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Integrated ecological and health risk assessment of heavy metals in surface water, soil and vegetables along Asa River, Ilorin, Nigeria

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Abstract

This study examined the multimedia pollution status, ecological and health risks of heavy metals (Cd, Mn, Fe, Cu, Pb, Zn, Cr) in water, soil and vegetable sampled along Asa River, Ilorin, Nigeria. Ten (10) soil, water, and vegetable samples were taken specifically from areas where the river is commonly used for irrigation. The collected samples were prepared and evaluated for metal contents with Atomic Absorption Spectrometer. The pollution and ecological states of soil, water, and vegetables samples were assessed using already established indices whereas health risks were evaluated by both carcinogenic and non-carcinogenic risk indices. The results revealed that Fe concentration was highest in soil, water and vegetables with range 988.32–3407.60 mg/kg, 1.32–10.31 mg/kg, and 15.12–68.04mg/kg respectively. The computed values of contamination factor and geo-accumulation index showed low contamination from individual metals while the overall pollution index showed that sites 5, 6, and 7 were polluted with the metals. All the metals combined presented low ecological and potential ecological risks in all sites investigated. Results of heavy metal toxicity load showed both Cu and Zn were within the permissible limit whereas Mn exceeded the limit across A4 to A10. All the metals combined showed low toxicity effect on the water quality as estimated by heavy metal pollution index. The vegetables samples had low potential for heavy metal bioaccumulation. Findings revealed that exposure to soil, water, and vegetables in the study area poses low health risk to humans and insignificant cancer risk due to heavy metals.

Nomenclature and units

mg/kg	Milligram per kilogram
$g/cm3$	Gram per centimeter cube
cm	Centimeter
mL	Milliliter
g	Gram

1.0 Introduction

Elements having an atomic density exceeding 5 g/cm³ are classified as heavy metals (Sadak, 2023). These metals rank among the most prevalent environmental pollutants, posing significant toxicity even at trace levels (Jia et al., 2020). Their occurrence in water bodies and biota signals contamination of such environmental media from either natural or human activities (Bawa-Allah, 2023). Environmental contamination can occur naturally due to geological occurrences like lithogenesis, weathering, volcanoes, as well as forest fires (Timothy and Williams, 2019), whereas human contamination includes emissions from traffic, agricultural, mining, smelting, and industrial discharge (Masindi et al., 2021).

Excessive levels of these metals have been found in soil, natural waters, and living things due to the growth of urban and industrial areas (Angon et al., 2024; Oloruntoba et al., 2024; Xu et al., 2024). Owing to their toxicity, non-degradability, and capacity to bio-accumulate and bio-magnify in living tissues, heavy metals present serious risks to human and the ecosystems (Laoye et al., 2025; Saleh and Hassan, 2022; Briffa et al., 2020). Cancer, digestive disorder, cardiovascular issues, and skin lesions have all been linked to arsenic exposure (Rahaman et al., 2021; Speer et al., 2023; Khan et al., 2020). Asides its effects on the hematopoietic system (Sani and Amanabo, 2021), lead also affects the central nervous system (Araki et al., 2020; Shvachiy et al., 2020). Chromium is a known respiratory system carcinogen (Shin et al., 2023). Excessive molybdenum exposure can cause reproductive defects in humans and other animals (Albin and Oskarsson, 2022). Intake of cadmium, a human carcinogen can also cause respiratory failure (Rasin et al., 2025), anemia (Fujiwara et al., 2020), immune system, fertility, lungs, and kidney defects (Knoell and Wyatt, 2021; Wang et al., 2021). Overexposure to copper can cause lung cancer and depression (Ge et al., 2022; Guan et al., 2023). Nickel is linked to respiratory tract cancer, asthma, cardiovascular diseases, lung defects, and dermatitis (Genchi et al., 2020).

There is an alarming rate of heavy metal deposition in aquatic systems (Bawa-Allah, 2023) with rivers and other freshwater bodies serving as the main pathways for metal transport (Udongwo, 2023), resulting in their prevalence as pollutants in several riverine areas (Gavhane et al., 2021). Toxic metal accumulation in water reservoirs presents a significant danger to aquatic life (Uchendu and Edogbo, 2025).

Heavy metal pollution of soil presents serious environmental challenges globally (Hou et al., 2025). Excessive enrichment of soil by toxic metals tends to degrade the soil and adversely affect plants growth (Angon et al., 2024). Consuming food grown in metal-polluted soil is associated with some medical conditions (Alegbe et al., 2025), as the food chain is the major path through which humans take in heavy metal (Rai et al., 2019). Vegetables cultivated in such polluted soils absorb and store these toxic metals in both edible and inedible parts, in amounts sufficient to pose health related issues (Alegbe et al., 2025).

Asa river is the main water body that serves Ilorin metropolis. Many Ilorin residents and those residing in surrounding areas depend on the river as the main water source for agricultural purposes, including its use for irrigation of farms and fishing. The river receives domestic and agricultural waste along its banks, in addition to industrial effluents from various manufacturing plants in the city. Previous research has investigated heavy metal contamination of Asa River (Eletta et al., 2003; Adekola and Eletta, 2007; Olawale et al., 2016; Opasola et al., 2019; Adewoye et al., 2021). However, most of these reports have focused on either water quality or sediment contamination in isolation, with limited attention to the transfer of contaminants across environmental media and their potential human health implications. Consequently, there remains a knowledge gap in understanding the ecological connectivity between the river water, adjacent soils, and food crops irrigated with the contaminated water.

This study therefore adopts an integrated environmental assessment approach that simultaneously examines heavy metal concentrations in water, soil, and vegetables along the Asa River corridor. Such a holistic framework allows for a more accurate estimation of pollution pathways, bioaccumulation potential, and associated ecological and health risks, providing evidence essential for risk management and policy interventions. A key limitation of this research is that sampling was conducted only once during the study period, which restricts the ability to capture seasonal fluctuations in heavy metal concentrations. Consequently, the findings of this research represent a snapshot of the pollution status and may not fully reflect the temporal dynamics of heavy metal distribution across different seasons.

2.0 Materials and Methods

2.1 Study Area

Asa River, located between longitudes 4°30´ to 4°37´E and latitudes 8°27´ to 8°32´N (Oladimeji and Abdulsalam, 2014), with a 14 meters' depth and 302 hectares surface area (Adekeye, 2004). It runs through Ilorin township; it enters the industrial estate from the south and flows north through residential and commercial areas (Kolawole et al., 2011). As a result, it receives domestic, agricultural, and industrial waste from its various tributaries within Ilorin metropolis. It is extensively used for irrigation by farmers for cultivation of different crops and vegetables.

2.2 Sample Collection

Samples were collected at locations where irrigation is practiced along the bank of the river. Ten (10) sampling points, tagged A1, A2, A3, ------------A10 were identified along the plain of Asa River: soil, water, and vegetable (*Celosia argentea*) samples were taken at these points. Sites A1, A2 and A3 are within the upper stream of the river while sites A4 to A8 are within the densely populated area of the city serving as the midstream and sites A9 & A10 are downstream. Samples were collected only during dry season period (February 2025), thus limiting the research's ability to determine seasonal variations in heavy metal concentrations across sampling points. The sampling points' coordinates were taken using global positioning system (GPS) device. This was used to develop study area map (Figure 1).

