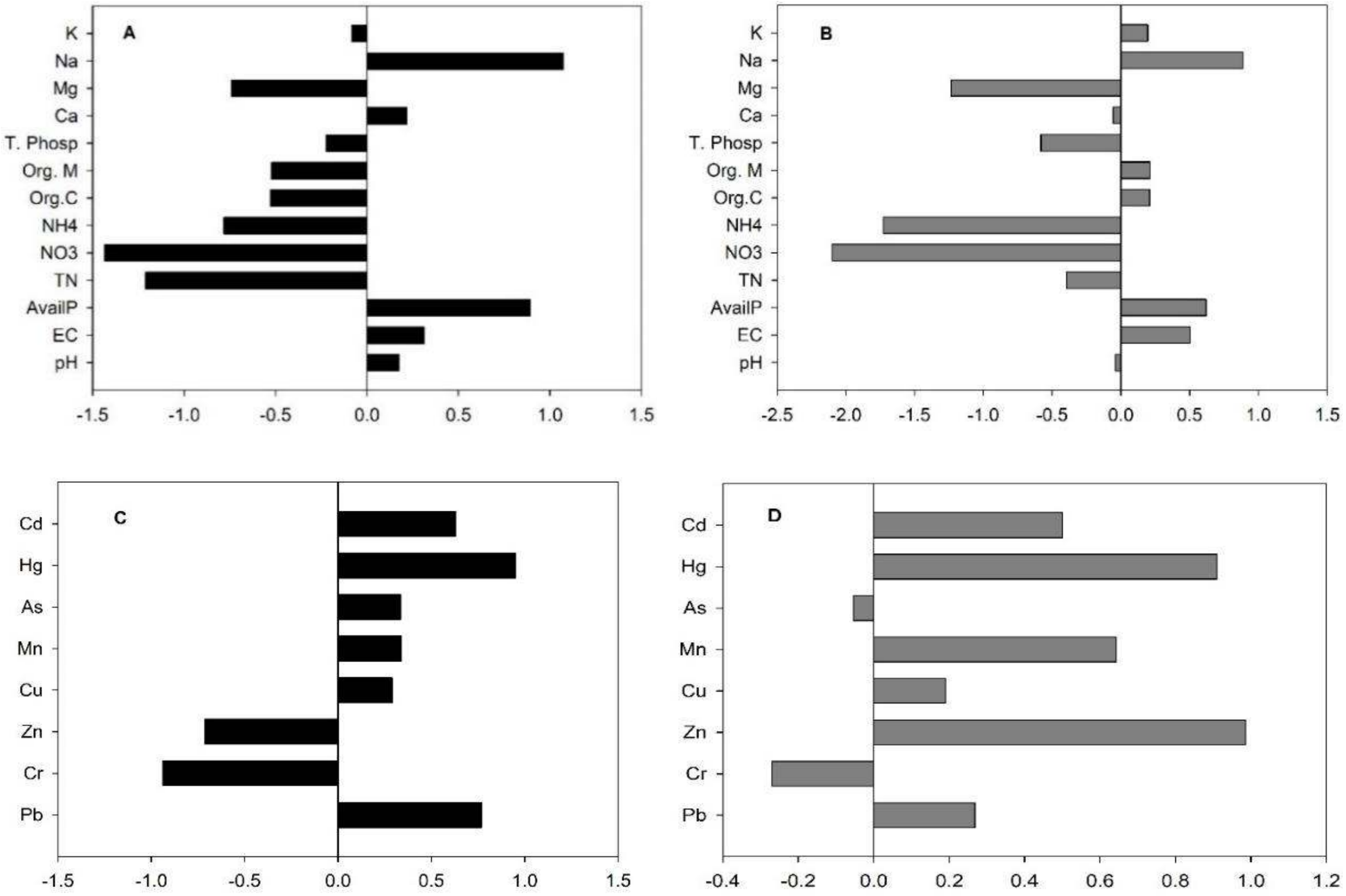

Figure 3: Effects sizes of soil chemical properties (A and B) and heavy metal levels (C and D) of reclaimed and reference sites in three mining areas in Ghana.

