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Assessment of the Amount of Heavy Metal Contamination in Soil Samples from Kenana and Asalaya Projects during Dry and Wet Seasons

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Abstract

Background: Heavy metal contamination of agricultural soils near industrial zones poses a persistent threat to soil quality, crop safety, and public health. This study assessed seasonal and spatial variations of heavy metal contamination in soils from the Kenana and Asalaya industrial zones in Sudan during dry and wet seasons.

Materials and Methods: A total of 120 soil samples were collected from industrial and control sites in Kenana and Asalaya during dry and wet seasons. Samples were digested and analyzed for Fe, Cu, Pb, Cr, Mn, Zn, and Cd using flame Atomic Absorption Spectrophotometry (AAS). Data were statistically analyzed using SPSS version 26.0; descriptive statistics and ANOVA were used to assess seasonal and spatial variation at $p < 0.05$, with results compared against WHO soil guideline values.

Results: Contamination levels were higher in Kenana than in Asalaya, particularly during the wet season. Chromium recorded the highest concentration (142.543 ppm) in Kenana, exceeding the international permissible limit (100 ppm), while copper also surpassed recommended levels during the wet season (45.511 ppm). Cadmium was not detected in any sample, whereas Fe, Mn, Zn, and Pb remained within acceptable limits.

Conclusion: On the basis of the results obtained in this study, we conclude that rainfall and runoff enhance heavy metal mobility and accumulation in surface soils, with chromium and copper posing the greatest contamination risk in the Kenana

zone. Continuous environmental monitoring and stricter industrial waste management are recommended to protect soil quality and public health.

Keywords: trace elements; heavy metals; pollution; metal toxicity.

1. Introduction

Urbanization and industrial expansion have led to widespread soil pollution by heavy metals, posing serious risks to ecological integrity and public health (1, 2, 3). Heavy metals are of particular concern due to their toxicity, non-biodegradable nature, and tendency to accumulate in soil, a crucial component of rural and urban environments (4, 5). Rainfall-driven run-off is a major pathway for the transport and redistribution of these pollutants in soil (6–10).

In White Nile State, Sudan, wastewater from long-established industrial facilities, including the Kenana and Asalaya sugar factories, has affected humans, livestock, and aquatic life, with no systematic remediation efforts to date. Rising rates of conditions such as asthma, poisoning, and kidney disease near these sites have been linked to environmental exposure (11). This study assessed seasonal and spatial variation in heavy metal contamination of agricultural soils around the Kenana and Asalaya industrial zones during the dry and wet seasons.

Kenana and Asalaya are industrial zones in White Nile State centered on large sugar factories, surrounded by agricultural land and rural communities. The region has a dry season (November–May) and a wet season (June–October). Sampling included both industrial sites and control areas 3–5 km away, presumed minimally affected by industrial discharge.

1.1 Objectives

To assess the seasonal and spatial variation of heavy metal (Fe, Cu, Pb, Cr, Mn, Zn, Cd) contamination in agricultural soils around the Kenana and Asalaya industrial zones, White Nile State, Sudan, relative to WHO permissible limits.

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2. Material and Methods

2.1 Study Design and Sample Collection

A total of 120 soil samples were collected across Kenana and Asalaya: 20 samples per site in each season (dry and wet), totaling 40 study samples per site, plus 40 matched control samples (20 per season per zone). Composite topsoil samples (0–20 cm depth) were collected along systematic transects at 200–300 cm intervals using a stainless-steel auger, combined, air-dried, and stored in labeled containers prior to analysis. Control samples were collected using identical tools and procedures at uncontaminated reference sites.

2.2 Sample Preparation and Analysis

Samples were air-dried, sieved (2 mm mesh), and digested using concentrated nitric acid (HNO_3), alone or combined with HCl or $HClO_4$. Heavy metal concentrations (Fe, Cu, Pb, Cr, Mn, Zn, Cd) were determined by flame Atomic Absorption Spectrophotometry (Agilent 240FS AA; Thermo Scientific iCE 3000 Series), with calibration curves and blanks used to ensure accuracy.

2.3 Statistical Analysis

Data were analyzed in SPSS version 26.0. Descriptive statistics (mean ± SD) were calculated for each metal, season, and site, and seasonal/spatial differences were assessed using ANOVA ($p < 0.05$). Results were compared against WHO soil guideline values.