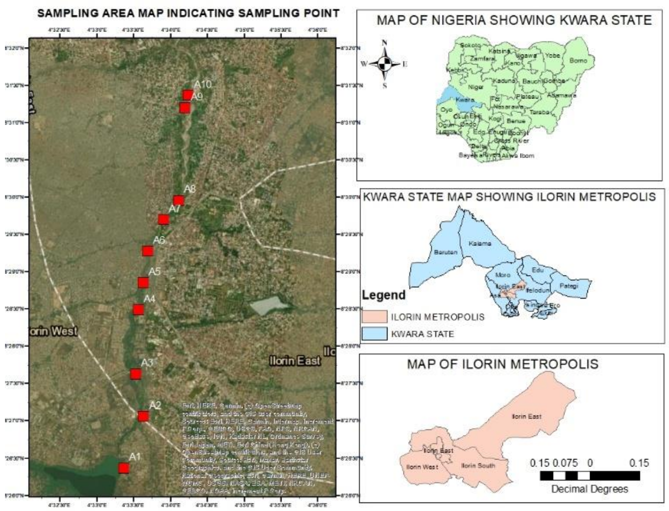

Figure 1: Location of Water, Soil and Vegetable Sampling along Asa River, Ilorin

Water Sample

Using 250 ml polyethylene bottles that were initially cleaned with deionized water and rinsed with ambient water, water samples were taken in triplicate. Upon collection, the samples were acidified using 1% HNO_3, labeled, and transported to the laboratory.

Soil Sample

Triplicate samples were collected a few meters away from the water sampling point using stainless-steel soil auger at a depth of 0 – 30cm. Samples were thoroughly mixed, afterwords pebbles, stones and other dirt removed. The samples were then properly stored and labeled in polyethylene bags.

Vegetable (*Celosia argentea*)

Fresh vegetables (*Celosia argentea*) were harvested at the soil sampling points. Three whole plants were randomly harvested from each sampling point. Edible parts of the vegetable were removed, washed, and kept in a clean polythene bag.

2.3 Preparation and Digestion of Samples

Soil samples were air-dried for twenty-four (24) hours, crushed to achieve a uniform mixture, and sieved through a 2mm sieve. A mixture of HF, $HClO_4$, and HNO_3 in a ratio of 3:1:3 was added to 1g of the sample in a 250-mL volumetric flask, following the method described by Nwajei and Gagophien (2000). This was placed on hotplate, heated for a brief period at 145°C to digest. After digestion, the sample was cooled, passed through a filter to a 100-ml flask, and added deionized water to fill it to 100 ml mark. 100 mL of sampled water was measured into a 250 mL beaker, 10 mL HNO_3 added and heated at 90 °C until evaporation to about 40ml. The digestate was then filtered in 100 ml conical flask and deionized water was added to reach the 100 ml mark (APHA, 2012).

Celosia argentea were oven-dried at 70^{0}C, crushed and passed through 2 mm sieve to have homogenous fine particles. 1 g was weighed, and put in a beaker, with 5mL of conc. HNO_3 added in the fume hood and swirled carefully. The mixture was heated to 145^{o}C and 10 mL of di-acid (reagent mixed HNO_3 and $HClO_4$ in 9:4 ratio) added and swirled carefully until thorough mixing was observed. The temperature was increased to about 200^{o}C until a dense white fume evolved. This was then cooled at room temperature, filtered with Whatman filter paper No. 2 and deionized water added to 100 mL mark.

All samples were transferred to Atomic Adsorption Spectrophotometer for determination of heavy metals (Mn, Zn, Fe, Pb, Cd, Cr and Cu).

Quality assurance was upheld by following standard procedures, using reagent blanks, and performing spiked sample recovery tests to verify the reliability and consistency of the results.

Data Analyses

Laboratory data were analyzed, with mean and standard deviation computed. Pearson's correlation analysis was used to examine the relationship between heavy metals. Additionally, principal component analysis was used to reveal hidden patterns in the data and examine the variables that contribute to most of the variance in the dataset. For all statistical analyses conducted, excel and R software (version 4.3.0) were used.

2.4 Risk Assessment

Pre-existing indices, such as the contamination factor, enrichment factor, pollution load index, geo-accumulation index, ecological risk factor, and potential ecological risk index were deployed to assess the ecological risk of heavy metals on soil. Water pollution level was assessed with indices such as heavy metal pollution index and heavy metal toxicity load. Plant's ability for metal uptake was evaluated with bio-accumulation factor while health risks were assessed for samples using both carcinogenic and non-carcinogenic indices.

Contamination Factor (CF)

CF was used to estimate the soil contamination caused by a specific heavy metal due to human activities, as described by Hakanson (1980). It represents the proportion of the soil's metal concentration to the geochemical background content. The formula for calculating CF is

$$CF = \frac{\text{Concentration of the metal in soil}}{\text{Background value}} \qquad \text{eq (1)}$$

The background values used in this study are 47,200, 850, 45, 95, 20, 90 and 0.3 for Fe, Mn, Cu, Zn, Pb, Cr and Cd respectively (Hakanson, 1980; Alahabadi and Malvandi, 2018; Ohiagu et al., 2021). CF can be grouped into four classes as presented in Table 1.

Geo-accumulation Index (Igeo)

Igeo determines soil contamination by heavy metal due to either anthropogenic or natural input and was determined by Muller (1969) as:

$$\text{Igeo} = log_2 \frac{C}{1.5B} \qquad \text{eq (2)}$$

where B is the metal's geochemical background value and C is the heavy metal contents in the soil.

Table 1 shows the seven classes of Igeo as identified by Muller (1979) and used by Orellana-Mendoza et al. (2022).

Enrichment Factor (EF)

EF estimates the increase in heavy contents in soil resulting from anthropogenic sources in comparison with average natural sources. The reference metal used in the study is Fe; this is because it is similar in geochemistry with other trace metals and also due to uniformity in its natural occurrence (Rehman et al., 2018; Varol, 2011). It is computed as:

$$EF = \frac{(metal/Fe)/Fe\ sample}{(\frac{metal}{Fe})/Fe\ background} \qquad \text{eq (3)}$$

Turekian and Wedepohl, 1961).

EF can be interpreted with regards to the degree of enrichment as presented in Table 1.

Pollution Load Index (PLI)

PLI reflects the pollution status of the soil with regards to all the metals present, thereby suggesting the requisite actions to be taken. It can be calculated using the equation: (Tomlinson et al., 1980)

$$PLI = (\text{CF1} \times \text{CF2} \times \text{CF3} \times \text{CF4} \dots \dots \times \text{CFN})^{1/\text{N}} \qquad \text{eq (4)}$$

where CF is the contamination factor for each metal and N is the number of metals examined at the site.