3.1.4 Geo-accumulation Index

The calculated geo-accumulation indices for arsenic, lead, chromium, zinc and manganese indicated that the soils of all the mining sites and their respective reference sites were uncontaminated with these metals. Except for Site 1, which recorded mercury levels characteristic of moderately contaminated sites, all the other sites were uncontaminated with mercury. Regarding copper and cadmium, all the sites had sediment qualities fell within the uncontaminated to moderately contaminated category. Table 4 below shows the calculated geo-accumulation indices for the sampled sites and the different sampling depths.

Table 4: Geo-accumulation indices for the monitored heavy metals at the different sites

Site	Cu	As	Hg	Cd	Pb	Cr	Zn	Mn
Site 1 $_{0-20*}$	0.28	-5.91	-1.25	0.95	-5.04	-5.17	-2.66	-3.74
Site 1 $_{20-40*}$	0.22	-5.92	-0.83	0.57	-5.21	-5.37	-2.88	-4.54
Site 1 $_{0-20\#}$	0.41	-5.25	0.81	1.50	-1.58	-2.93	-1.38	-2.19
Site 1 $_{20-40\#}$	0.39	-5.02	1.09	0.25	-4.98	-3.78	-1.32	-2.19
Site 2 $_{0-20*}$	0.29	-5.55	-0.58	0.82	-5.02	-2.77	-2.14	-4.86
Site 2$_{20-40*}$	0.26	-5.95	-0.28	1.49	-5.26	-2.77	-2.18	-5.16
Site 2 $_{0-20\#}$	0.33	-4.94	-0.73	1.68	-0.75	-2.54	-1.63	-3.71
Site 2 $_{20-40\#}$	0.31	-4.97	-0.55	1.34	-1.83	-2.08	-2.17	-4.35
Site 3 $_{0-20*}$	0.30	-6.46	-0.44	1.55	-4.41	-4.68	-2.04	-4.97
Site 3 $_{20-40*}$	0.27	-6.63	-0.87	1.82	-4.51	-5.79	-2.20	-5.24
Site 3 $_{0-20\#}$	0.94	-5.44	0.49	2.14	-2.63	-4.38	-1.75	-3.70
Site 3 $_{20-40\#}$	0.63	-6.00	0.28	2.31	-2.98	-3.49	-1.72	-3.67

3.1.5 Principal Component Analysis

Tables 5 and 6 below summarize the PCA results for the different sampled soil depths of the reference and reclaimed sites. The tables show the loadings, eigenvalues and variance explained by each PC. For the 0-20 cm sampling depth, PC1 explaining 39.79% of total variance has strong positive loadings on Manganese, mercury, chromium and zinc; it also had moderate positive loadings on lead. PC2 had a strong positive variance on copper and cadmium and a moderate negative loading on chromium. For the 20-40 cm depth, PC1 had strong positive loadings on manganese, arsenic and mercury and moderate positive loadings on zinc. PC2 had a strong positive loading on lead and moderate positive loadings on arsenic and chromium. That component also had a moderate negative loading on manganese. PC3 had strong and moderate positive loadings on cadmium and copper respectively.

Table 5: Loadings of variables on the principal components (PCs) for the combined heavy metal dataset from the reclaimed and reference sites in the 0-20 cm soil layer

	PC 1	**PC 2**	**PC 3**	**PC 4**	**PC 5**	**PC 6**	**PC 7**	**PC 8**
Copper	0.31	**0.73**	-0.37	0.11	0.44	0.13	-0.11	0.00
Manganese	**0.80**	-0.20	-0.32	0.13	-0.27	0.30	-0.07	0.17
Arsenic	0.44	-0.04	**0.67**	**0.56**	0.05	0.17	0.00	-0.11
Mercury	**0.76**	0.30	-0.25	0.22	-0.25	-0.35	-0.13	-0.10
Cadmium	0.22	**0.85**	0.33	-0.11	-0.16	-0.03	0.27	0.11
Lead	**0.62**	0.02	**0.53**	**-0.51**	0.07	-0.02	-0.28	0.05
Chromium	**0.74**	**-0.50**	0.02	0.13	0.31	-0.26	0.17	0.14
Zinc	**0.83**	-0.16	-0.17	-0.38	0.02	0.15	0.22	-0.20
Eigenvalue	3.18	1.63	1.17	0.82	0.46	0.35	0.26	0.13
%Variance	39.79	20.43	14.62	10.21	5.76	4.38	3.22	1.59

