Green and Sustainable Chemistry, 2025, 15(4), 76-98
https://www.scirp.org/journal/gsc
ISSN Online: 2160-696X
ISSN Print: 2160-6951

Exposure and Health Risks of Highway-Associated Heavy Metal Pollution in Orchard Soils and Fruits in Eastern Uganda

Charles Oboi, Irene Nalumansi, Denis Byamugisha, Caroline Kiwanuka Nakiguli, Paul Mukasa, Emmanuel Ntambi*

Department of Chemistry, Faculty of Science, Mbarara University of Science and Technology, Mbarara, Uganda
Email: *emmantambi@must.ac.ug

How to cite this paper: Oboi, C., Nalumansi, I., Byamugisha, D., Nakiguli, C.K., Mukasa, P. and Ntambi, E. (2025) Exposure and Health Risks of Highway-Associated Heavy Metal Pollution in Orchard Soils and Fruits in Eastern Uganda. *Green and Sustainable Chemistry*, **15**, 76-98.
https://doi.org/10.4236/gsc.2025.154006

Received: August 20, 2025
Accepted: November 1, 2025
Published: November 4, 2025

Abstract

Anthropogenic activities introduce heavy metals (HMs) into soils which can be absorbed by plants. We, in the present study, determined the concentration of four priority HMs (Cu, Pb, Cd and Zn) in orchard soils and edible fruits (sweet oranges and mangoes) grown along the arterial Mbale-Soroti Highway of Uganda. A total of 78 fruit samples were systematically obtained from the fruit trees at distances of 10 m, 100 m, 300 m and 5000 m from the Highway, along with 78 soil samples. They were analyzed for the HMs using inductively coupled plasma-optical emission spectrometry. Health risks were assessed using the hazard index and incremental life cancer risk methods, while ecological risks were evaluated based on geoaccumulation and pollution indices. The mean metal total concentrations followed the order Zn > Cu > Pb > Cd, and were all within permissible limits. In the fruit and soil samples, the concentration ranges (mg/kg) were Cu (0.05 ± 0.01 - 1.81 ± 0.37 and 11.42 ± 3.00 - 30.85 ± 5.97), Zn (2.41 ± 2.18 - 8.11 ± 1.20 and 19.00 ± 1.30 - 40.03 ± 7.28), Pb (0.01 ± 0.00 - 0.06 ± 0.03, and 7.72 ± 1.05 - 21.00 ± 3.13) and Cd (<0.001, and <0.001 - 0.44 ± 0.21), respectively. The metal concentrations were higher in soils than fruits, and decreased with distance from the highway, with a strong soil-to-fruit transfer correlation. Health risk assessment revealed that mango pulp and orange juices had hazard indices less than 1 for all the samples, indicating no potential health risks at these proximities.

Keywords

Citrus sinensis, *Mangifera indica*, Orchards, Acceptable Limit, Hazard Index

1. Introduction

Increasing global population continues to mount towering pressure on agricultural systems to meet the growing food demands. As of December 2024, the global population was estimated at 8.2 billion people [1]. With this growth, the total global food demand is expected to increase by up to 56% in 2050, suggesting that at least 8% of the global population is likely to be at risk of hunger in the same year [2]. Compounding this issue is the climate change risk, which necessitates agricultural systems to balance food production and environmental conservation. Orchard farming (urban food forestry) is increasingly considered to be a viable alternative for addressing this complex scenario, offering opportunities to enhance food security and nutrition, sustainable land-use practices, ecosystem service provision and green urbanization [3]-[6].

Fruit orchard farming provides nutritious fruits, nuts and edible leaves while also supporting agricultural productivity by enhancing soil fertility, water retention, erosion control and cutting down the need for synthetic fertilizers [7] [8]. However, urban fruit orchard farming can serve as a potential pathway for the transfer of heavy metals (HMs) from vehicular emissions to soil and food crops cultivated along roadside or highway verges [9]-[11]. Heavy metals, also debatably called potentially toxic elements or simply toxic elements, are elements with relatively high densities (>5 g/cm^3) and high atomic weights (typically >65) that are toxic at trace amounts (*i.e.*, parts per million and/or parts per billion levels) [12] [13]. They comprise metals like cobalt, mercury, lead (Pb), cadmium (Cd), chromium, nickel, manganese, vanadium, copper (Cu), zinc (Zn), iron, as well as metalloids such as arsenic and antimony [14].