PLI can be classified into three categories as presented in Table 1.

Ecological Risk Factor (E)

The possible ecological risk connected to each individual heavy metal is indicated by the ecological risk factor (Hakanson, 1980). This is computed as follows:

$$E = T \times CF \qquad \text{eq (5)}$$

where T is a particular heavy metal's toxic response factor and CF is its contamination factor. For Mn, Fe, Cd, Cr, Pb, Zn, and Cu, the corresponding toxic response factors are 1, 1, 30, 2, 5, 1, and 5 (Hakanson, 1980; Orellana-Mendoza et al., 2022). Table 1 shows the different categories of ecological risk factors.

Potential Ecological Risk Index (RI)

While E estimates the ecological risk factor with respect to individual metal, RI expresses the risk connected with all toxic metals present in a particular site (Hakanson, 1980). RI is calculated as:

$$RI = \sum E \qquad \text{eq (6)}$$

As indicated in Table 1, RI is divided into four classes.

Table 1: Classification of Contamination and Ecological Risk Indices

Category	Classification
Contamination Factor (Hakanson, 1980)	
CF<1	low contamination
1<CF<3	moderate contamination
3<CF<6	considerable contamination
CF>6	very high contamination
Geo-accumulation Index (Muller, 1979; Orellana-Mendoza et al., 2022)	
Igeo≤0	uncontaminated site
0<Igeo≤1	uncontaminated to moderately contaminated site
1<Igeo≤2	moderately contaminated site
2<Igeo≤3	moderately to heavily contaminated site
3<Igeo≤4	heavily contaminated site
4<Igeo≤ 5	heavily to extremely contaminated site
Igeo>5	extremely contaminated site
Enrichment Factor (Turekian and Wedepohl, 1961; Rehman et al., 2018)	
EF<1	no enrichment
1<EF<3	minor enrichment
3< EF< 5	moderate enrichment
5<EF<10	moderately severe enrichment
10<EF<25	severe enrichment
25< EF< 50	very severe enrichment
EF>50	extremely severe enrichment
Pollution Load Index (Tomlinson et al., 1980)	
PLI<1	unpolluted site
PLI = 1	moderate pollution
PLI>1	polluted site
Ecological Risk Factor (Hakanson, 1980)	
E<40	low ecological risk
40 ≤E<80	moderate ecological risk
80≤ E<160	considerable ecological risk
160≤E<320	high ecological risk
E≥320	very high ecological risk
Potential Ecological Risk Index (Hakanson, 1980)	
RI<150	low risk
150≤RI<300	moderate risk
300≤RI<600	high risk
RI≥600	very high risk

Heavy Metal Toxicity Load (HMTL)

HMTL quantifies the level of heavy metals that have an impact on human health in natural water (Saha, 2018), indicating how much treatment is necessary to guarantee the water's safety for human consumption. HMTL is determined by multiplying each heavy metal's concentration (Mi) by its hazard intensity score (HISi) (ATSDR, 2017).

$$HMTL = \sum Mi \times HISi \qquad \text{eq (7)}$$

Heavy Metal Pollution Index (HPI)

Combined impacts of heavy metals on the quality of water can be assessed with HPI (Kumar et al., 2019; Dhaliwal et al., 2021). HPI is calculated as:

$$HPI = \frac{\sum WiQi}{\sum wi} \quad \text{eq (8)}$$

$$Q = \sum \frac{Mi - Li}{Si - Li} \times 100 \quad \text{eq (9)}$$

Si is the acceptable limit of heavy metal ith in drinking water, Li is the standard value of heavy metals in drinking water, Mi is the determined value of heavy metal ith, Qi is the sub-index of heavy metal ith, and Wi is the unit weight of heavy metal ith. Value of HPI below 100 represents low pollution of heavy metals, whereas 100 is the threshold value at which harmful health consequences are probable. An HPI value greater than 100 indicates the water is unsuitable for consumption.

Plant's Bioaccumulation factor (BAF)

The bio-accumulation factor is the proportion of heavy metals in food samples in comparison with soil samples (Ali et al. 2013; Dhaliwal et al., 2021). It is expressed as:

$$BAF = \frac{\text{Heavy metal concentration in food}}{\text{Heavy metal concentration in soil}} \quad \text{eq (10)}$$

BAF is used to evaluate how soil heavy metals affect the food chain. Higher BAF values indicate a plant's greater potential to accumulate metals. A BAF score that exceeds 1 suggests that the plant is an effective accumulator of heavy metals, whereas values less than 1 imply a lower potential for metal accumulation (Lian et al., 2019; Dhaliwal et al., 2021).

Non-Carcinogenic Health Risk

The non-carcinogenic risk connected with human exposure to heavy metal was assessed using a template developed by the US-EPA (USEPA, 1999, 2013, 2016). For accurate assessment, this study considered the differences in risk to different age groups and therefore assessed the risk to adults and children. The USEPA method involves the use of hazard quotient (HQ) or hazard index (HI) to evaluate the possible danger of exposure to toxic metals in soil, food, and water. HQ represents the non-carcinogenic health risk, and can be computed as follows:

$$HQ = \sum \frac{ADD}{RfD} \quad \text{eq (11)}$$

While HQ represents the health risk connected with exposure to a single toxic metal, HI sums the risk related with exposure to all metals in a specific site (Ferreira-Baptista and DeMiguel, 2005; Zheng et al., 2010).

$$HI = \sum HQ \quad \text{eq (12)}$$

Ingestion, inhalation, and the skin are the major routes through which metals enter the human body, therefore, average daily dose (ADD) for ingestion, dermal absorption, and inhalation are expressed as follows:

$$ADDing = C \times \frac{Ring}{BW} \times \frac{EF}{AT} \times ED \times 10^{-6} \quad \text{eq (13)}$$

$$ADDder = C \times SA \times \frac{AF}{BW} \times \frac{ABS}{AT} \times EF \times ED \times 10^{-4} \quad \text{eq (14)}$$

$$ADDinh = \frac{C}{PEF} \times \frac{Ring}{BW} \times \frac{EF \times ED}{AT} \quad \text{eq (15)}$$

where ADDing, ADDder and ADDinh are average daily dose through ingestion, inhalation and dermal pathways, C = heavy metal content. Other parameters and their values are shown in Table 2.

Reference dose is the maximum *permissible* exposure expected to pose no significant risk. The RfD values used in this study for Fe, Mn, Cu, Zn, Pb and Cr were 7E-1, 4.6E-2, 4E-2, 3E-1, 3.5E-3, 3E-3 (ingestion), 7E-1, 1.43E-5, 4E-2, 3.1E-1, 3.5E-3, 2.86E-5 (inhalation) and 1.4E-1, 1.84E-3, 1.2E-2, 6E-2, 5.25E-4, 6E-5 respectively (Ferreira-Baptista and DeMiguel, 2005; Kong et al., 2012; Kumar et al., 2019; Oni et al., 2022). Where RfD inhalation values were not available, the corresponding oral RfD values were used (Ferreira-Baptista and DeMiguel, 2005).