Table 6: Loadings of variables on the principal components (PCs) for the combined heavy metal dataset from the reclaimed and reference sites in the 20-40 cm soil layer

	PC 1	**PC 2**	**PC 3**	**PC 4**	**PC 5**	**PC 6**	**PC 7**	**PC 8**
Copper	0.12	-0.30	**0.63**	**0.64**	-0.28	-0.12	0.01	-0.04
Manganese	**0.82**	**-0.50**	-0.06	-0.07	-0.09	-0.04	-0.02	0.25
Arsenic	**0.71**	**0.52**	-0.12	0.08	-0.20	0.20	0.37	-0.02
Mercury	**0.80**	-0.31	-0.11	0.19	0.24	0.33	-0.21	-0.12
Cadmium	-0.34	-0.08	**0.82**	-0.25	0.15	0.32	0.08	0.07
Lead	0.38	**0.71**	0.28	-0.23	-0.35	0.02	-0.31	0.00
Chromium	0.38	**0.65**	0.25	0.25	**0.51**	-0.20	0.00	0.07
Zinc	**0.66**	-0.32	0.34	-0.49	0.06	-0.26	0.10	-0.14
Eigenvalue	2.66	1.75	1.35	0.87	0.60	0.38	0.29	0.11
%Variance	33.22	21.84	16.87	10.90	7.50	4.70	3.63	1.34

From the PCA analysis, the first 2 computed principal components explained 60.22% and 55.06% of the observed variances in the 0-20 cm and 20-40 cm sampling profiles, respectively. The loadings and scores of the first two principal components (Component 1 & Component 1) are plotted in Figures 4 and 5. The plot for the 0-20 cm depth profile indicated a mutual correlation between cadmium and copper levels and a strong mutual correlation between mercury and zinc, as evidenced by their closeness. In the 20-40 cm depth, lead and chromium were strongly correlated while mercury, zinc and manganese were also mutually correlated. The score plots show the distribution of heavy metals within the different sampling depths as well as their spatial distributions and associations with the reclaimed and reference sites. Overall, the PCA analysis showed clear trends of heavy metal enrichment in the soil samples of the reclaimed sites compared to the reference sites. The reclaimed sites of the three mining areas were generally found in the upper and lower right quadrants of the plot and were more associated with the assayed heavy metals. The reference sites were more distributed in the left quadrants and were less associated with elevated levels of heavy metals.

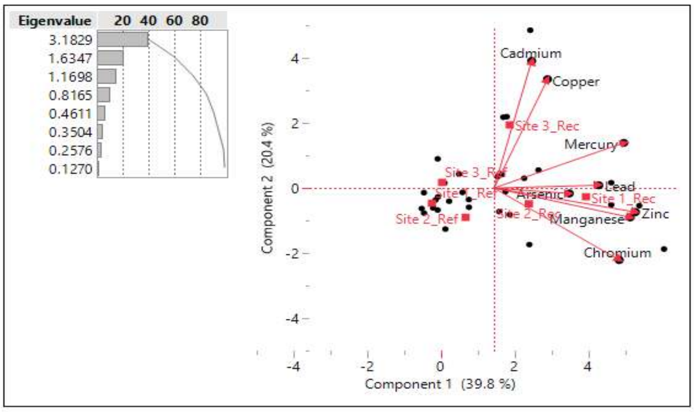

Figure 4: PCA biplot showing relationships of heavy metals concentrations and the reclaimed and reference sites for the 0-20 cm soil layer

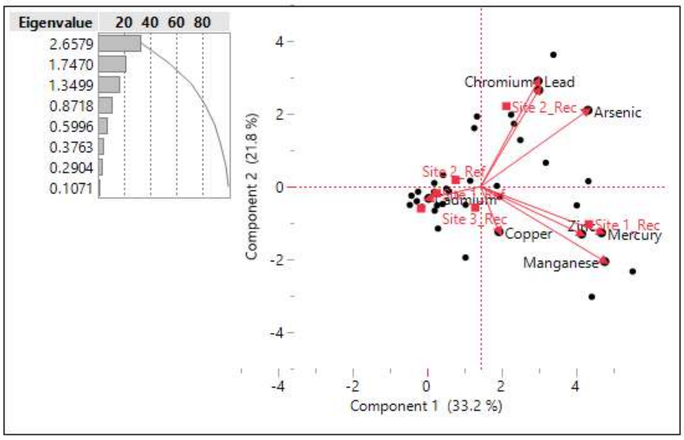

Figure 5:. PCA biplot showing relationships of heavy metals concentrations and the reclaimed and reference sites for the 20-40 cm soil layer