Most HMs occur naturally in the Earth crust but become increasingly enriched in the environment due to various anthropogenic activities [15]. As trace elements, some HMs such as Zn, Cu, manganese, cobalt, iron and selenium (Se) are essential to the metabolic functions of the human body [16]. At higher concentrations, however, intake of all HMs can lead to poisoning. For instance, intake of Se above the tolerable upper intake level of 400 μg/day can cause selenosis: a condition marked by symptoms such as hair loss, nail deformities and loss, severe tooth decay and discoloration, skin rashes, keratosis, weakness, rickets, reduced cognitive function, nervous system disorders, and gastrointestinal issues [17]. Non-essential HMs are physiologically unnecessary elements and are inherently toxic. Environmental exposure to Pb, for example, is responsible for at least 500,000 new cases of intellectual disabilities in children annually [18]. Long-term Pb poisoning has been linked to hypertension [19], and most inorganic compounds of Pb are classified as probable human carcinogens [20]. Collectively, the toxicity of HMs is dictated by the species involved, its concentration, exposure route and duration, age and sex of the organism among other extraneous factors [21]. Based on toxicity coefficients, elements such as arsenic, mercury, Pb, Zn, nickel, Se and Cd are classified under first class of hazard HMs. Boron, cobalt, molybdenum, Cu, and antimony fall under second class of hazard, while the rest are under third class of hazard [22] [23].

The current study aimed at investigating the concentration and distribution of four HMs (Cu, Pb, Cd and Zn) in orchard soils and selected edible fruits (sweet oranges and mangoes) grown along the Mbale-Soroti Highway in Eastern Uganda, and the health risks associated with fruit consumption. This Highway is part of the Tororo-Mbale-Soroti-Dokolo-Lira-Kamdini stretch of the Great North Road (present day Pan-African Highway) in Uganda. It is a major national road for the landlocked Uganda, and links the Kenyan Port City of Mombasa to Northern Uganda, South Sudan and other parts of Africa [24]. The arterial stretch of the Pan-African Highway (PAH) considered in this study covers Eastern Uganda, which is flood-prone [25] [26] and also serves the busiest border crossing on the Northern Corridor [27] [28]. Accordingly, Highways in Eastern Uganda have one of the highest traffic in Uganda, especially with cargo trailers from Mombasa port (Kenya) which handles roughly 60% of the East African Community imports [29]. Our interest in this area is also from its distinct tourist attraction sites, especially Mt. Elgon (with the largest volcanic base of 4000 km^2 in the world) in Mbale district, the Tororo rock (with various caves and ancestral paintings) in Tororo and Sipi falls in Kapchorwa district [30]. These tourist activities could potentially expedite the emission and deposition of HMs due to increased vehicular activities.

2. Methods

2.1. Study Area

We chose Soroti and Ngora districts in Teso subregion, Eastern Uganda (**Figure 1**). The two districts share common frontiers, and are traversed by the Mbale-Soroti highway, an arterial stretch of the PAH. They were chosen because of the popularity of commercial orchards along the highway and in the villages [31]. This region belongs to the Kyoga plains agricultural zone (Teso subregion) where citrus production is highest, with over 700 hectares of land with citrus. They had a production volume of over 200,000 tonnes of citrus and approximately 67 billion Uganda shillings (US$ 28.3 million) to smallholder income in the region [32] [33]. Specifically, the Soroti Fruits Factory was commissioned in 2019 in Soroti to handle the processing of sweet oranges. Ngora district is located at coordinates 1˚29'59.99"N 33˚47'59.99"E while Soroti district lies between 1˚35'59.99"N and 33˚38'59.99"E. The vegetation in the two districts is savannah grassland with light, well-drained and sandy loam soils that favor fruit growing [34]. The rainfall regime in these two districts is bi-modal with peaks in April-May and July-August [35]. The mean annual rainfall ranges between 800 - 1000 mm while the mean annual temperature is 24˚C. The main economic activity in Soroti and Ngora districts is agriculture where small scale livestock rearing alongside cropping is practiced.