Table 2: Average Daily Dose Values for Adults and Children (USEPA 2001; Ferreira-Baptista and DeMiguel, 2005; Ihedioha et al., 2017; Rehman et al., 2018)

Parameters	**Symbol**	**Ingestion**		**Inhalation**		**Dermal**	
		Adult	**Children**	**Adult**	**Children**	**Adult**	**Children**
Rate	R	100mg/day	200m/day	20m3/day	10m3/day	-	-
Exposure Duration	ED	25years	6years	25years	6years	25years	6years
Body Weight	BW	70kg	15kg	70kg	15kg	70kg	15kg
Exposed Skin Surface Area	SA	_	_	_	_	3300cm3	2800cm3
Exposure Frequency	EF	350days/year	350days/year	350days/year	350days/year	350days/year	350days/year
Adherence Factor	AF	-	-	-	-	0.2mg/cm2	0.2mg/cm2
Dermal Absorption Factor	ABS	-	-	-	-	0.001	0.001
Particle Emission Factor	PEF	-	-	1.32×109 m3/kg	1.32×109 m3/kg	-	-
Average Time for Non-Carcinogens	AT	ED*365 days/year	ED*365 days/year	ED*365 days/year	ED*365 days/year	ED*365 days/year	ED*365 days/year

When HI score below 1 (HI< 1), this signifies no potential human health risk while there is health risk connected with the heavy metals if the HI score exceeds 1 (HI>1) (Zheng et al., 2010).

Carcinogenic Risk Index (CR)

CR estimates the likelihood that a person exposed to an environmental carcinogen will develop cancer. CR is expressed as:

$$CR = ADD \times SF \quad \text{eq (16)}$$

SF represents cancer slope factor and ADD is the average daily dose. The SF values for Pb, Cr, and Cd are 8.50E-03, 4.20E-01, and 6.30 respectively (Mo et al., 2015; Rehman et al., 2018). A CR value less than 10^{-6} shows insignificant risk, higher value of above 10^{-4} indicates significant risk of cancer occurrence whereas values between 10^{-6} and 10^{-4} indicates tolerable cancer risk occurring in exposed individuals (Hu et al., 2012).

3.0 Results and Discussions

Concentration of Heavy Metal in Samples

Heavy metal contents in soil, water, and vegetables along the plain of Asa River are presented in Table 3. The metal distribution across all samples varied widely. In soil, the highest mean concentration of Fe and Pb were observed at point 5, Mn and Zn at point 7, Cu at point 9, Cr at point 2 while Cd was not detected in any of the 10 sampling points. The order metal concentrations in soil across all sites were Fe>Zn>Mn>Cu>Pb>Cr. All the metals studied had values below the global geochemical values. The study conducted by Adekola and Eletta (2007) at Asa River showed heavy metal content in sediments was in the range obtained in this research except for Mn with values exceeding those obtained here. Although the metal concentrations obtained in this study were below the geochemical values, they, however, exceeded the values reported by Adewoye et al. (2021) in sediment of Asa River but below the results presented by Alahabadi and Malvandi (2018) in Tajan River's sediments, Iran. Out of the six metals examined in surface water, Fe, Mn, Cu and Zn were detected (Table 3). The highest concentration of Fe was seen at point 5, Mn and Cu at point 7 and Zn at point 10. The Fe concentration ranged from 1.32 -10.13 mg/L, Mn from 0.96 to 2.51 mg/L, Cu from 0.24 to 0.84 mg/L, and Zn from 0.65 to 2.14 mg/L. The results showed that both Fe and Mn had higher values, this agrees with the study of Rehman et al. (2018) and Dhaliwal et al. (2021). As can be seen in Table 3, Cu and Zn in water fell below the permissible limits of WHO (WHO, 2022) whereas Fe and Mn concentrations in water exceeded the limits, indicating potential anthropogenic inputs from industrial effluents at sites 5 and 7. This aligns with the enrichment patterns in Figure 4, which show moderate enrichment of Cu and Zn in soils near these sites (Kuznietsov and Biedunkova, 2025).

Intake of water contaminated with Fe and Mn through oral and dermal routes can result in the deposition of these metals in the human body. Accumulation of Fe in the body has been implicated in diseases such as male reproductive defects (Gabrielsen et al., 2018), atherosclerosis (Gackowski et al., 2002), hypertension (Piperno et al., 2002), obesity and type II diabetes (McCarty, 2003) while overexposure to Mn is associated with infertility (Williams et al., 2013) and neurological disorder (Miah et al., 2020). Based on the Food and Agriculture Organizations guidelines for irrigation water (FAO, 1992), Fe and Zn values fell below the limit whereas Cu and Mn values were greater than the permissible limit. Excessive use of Cu and Mn contaminated water for irrigation leads to their deposition in the soil. Excess Cu and Mn affect soil quality and plant growth (Zhao et al., 2014; Adrees et al., 2015).

The mean heavy metals concentrations (mg/kg) of edible portions of the vegetable ranged between 15.12 and 68.04 for Fe, 1.36 and 8.45 for Mn, 1.03 to 1.50 for Cu, 0.75 to 3.63 for Zn and 0.1 to 0.27 for Pb (Table 3). The results of all metals across the sampling points were below the permissible limit of WHO/FAO. These results align with the work of Dhaliwal et al. (2021) and Setia et al. (2021) whose findings revealed heavy metal concentration in rice and grains to be below the permissible limit. However, toxic metal contents in vegetable reported in this work are lower when compared with those obtained by Ahmad and Goni (2010).

Multivariate Analysis

The PCA results (Table 4) revealed two principal components explaining 67.17% of the variance. PC1, dominated by Mn, Pb, Zn, and Cr, suggests a common source likely associated with industrial activities and urban runoff, consistent with the location of sites 5–7 near industrial zones. PC2, dominated by Cu and Fe, may reflect agricultural inputs and natural soil composition. Pearson's correlation (Figure 2) supports this interpretation, showing strong positive relationships between Cr and other metals, indicating co-occurrence from similar sources. These patterns highlight the influence of anthropogenic activities on metal distribution and potential ecological risks, despite overall low contamination indices (Bashir and Selvasembian, 2025; Kahangwa, 2022).