4.0 DISCUSSION

4.1 Soil Physicochemical Properties

The 0-20 cm sections of both the reclaimed and reference sites had higher levels of phosphorus, nitrogen, organic matter and organic carbon contents compared to the 20-40 cm sections. This is a result of most areas in the study locations having topsoil up to depths of 20 cm. Topsoil usually contain most of the nutrients required for plant growth. The higher phosphorus levels in some of the reclaimed sites compared to their respective reference sites are possibly due to the mining rocks deposited on these sites, such rocks usually contain higher amount of phosphorus. The initial reclamation processes, including topsoil amendments and nutrient enhancements through biochar and compost could also improve soil nutrient levels [33]. For successful phyto-stabilization in the initial stages of the reclamation process, soil amendments are usually required to create optimum growing conditions for re-vegetation, immobilize accumulated heavy metals and decrease their bioavailability to water sources or the food web [34].

Reclamation projects by some mining companies in Ghana consist of backfilling the site with topsoil before vegetation establishment [35]. On severely impacted sites, it becomes necessary to spread topsoil on the site to aid vegetation establishment. Some post-mining reclamation strategies also involve the spreading of oxide materials to improve soil nutrient availability. These practices usually result in soils with better fertility attributes than unrepaired soils. Organic matter and organic carbon contents were, however, lower in the soils of the reclaimed sites compared to the reference site. The soils of mine-disturbed sites are usually characterized by low organic matter, low pH and higher concentrations of heavy metals compared to adjacent undisturbed sites [13]; [36].

Some mining companies apply biochar to degraded soils as an economical but effective means of improving soil properties and immobilizing heavy metals. Biochar, with their unique properties of high pH play a significant role in increasing soil pH to optimum levels [37], [33] which possibly explains why the soils of the reclaimed sites had similar pH to the reference sites. The elevated soil nitrogen levels of most of the reclaimed sites could also be due to the establishment of nitrogen-fixing tress such as *Acacia mangium, Gliricidia sepium, Leucaena leucocephala and Senna siamea.*

4.2 Depth-wise Distribution of Heavy Metals

The extent of contamination and vertical migration of metals in reclaimed and reference sites was assessed by analyzing the total environmentally available heavy metal concentrations at depths of 0-20cm and 20-40 cm. Although not consistent for all metals, there was a trend of heavy metal concentrations decreasing with increasing depth, which is consistent with previous reports that sites contaminated by anthropogenic activities typically contain higher levels of heavy metals in the surface horizons [38].

The presence of tailing debris beneath the reclaimed sites may account for the observed patterns of elevated heavy metal concentrations with depth, as these profiles extend downward toward the tailing layer. The variations in the vertical distribution profiles of heavy metals in each sampling area may reflect differences in the depth between the topsoil and the underlying tailing debris. Higher metal levels in the topsoil layers relative to the lower layer is indicative of anthropogenic influence coupled with low metal mobility within the depth profiles [39]. Heavy metals also exist in different geochemical forms in soil either as water-soluble, exchangeable, carbonate-bound, Fe-Mn oxide-bound, organic matter bound or residual [40]. The non-residual fractions of heavy metals generally tend to be more available and mobile than metals associated with residual fractions [41]. Variations in soil pH can also influence the mobility of certain metals in soils. Studies have shown that high pH results in stable forms of lead and cadmium while a low soil pH can facilitate the release of lead and cadmium [42]. Lead was one of the heavy metals that consistently had higher levels in the 0-20 cm layer of the reclaimed sites. Lead in soils has a very high affinity for organic matter and in instances where soil organic matter is fairly high, the downward mobility of lead can be reduced [43]. Physical characteristics such as soil permeability or porosity may also affect the variability of heavy metals [44].