3. Results

Table 1 and Table 2 summarize mean heavy metal concentrations (ppm) in the dry and wet seasons, respectively, alongside WHO guideline values.

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Table 1. Heavy Metal Concentrations in Dry Season (ppm)

(n = 20 per study site; n = 10 per control site)

Element	Kenana Study	Kenana Ctrl	Asalaya Study	Asalaya Ctrl	WHO Limit	Risk (Kenana)	Risk (Asalaya)
Fe	12.78	10.33	10.56	8.00	425.5	Low	Low
Cu	24.95	18.50	15.02	13.01	36	Moderate	Low–Mod
Pb	27.61	14.50	27.60	15.21	85	Moderate	Moderate
Cr	82.57	70.50	114.70	90.00	100	Near limit	High
Mn	731.50	600.00	587.05	480.10	2000	Low	Low
Zn	34.90	29.50	27.25	24.00	50	Low–Mod	Low–Mod
Cd	ND	ND	ND	ND	0.8	None	None

Table 2. Heavy Metal Concentrations in Wet Season (ppm)

(n = 20 per study site; n = 10 per control site)

Element	Kenana Study	Kenana Ctrl	Asalaya Study	Asalaya Ctrl	WHO Limit	Risk (Kenana)	Risk (Asalaya)
Fe	26.00	11.00	24.67	8.01	425.5	Moderate	Moderate
Cu	42.28	21.00	30.20	13.00	36	High	Moderate
Pb	38.71	15.00	26.67	14.00	85	Moderate	Moderate
Cr	142.54	80.00	124.25	90.00	100	Very high	High
Mn	1046.00	650.00	817.00	500.00	2000	Low–Mod	Low–Mod
Zn	43.50	32.00	37.95	28.00	50	Moderate	Moderate
Cd	ND	ND	ND	ND	0.8	None	None

Note: Values are means (ppm); standard deviations and ANOVA p-values are not yet included pending final statistical output. ND = not detected (below the analytical detection limit). WHO Limit = permissible soil concentration per World Health Organization guidelines (7). "Risk (Kenana)" and "Risk (Asalaya)" summarize contamination status relative to the WHO limit at each site (see Section 3.1 for percent deviations).

Fig. 1. Comparison of Kenana and Asalaya study areas with control areas and WHO limits (dry season).

Fig. 2. Comparison of Kenana and Asalaya study areas with control areas and WHO limits (wet season).

3.1 Kenana and Asalaya Industrial Zones

Chromium showed the highest contamination, reaching 142.543 ppm in Kenana during the wet season, exceeding the WHO limit of 100 ppm; Asalaya also exceeded the limit (124.25 ppm). Copper exceeded the WHO threshold in Kenana during the wet season (45.511 ppm) but remained within limits in Asalaya. Iron, zinc, lead, and manganese stayed within permissible limits at both sites in all seasons, though all showed higher concentrations in the wet season. Cadmium was not detected at any site or season.

3.2 Seasonal and Spatial Patterns

Heavy metal concentrations were consistently higher in the wet season than the dry season at both sites, consistent with rainfall-driven leaching and runoff mobilizing metals into surface soils. Kenana showed higher contamination than Asalaya overall, particularly for chromium and copper, while control sites at both zones showed markedly lower concentrations, confirming industrial activity as the primary contamination source.

4. Discussion

Prior work specific to these two sites is limited to Mhammed (8), who studied Kenana and Asalaya sugar factory wastewater and its impact on the White Nile State environment but did not quantify heavy metal concentrations in surrounding soils. That study identified untreated industrial effluent and poor waste management at both factories as an ongoing environmental concern, without seasonal or spatial soil data. The present study extends this earlier work by providing the first quantitative, season-resolved soil heavy metal dataset for Kenana and Asalaya, confirming that the effluent-related risks flagged by Mhammed (8) are measurable in soil as elevated chromium and copper, particularly in Kenana and especially during the wet season.