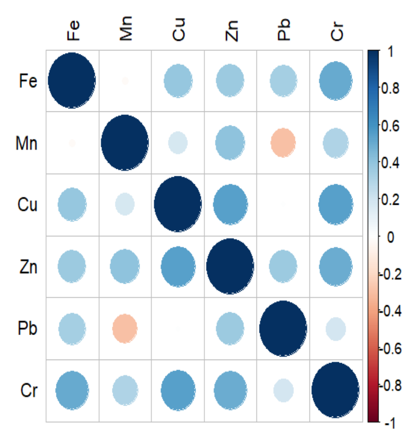

Figure 2: Pearson's Correlation Analysis of Heavy Metals in Samples

Table 3: Heavy Metal Concentrations in Soil, Water, and Vegetable Samples from Asa River Plain

Site		**Soil (mg/kg)**							**Water (mg/L)**							**Vegetable (mg/kg)**						
		Fe	Mn	Cu	Zn	Pb	Cr	Cd	Fe	Mn	Cu	Zn	Pb	Cr	Cd	Fe	Mn	Cu	Zn	Pb	Cr	Cd
A1	Mean	1604.80	15.30	13.50	19.00	3.02	1.26	ND	1.33	1.14	0.36	1.07	ND	ND	ND	33.54	2.47	1.45	2.08	0.15	0.05	ND
	SD	90.21	3.44	0.34	2.01	0.54	0.42		0.82	0.30	0.12	0.71				12.11	0.34	0.22	1.29	0.11	0.01	
A2	Mean	2318.89	16.14	13.39	11.18	3.55	3.90	ND	1.32	0.96	0.43	0.65	ND	ND	ND	22.24	8.45	1.32	2.76	0.15	0.05	ND
	SD	58.50	4.86	2.21	5.12	2.64	1.42		0.62	0.14	0.34	0.21				5.62	1.54	0.28	0.26	0.07	0.03	
A3	Mean	2011.50	14.67	13.64	16.95	6.21	1.35	ND	1.42	0.99	0.51	0.69	ND	ND	ND	21.43	1.38	1.25	1.29	0.10	0.01	ND
	SD	83.26	2.18	7.12	2.52	1.12	0.26		0.79	0.21	0.16	0.31				8.11	0.62	0.81	0.08	0.02	0.00	
A4	Mean	988.32	15.88	15.80	34.35	2.10	1.10	ND	1.51	1.12	0.52	1.71	ND	ND	ND	50.51	3.29	1.23	1.06	0.21	0.02	ND
	SD	72.80	5.69	4.01	8.11	1.86	0.61		0.26	0.21	0.12	0.64				12.55	0.71	0.50	0.09	0.08	0.03	
A5	Mean	3407.6	18.47	16.73	32.60	7.18	2.51	ND	1.51	1.01	0.43	0.81	ND	ND	ND	29.91	4.44	1.36	1.95	0.16	0.03	ND
	SD	63.28	6.38	6.51	6.69	2.46	0.26		0.21	0.42	0.11	0.53				20.39	3.17	0.10	0.51	0.12	0.02	
A6	Mean	1534.27	17.89	14.93	41.10	6.89	2.44	ND	1.45	1.70	0.24	0.92	ND	ND	ND	15.12	1.52	1.40	1.90	0.27	0.03	ND
	SD	36.62	1.95	3.11	13.4	1.80	1.21		0.11	0.85	0.20	0.26				9.57	0.22	0.23	0.16	0.05	0.00	
A7	Mean	2363.78	19.66	15.38	50.83	5.31	2.66	ND	10.13	2.51	0.84	0.92	ND	ND	ND	68.04	2.27	1.50	2.91	0.26	0.07	ND
	SD	43.28	6.12	3.75	8.83	2.23	1.93		2.27	0.86	0.61	0.55				13.89	0.60	0.92	0.75	0.20	0.01	
A8	Mean	1268.59	17.07	12.65	22.64	5.20	1.78	ND	1.63	1.48	0.40	0.94	ND	ND	ND	26.78	1.36	1.03	1.83	0.27	0.03	ND
	SD	94.42	1.09	2.82	13.65	3.62	0.14		0.96	0.75	0.33	0.39				24.30	0.71	0.04	0.50	0.07	0.00	
A9	Mean	2447.61	14.27	18.32	17.04	3.12	0.48	ND	1.48	1.18	0.75	1.16	ND	ND	ND	18.65	1.67	1.23	0.75	0.18	0.02	ND
	SD	44.53	6.52	4.38	2.15	1.51	0.33		0.34	0.23	0.41	0.46				13.1	0.93	0.44	0.15	0.04	0.01	
A10	Mean	1512.52	17.73	10.51	17.18	5.28	1.17	ND	1.48	1.28	0.50	2.14	ND	ND	ND	39.55	3.40	1.40	3.63	0.26	0.02	ND
	SD	92.90	3.86	3.68	5.82	2.50	0.15		0.74	0.51	0.27	0.93				30.81	0.43	0.34	0.58	0.04	0.03	

SD = Standard deviation ND = Not detected

Table 4: Principal Component Analysis of Heavy Metals in Soil of Asa River

Component	**Eigenvalue**		**% of Variance**	**Cumulative %**
1	2.62		43.78	43.78
2	1.40		23.39	67.17
	Component Matrix		% Contribution to each component	
Variable	PC1	PC2	PC1	PC2
Fe	**0.68**	0.37	**17.62**	9.91
Mn	0.36	**− 0.78**	4.96	**44.09**
Cu	**0.74**	− 0.16	**21.26**	1.98
Zn	**0.82**	− 0.07	**25.72**	0.36
Pb	0.35	**0.77**	4.92	**43.18**
Cr	**0.81**	−0.08	**25.52**	0.47

*Values in bold are the values of the variables that dominate each component

Table 5: Contamination Factors and Pollution Load Index of Heavy Metals in Soil Along Asa River

Site	Contamination factors						PLI	Comments
	Fe	Mn	Cu	Zn	Pb	Cr		
A1	0.034	0.018	0.30	0.20	0.15	0.014	0.716	Unpolluted
A2	0.049	0.019	0.30	0.12	0.18	0.043	0.711	Unpolluted
A3	0.043	0.017	0.30	0.18	0.31	0.015	0.865	Unpolluted
A4	0.021	0.019	0.35	0.36	0.11	0.012	0.872	Unpolluted
A5	0.072	0.022	0.37	0.34	0.36	0.028	1.192	Polluted
A6	0.033	0.021	0.33	0.43	0.34	0.027	1.181	Polluted
A7	0.050	0.023	0.34	0.54	0.27	0.030	1.253	Polluted
A8	0.027	0.020	0.28	0.24	0.26	0.020	0.847	Unpolluted
A9	0.052	0.017	0.41	0.18	0.16	0.005	0.824	Unpolluted
A10	0.032	0.021	0.23	0.18	0.26	0.013	0.736	Unpolluted

Risk Assessment

Soil

Table 5 shows the calculated values of CF and PLI in soils sampled along Asa River. Basically, all soil samples analyzed present low contamination as the values of CF for all metals across all sites fall below 1. CF represents contamination in respect of individual heavy metal whereas PLI sums the contamination of all toxic metals on a particular site. In contrast to CF, sites 5, 6, and 7 are polluted while the remaining seven sites are unpolluted. These three sites fall within the industrial areas within the metropolis where most of the tributaries enter the river. The low CF and PLI values indicate minimal soil contamination; however, the heterogeneity in enrichment (Figure 3) for Cu and Zn suggests localized anthropogenic influence, which could affect soil fertility and plant uptake over time (Egah *et al*., 2025).