4.3 Contamination Levels and Spatial Distribution of Heavy Metals

It is unsurprising that the PCA analysis showed clear trends of high heavy metals in the soil samples of the reclaimed sites compared to the reference sites, even though most of the assayed metals fell into the “uncontaminated” category following the calculations of the geo-accumulation indices. The low levels of heavy metals on the reclaimed sites could be attributed to the high bioaccumulation affinity of the planted vegetation for some metals. Plants predominantly absorb zinc from soils as a divalent cation, which in plant tissues and cells serve as cellular component, as enzymes, or as a functional, structural, or regulatory co-factor of many enzymatic reactions [45]. Only cadmium and copper for all the sites and mercury for the Chirano Gold Mine site (CHREC) site had moderate levels of contamination. Gold mining is linked to elevated soil mercury levels. Mercury is generally introduced from mining activities through the gold amalgamation process [46].

According to [46], about 29% of the mercury used in ore amalgamation is lost in the mining process. The majority of mercury is usually accumulated within the top 25 cm of the soil layer and has a mobility rate of 0.03–0.07 cm/year [47] which explains the high mercury concentration within the 20-40 cm layer of the CHREC site. Cadmium is a heavy toxic metal of adverse environmental and health concerns, and a by-product of mining [48]. In gold processing and ore concentration processes, other metal elements with high density, such as copper, can potentially be concentrated in the tailings, generating geochemical anomalies and contamination hotspots [49]. Metals such as copper and mercury in soils have low mobility in soils and are often less taken up by plants [50]. This possibly explains the moderate contamination of the soils with these metals.

5.0 CONCLUSION

There was a general trend of higher levels of assayed heavy metals from the reclaimed sites compared to their respective reference sites. Higher heavy metal levels were associated with the top soil layer (0-20 cm) indicating a potential low metal mobility in the soils of the study area. The calculated geo-accumulation indices for arsenic, lead, chromium, zinc and manganese indicated that the soils of all the mining sites and their respective reference sites were uncontaminated with these metals. Although mercury, cadmium and copper levels were characteristic of moderate contamination in some of the reclaimed sites, the general trend was indicative of successful reclamation regimes that aim to restore the mine-impacted areas to acceptable environmental conditions or pre-mining characteristics. Reclamation of mine sites with biochar and compost hold a great potential to improve soil physicochemical properties and reduce heavy metal concentration. Further studies should evaluate the duration of the reclamation practice on soil properties and heavy metals levels. Since the metal concentration was higher at 0-20 cm soil depth, some grasses (shallow-rooted) which have the ability to adsorb heavy metals should be tested.

6.0 RECOMMENDATION

This study has four recommendations First, adopt Site-Specific Reclamation Strategies: Since contamination trends and soil properties varied among sites, reclamation interventions should be tailored to site-specific conditions rather than applying uniform approaches. For example, areas with persistently high mercury contamination may require more advanced remediation such as soil washing or immobilizing agents (e.g., lime, phosphates). Secondly, strengthen Policy and Compliance Frameworks: Mining companies should be mandated to conduct independent post-reclamation environmental audits, verified by Ghana's Environmental Protection Agency (EPA), to ensure full compliance with reclamation bond agreements. Clear success criteria should be defined—not just vegetation establishment, but also soil nutrient recovery and heavy metal stabilization within safe thresholds. Furthermore, promote Community Participation in Reclamation: Involving local communities in monitoring, vegetation establishment, and land-use planning after reclamation can improve transparency, ensure sustainable land management, and build trust between mining firms and host communities. Lastly, encourage Research on Remediation Technologies: Further studies should test the effectiveness of different grasses, cover crops, and microbial inoculants in immobilizing or extracting heavy metals from reclaimed soils. Longitudinal research is needed to assess how reclamation efforts evolve beyond the short-term, particularly regarding heavy metal persistence and ecological restoration.

AUTHOR CONTRIBUTIONS

Conception or design of the work: E. Darko, B. Fie-Baffoe, J. N. Hogarh; Data collection: E. Darko, A. Anning, K A. Obirikorang; Data analysis and interpretation: A. Anning, K A. Obirikorang; Drafting the article: E. Darko, C. Afriyie-Debrah, A. Anning, K A. Obirikorang; Critical revision of the article: E. Darko, C. Afriyie-Debrah, B. Fie-Baffoe, J. N. Hogarh, D. Osei-Twumasi, A. K. Keteku; Final approval of the version to be published: All Authors

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy, have been completely witnessed by the authors.

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Negative AI Statement

The author(s) declared that no AI tools or services were not used or not highly applied during the preparation of this work.

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