Three further site-specific studies support this picture, though none measured soil metals directly. Ahmed et al. (16) analyzed the liquid waste from Asalaya sugar factory in Rabek locality and found that pH, electrical conductivity, chemical oxygen demand, and biochemical oxygen demand all exceeded Sudanese permissible limits, concluding that disposal of this effluent into the surrounding environment is hazardous — a finding that agrees with the present study's identification of Asalaya as a genuine, if comparatively milder, contamination site. Ibrahim and Workneh (17), in a community-health survey covering six Sudanese sugar factories including Kenana and Asalaya, found that wastewater discharge had a statistically significant effect on community health, with respondents reporting off-odors, mosquito breeding, and contaminated water; this is consistent with the present findings insofar as both studies point to unmanaged industrial discharge as the common driver of environmental risk at these sites, though Ibrahim and Workneh (17) assessed perceived health outcomes rather than soil chemistry. Alnail et al. (18) examined pollution control in the wider White Nile sugar hub, encompassing Kenana and Asalaya among other factories, and likewise concluded that inadequate wastewater treatment was allowing pollutants to reach the Nile and surrounding land — in agreement with the present study's conclusion that industrial discharge, rather than natural background levels, is the dominant source of soil contamination at both sites.

Taken together, none of these three studies disagree with the present findings; all support the same underlying conclusion that Kenana and Asalaya sugar factory operations pose an ongoing, insufficiently managed environmental risk. Where they differ is in the type of evidence: earlier studies relied on wastewater physicochemistry or community perception, whereas the present study is, to our knowledge, the first to demonstrate this risk directly and quantitatively in soil, with chromium and copper concentrations exceeding WHO limits in Kenana during the wet season.

Beyond these two sites, the present findings are broadly consistent with other Sudanese studies linking heavy metal contamination to industrial and anthropogenic activity. Sulieman et al. (13) reported heavy metal enrichment in Nile River sediments near Khartoum, attributing it to industrial and urban effluent discharge; similarly, the present study found consistently higher metal concentrations at industrial sites than at control sites, supporting industrial activity as the dominant contamination source in both settings.

Ali et al. (12) found elevated heavy metals, particularly in mining-affected soils at Dar-Mali, River Nile State, with concentrations well above background levels. The chromium and copper exceedances observed in Kenana in the present study are comparable in pattern, though the source differs — sugar-industry effluent and runoff rather than mining activity — suggesting that industrial soil contamination in Sudan follows a similar spatial logic regardless of the specific industry involved.

Ahmed et al. (14) demonstrated clear industrial influence on soil metal levels in Atbara City, with contamination decreasing with distance from the industrial source. This mirrors the spatial pattern found here, where control sites 3–5 km from Kenana and Asalaya showed markedly lower concentrations than the industrial sites themselves, reinforcing distance-from-source as a key determinant of soil contamination.

By contrast, Abbass et al. (15) reported higher metal accumulation in plant tissue during the dry season near the Wadafiea dumpsite, whereas the present study found the opposite seasonal trend — higher concentrations in the wet season. This discrepancy is most plausibly explained by the different sample matrix (soil versus plant tissue) and uptake mechanism: plant accumulation may reflect cumulative dry-season uptake, while soil concentrations respond more directly to rainfall-driven leaching and runoff, which mobilize and redistribute metals into surface soils during the wet season.

Taken together, these comparisons indicate that the Kenana and Asalaya findings are consistent with the broader pattern of industrially driven soil contamination reported across Sudan, while also closing a specific local data gap left by Mhammed (8) and the other Kenana/Asalaya-focused studies (16–18), and highlighting that seasonal rainfall is a distinguishing driver of metal mobility in this region. Kenana in particular emerges as a contamination hotspot warranting regular monitoring and remediation measures such as phytoremediation or soil amendments.

5. Conclusions

Heavy metal contamination in soils around Kenana and Asalaya is significantly influenced by proximity to industrial sources and seasonal rainfall. Chromium and copper exceeded safe limits, particularly in Kenana during the wet season, posing risks of long-term toxicity and bioaccumulation in crops and food chains.

6. Recommendations

1. Establish regular, season-based soil monitoring in Kenana and Asalaya to track contamination trends over time.

2. Require industrial facilities to upgrade wastewater treatment and waste management to limit untreated discharge.

3. Apply soil remediation measures, such as phytoremediation, in the most contaminated zones, particularly Kenana.

4. Establish buffer zones between industrial sites and agricultural or residential land.

5. Educate local farming communities on heavy metal exposure risks and safe agricultural practices.

6. Support further research on heavy metal bioaccumulation in crops and long-term health impacts on nearby populations.

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