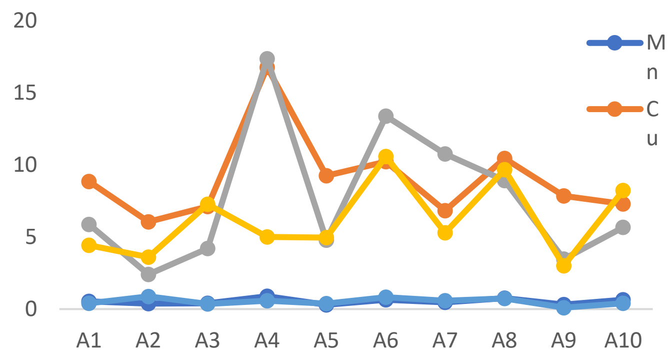

Figure 3: Enrichment Factor of Heavy Metals in the Soil

Figure 3 shows the enrichment pattern of soil in the studied sites. There was low enrichment with both Cr and Mn while Cu, Zn and Pb showed heterogeneity in enrichment, from no enrichment to moderate and significant enrichment across sampling areas.

Figure 4 presents the computed values of geo-accumulation values. The result showed homogenous values in all the soil samples to be less than zero (0) thus the sites are classified as uncontaminated.

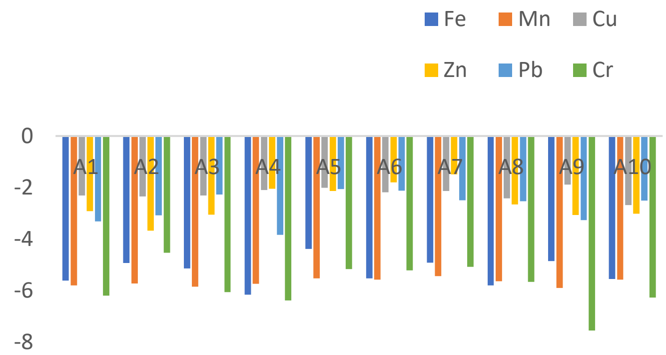

Figure 4: Geo-accumulation index of heavy metals in the soil

Table 6 presents the computed values of the individual ecological risks (E) and potential ecological risk index (RI) of metals in the soil. The table revealed low ecological risk associated with specific metals investigated across the entire sites. Similarly, there is also a low potential risk index resulting from the heavy metal presence in soil in all studied sites.

Water

The pollution state of water samples due to heavy metals was assessed using HPI and HMTL. The HPI values for water sampled at Asa River are shown in Table 7. It was computed based on the WHO standards to evaluate the pollution level of natural water. HPI value below 100 suggests the water is suitable for human use while value exceeding 100 implies the water is not good for use due to its associated health effects. The calculated HPI values for all sites fell below the set allowable limit, thus suggesting the water is safe for use with no expected health effects. Table 8 shows the computed HMTL for heavy metals in samples of water. The Pb, Cr, and Cd were undetected by AAS and thus considered insignificant in the overall water quality status. HMTL quantifies toxic metal available in water with negative impacts on human health. Moreover, HTML also provides information to the regulatory authorities relating to the necessary treatment to make the water safe for consumption (Saha and Paul, 2018). For the calculated HMTL, Cu and Zn showed values below their permissible limit whereas in 80% of all the sites, Mn had values exceeding the permissible limit. The percentage removal of Mn needed to decontaminate the water and make it good for use at sites 1, 4, 5, 6, 7, 8, 9, and 10 are 12%, 11%, 1%, 41%, 60%, 32%, 15%, and 22% respectively. The HMTL values ranged from 1707.84 to 3522.66 mg/L, which are below the acceptable toxicity load for heavy metals.

Plant's Bio-accumulation Factor (BAF)

BAF describes a plant's ability for heavy metal uptake from soil. The greater the BAF score the higher the potential of the plant's uptake of metals. Computed values of BAF are presented in Table 9. All values are less than 1, thus implying less potential for heavy metal uptake by the vegetable. This result agreed with the work

Table 6: Ecological Risk Factor and Ecological Risk Index Values of Heavy Metals in Soil Along Asa River Plain

Site	**Ecological risk factors**						**RI**	**Comments**
	Fe	Mn	Cu	Zn	Pb	Cr		
A1	0.034	0.018	1.50	0.20	0.75	0.028	2.53	Low risk
A2	0.049	0.019	1.50	0.12	0.90	0.086	2.67	Low risk
A3	0.043	0.017	1.50	0.18	1.55	0.030	3.32	Low risk
A4	0.021	0.019	1.75	0.36	0.55	0.024	2.72	Low risk
A5	0.072	0.022	1.85	0.34	1.80	0.056	4.14	Low risk
A6	0.033	0.021	1.65	0.43	1.70	0.054	3.89	Low risk
A7	0.050	0.023	1.70	0.54	1.35	0.060	3.72	Low risk
A8	0.027	0.020	1.40	0.24	1.30	0.040	3.03	Low risk
A9	0.052	0.017	2.05	0.18	0.80	0.010	3.11	Low risk
A10	0.032	0.021	1.15	0.18	1.30	0.026	2.71	Low risk

Table 7: Heavy Metal Pollution Index (HPI) in Water Samples of Asa River

Site	**Qi X Wi**				**∑QiWi**	**HPI**
	Fe	Mn	Cu	Zn		
A1	0.137	-0.086	0.003	-0.019	0.035	14.00
A2	0.136	-0.104	0.004	-0.023	0.013	5.20
A3	0.147	-0.101	0.005	-0.023	0.028	11.20
A4	0.157	-0.088	0.005	-0.013	0.061	24.40
A5	0.157	-0.099	0.004	-0.022	0.040	16.00
A6	0.150	-0.030	0.002	-0.021	0.101	40.40
A7	0.114	-0.050	0.008	-0.021	0.051	20.40
A8	0.170	-0.050	0.004	-0.021	0.103	41.20
A9	0.153	-0.080	0.007	-0.018	0.062	24.80
A10	0.153	-0.070	0.005	-0.019	0.069	27.60

Table 8: Heavy Metal Toxicity Load (HMTL) in Water Samples of Asa River

Metal	HIS	Mi X HIS										Permissible HMTL
		A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	
Mn	798	909.72	766.08	790.02	893.76	805.98	1356.60	2002.98	1181.04	941.64	1021.44	798
Cu	807	290.52	347.01	411.57	419.64	347.01	193.68	677.88	322.80	605.25	403.50	2421
Zn	915	979.05	594.75	631.35	1564.65	741.15	841.80	841.80	860.01	1061.14	1958.10	4575
HMTL (mg/L)		2179.29	1707.84	1832.94	2878.05	1894.14	2392.08	3522.66	2363.85	2608.03	3383.04	7794

Table 9: Bio-accumulation Factor of Heavy Metals in Vegetable Samples from Asa River

Site	Fe	Mn	Cu	Zn	Pb	Cr
A1	0.02	0.16	0.11	0.11	0.05	0.04
A2	0.01	0.52	0.10	0.25	0.04	0.01
A3	0.01	0.09	0.09	0.08	0.02	0.01
A4	0.05	0.21	0.08	0.03	0.10	0.02
A5	0.01	0.24	0.08	0.06	0.02	0.01
A6	0.01	0.08	0.09	0.05	0.04	0.01
A7	0.03	0.12	0.10	0.06	0.05	0.03
A8	0.02	0.08	0.08	0.08	0.05	0.02
A9	0.01	0.12	0.07	0.04	0.06	0.04
A10	0.03	0.19	0.13	0.21	0.05	0.02

Table 10: Hazard Quotient and Hazard Index of Heavy Metals in Soil Samples along Asa River

Site	category	Ingestion (HQ)						HI	Inhalation (HQ)						HI	Dermal (HQ)						HI
		Fe	Mn	Cu	Zn	Pb	Cr		Fe	Mn	Cu	Zn	Pb	Cr		Fe	Mn	Cu	Zn	Pb	Cr	
A1	Adults	3.14E-03	4.57E-04	4.63E-04	8.67E-05	1.18E-03	5.77E-04	5.90E-03	4.76E-07	2.22E-04	7.00E-08	1.31E-08	1.79E-07	9.16E-06	2.32E-04	1.04E-04	1.04E-04	1.02E-05	2.87E-06	5.20E-05	1.90E-04	4.63E
	Children	2.93E-02	4.26E-03	4.33E-03	8.10E-04	1.10E-02	5.37E-03	5.51E-02	1.11E-06	5.17E-04	1.64E-07	3.07E-08	4.17E-07	2.13E-05	5.40E-04	4.10E-04	4.10E-04	4.03E-05	1.13E-05	2.06E-04	7.52E-04	1.83E
A2	Adults	4.54E-03	4.80E-04	4.58E-04	5.10E-05	1.39E-03	1.78E-03	8.70E-03	6.87E-07	2.34E-04	6.95E-08	7.73E-09	2.11E-07	2.83E-05	2.63E-04	1.50E-04	1.50E-04	1.01E-05	1.68E-06	6.11E-05	5.88E-04	9.61E
	Children	4.23E-02	4.48E-03	4.28E-03	4.77E-04	1.30E-02	1.66E-02	8.11E-02	1.60E-06	5.47E-04	1.62E-07	1.80E-08	4.91E-07	6.61E-05	6.15E-04	5.93E-04	5.93E-04	3.99E-05	6.67E-06	2.42E-04	2.33E-03	3.80E
A3	Adults	3.94E-03	4.37E-04	4.68E-04	7.73E-05	2.43E-03	6.17E-04	7.97E-03	5.96E-07	2.13E-04	7.08E-08	1.17E-08	3.69E-07	9.79E-06	2.24E-04	1.30E-04	1.30E-04	1.03E-05	2.55E-07	1.07E-04	2.03E-04	5.81E
	Children	3.67E-02	4.09E-03	4.35E-03	7.23E-04	2.27E-02	5.77E-03	7.43E-02	1.39E-06	4.97E-04	1.65E-07	2.74E-08	8.57E-07	2.29E-05	5.22E-04	5.14E-04	5.14E-04	4.07E-05	1.01E-05	4.23E-04	8.05E-04	2.31E
A4	Adults	1.93E-03	4.74E-04	5.40E-04	1.57E-04	8.23E-04	5.03E-04	4.43E-03	2.93E-07	2.31E-04	8.20E-08	2.38E-08	1.25E-07	7.97E-06	2.39E-04	6.39E-05	6.39E-05	1.19E-05	5.18E-06	3.62E-05	1.66E-04	3.47E
	Children	1.80E-02	4.41E-03	5.05E-03	1.46E-03	7.66E-03	4.70E-03	4.13E-02	6.84E-07	5.38E-04	1.91E-07	5.53E-08	2.91E-07	1.86E-05	5.58E-04	2.53E-04	2.53E-04	4.72E-05	2.05E-05	1.43E-04	6.57E-04	1.37E
A5	Adults	6.67E-03	5.50E-04	5.73E-04	1.49E-04	2.81E-03	1.15E-03	1.19E-02	1.01E-06	2.68E-04	8.68E-08	2.26E-08	4.26E-07	1.82E-05	6.72E-04	2.20E-04	2.20E-04	1.26E-05	4.92E-06	1.24E-04	3.78E-04	9.60E
	Children	6.23E-02	5.13E-03	5.35E-03	1.39E-03	2.62E-02	1.07E-02	1.11E-01	2.36E-06	6.26E-04	2.03E-07	5.27E-08	9.94E-07	4.27E-05	2.88E-04	8.71E-04	8.71E-04	4.99E-05	1.95E-05	4.90E-04	1.50E-03	3.80E
A6	Adults	3.00E-03	5.33E-04	5.13E-04	1.88E-04	2.70E-03	1.11E-03	8.04E-03	4.56E-07	2.59E-04	7.75E-08	2.84E-08	4.09E-07	1.77E-05	6.50E-04	9.93E-05	9.93E-05	1.13E-05	6.20E-06	1.19E-04	3.68E-04	7.03E
	Children	2.80E-02	4.96E-03	4.78E-03	1.75E-03	2.51E-02	1.04E-02	7.50E-02	1.06E-06	6.06E-04	1.81E-07	4.00E-08	9.54E-07	4.13E-05	2.78E-04	3.92E-03	3.92E-03	4.45E-05	2.45E-05	4.70E-04	1.46E-03	9.84E
A7	Adults	4.63E-03	5.85E-04	5.28E-04	2.32E-04	2.08E-03	1.21E-03	9.27E-03	7.01E-07	2.85E-04	7.98E-08	3.50E-08	3.14E-07	1.93E-05	7.14E-04	1.53E-04	1.53E-04	1.16E-05	7.67E-06	9.14E-05	4.00E-04	8.17E
	Children	4.31E-02	5.46E-03	4.93E-03	2.17E-03	1.94E-02	1.13E-02	8.64E-02	1.63E-06	6.66E-04	1.86E-07	8.20E-08	7.34E-07	4.54E-05	3.05E-04	6.04E-04	6.04E-04	4.59E-05	3.03E-05	3.62E-04	1.59E-03	3.24E
A8	Adults	2.49E-03	5.09E-04	4.33E-04	1.03E-04	2.03E-03	8.13E-04	6.38E-03	3.76E-07	2.48E-04	6.58E-08	1.57E-08	3.09E-07	1.29E-05	6.10E-04	8.21E-05	8.21E-05	9.50E-06	3.42E-06	8.95E-05	2.68E-04	5.35E
	Children	2.31E-02	4.74E-03	4.05E-03	9.63E-04	1.90E-02	7.60E-03	5.95E-02	8.77E-07	5.78E-04	1.53E-07	3.67E-08	7.20E-07	3.01E-05	2.62E-04	3.24E-04	3.24E-04	3.78E-05	1.35E-05	3.54E-04	1.06E-03	2.11E
A9	Adults	4.79E-03	4.24E-04	6.28E-04	7.77E-05	1.22E-03	2.19E-04	7.36E-03	7.26E-07	2.07E-04	9.50E-08	1.18E-08	1.85E-07	3.48E-06	4.93E-04	1.58E-04	1.58E-04	1.38E-05	2.57E-06	5.37E-05	7.23E-05	4.58E
	Children	4.47E-02	3.96E-03	5.85E-03	7.27E-04	1.14E-02	2.05E-03	6.87E-02	1.70E-06	4.83E-04	2.22E-07	2.75E-08	4.31E-07	8.11E-06	2.11E-04	6.26E-04	6.26E-04	5.47E-05	1.02E-05	2.13E-04	2.87E-04	1.82E
A10	Adults	2.96E-03	5.28E-04	3.60E-04	7.83E-05	2.07E-03	5.33E-04	6.53E-03	4.49E-07	2.57E-04	5.45E-08	1.19E-08	3.14E-07	8.50E-06	6.23E-04	9.79E-05	9.79E-05	7.92E-06	2.58E-06	9.09E-05	1.77E-04	4.74E
	Children	2.76E-02	4.93E-03	3.35E-03	7.33E-04	1.93E-02	5.00E-03	6.09E-02	1.05E-06	6.01E-04	1.27E-07	2.77E-08	7.31E-07	1.98E-05	2.66E-04	3.86E-04	3.86E-04	3.13E-05	1.03E-05	3.60E-04	6.98E-04	1.87E
Mean HQ	Adults	3.81E-03	4.98E-04	4.96E-04	1.20E-04	1.87E-03	8.51E-04	7.65E-03	1.07E-06	4.46E-04	1.36E-07	3.23E-08	5.45E-07	2.43E-05	4.72E-04	1.26E-04	1.26E-04	1.09E-05	3.73E-06	8.25E-05	2.81E-04	6.30E
	Children	3.55E-02	4.64E-03	4.63E-03	1.12E-03	1.75E-02	7.95E-03	7.13E-02	8.50E-07	3.62E-04	1.14E-07	2.57E-08	4.01E-07	2.09E-05	3.85E-04	8.50E-04	8.50E-04	4.32E-05	1.57E-05	3.26E-04	1.11E-03	3.20E

of Ahmad and Goni (2009) and Dhaliwal et al. (2021) both of which showed BAF values of less than 1 in rice and vegetable respectively.

Health Risk

Non-carcinogenic

Table 10 shows the HQ and HI values for oral, dermal, and inhalation exposure to heavy metals in soil in adults and children. In all the three routes, the HQ values calculated for children were greater than for adults. HQ for Fe, Mn, Cu, Zn, Pb, and Cr across all sites were less than one for both adults and children. Thus, the exposed populace was unlikely to suffer from any non-carcinogenic health effects of toxic metal in soil through the three exposure routes. The order of HQ for adults and children alike are Fe > Pb > Cr > Mn > Cu > Zn (ingestion), Cr > Fe = Mn > Pb > Cu > Zn (dermal) and Mn > Cr > Fe > Pb > Cu > Zn.

The computed HI in soil through ingestion is highest at site 5 (1.19E-02 and 1.11E-01 for adults and children) and lowest at site 4 (4.43E-03 for adults and 4.13E-02 for children). The least HI for dermal exposure for both adults and children was found at site 4 while site 2 and 6 showed the highest for adults and children respectively. For inhalation, the highest HI for adults and children were observed at site 7 and site 2, and the lowest HI are found at site 3 and site 9 for adults and children respectively. The estimated HIs were below 1. Of the three exposure routes investigated, ingestion route presents the highest health risk to the populace.

The mean HQs of metals in water vial the mouth and skin pathways for both adults and kids are in the order of Mn > Cu > Zn > Fe with all values less than 1(Table 11). Hazard index (HI) values via ingestion in both adults and children ranged from 4.90E-05 to 1.28E-04 and 4.57E-04 to 1.19E-3 while the HI values through dermal exposure ranged from 5.25E-06 to 1.44E-06 and 2.08E-05 to 5.47E-05 for adults and children respectively. This result therefore showed that children are more vulnerable than adults. It can also be seen that site 7 presents the most health risk whereas site 2 showed the least risk.

The HQ values of all metals studied in vegetables were below 1 (Table 11) for both adults and children in the following order: Mn > Pb >Fe > Cu > Cr > Zn. For both adults and children, the greatest HI values were found at site 2 and the least values at site 3. The result of this study suggested that consuming vegetables in the study area presents no health-related risks.

The health risk assessment conducted in this study assumes uniform exposure across the population, which may not fully capture real-world variability. Key assumptions include similar dietary habits, exposure duration, and consumption patterns for all individuals. These assumptions introduce limitations, as actual exposure can differ significantly based on age, occupation, and lifestyle. Furthermore, the analysis does not incorporate sensitivity or uncertainty evaluation, which could provide a more robust understanding of risk variability (U.S EPA, 2007). Future studies should consider integrating uncertainty and sensitivity analyses to account for these factors and improve the accuracy of health risk predictions (Han *et al*., 2025).

Carcinogenic risk

Table 12 shows the computed values of carcinogenic risk from exposure to soil and vegetables in the study area. Out of the six toxic metals detected in soil and vegetables, only Pb and Cr are human carcinogens. The results indicate that all values for all the exposure routes presented insignificant risk, thus there is low possibility of cancer occurring due to exposure to soil and vegetables obtained from the study area. However, through soil ingestion, Cr showed a tolerable limit for both adults and children.

4.0 Conclusions

The current study provides valuable insights into the pollution status and health impacts of heavy metals (Fe, Mn, Cu, Zn, Pb, Cr, and Cd) on water, soil, and vegetables along the Asa River plain. Established indices indicate generally low soil contamination by the examined metals, resulting in minimal ecological risk to the soil. However, localized enrichment patterns for Cu and Zn (Figure 4) and elevated Mn concentrations in 80% of water samples highlight site-specific exceedances that warrant monitoring. The assessment of water pollution levels revealed overall low contamination by heavy metals using indices such as HPI and HMTL, but Mn exceedances suggest potential anthropogenic influence near industrial zones. Calculated BAF values demonstrated the plants' low potential to accumulate the studied metals. Based on the calculated non-carcinogenic health risks, all examined samples showed that exposure to water, soil, and vegetables in the study area poses insignificant health risks, though continued surveillance is recommended for areas with localized exceedances. The results of this investigation indicate that exposure to heavy metals in the samples analyzed presents low risk of cancer. It can, therefore, be inferred that the Asa River exhibits generally low contamination with localized exceedances requiring monitoring, rather than being completely unpolluted. Future research should incorporate seasonal and multi-temporal sampling to better capture fluctuations in heavy metal concentrations across wet and dry periods. Such an approach would help clarify the influence of rainfall intensity, river discharge, agricultural cycles, and urban runoff on contaminant dynamics.

Declaration of conflict of interest

The authors have collectively contributed to the conceptualization, design, and execution of this journal. They have worked on drafting and critically revising the article to include significant intellectual content. This manuscript has not been previously submitted or reviewed by any other journal or publishing platform. Additionally, the authors do not have any affiliation with any organization that has a direct or indirect financial stake in the subject matter discussed in this manuscript.

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