2.2. Sampling Procedure

In total, 36 sweet oranges (*Citrus sinensis* (L.) Osbeck) and 36 mango (*Mangifera indica* L.) fruits were purposively sampled from orchards in Aukot and Mukura

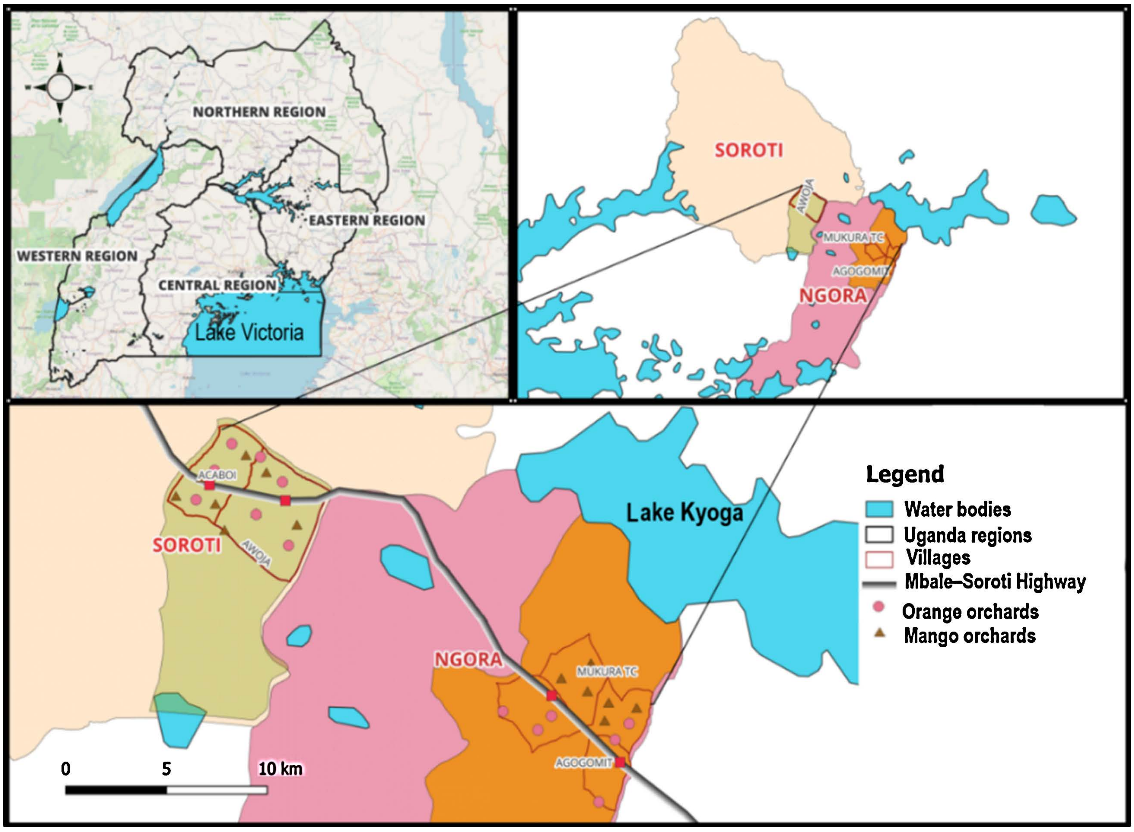


Figure 1. Location of the sampled orchards along the Mbale-Soroti Highway, Eastern Uganda. Inset is the map of Uganda showing its regional divisions. Map created using, (ArcGIS v10.8).

Sub-Counties in Soroti and Ngora districts, respectively. Sampling was done between 7th and 14th August 2023 from orchards where the fruit trees were grown at 10 m, 100 m, and 300 m from the highway, since levels of heavy metals in soil due to road transport operations decrease with increase in distance from the road [36]. Fruit samples were washed using deionized water to remove soil particles and/or dust on their surfaces [37].

A total of 72 soil samples were also obtained from the corresponding orchards. These distances in the increasing order were chosen basing on the fact that the concentrations of HMs in soils as a result of road transport operations decrease with the increase in distance from the road. For all the soil samples, surface litter was removed at the sampling spot. A stainless-steel spade was used to make a 'V' shaped cut into the soil to a depth of 25 cm. A slice of soil was obtained from the top to bottom and placed in a clean plastic bucket. Four slices of soil were obtained from each cut. The above procedure was repeated for several spots from the edges of the area under the tree canopy to ensure homogeneity. The samples were thoroughly mixed to make the composite sample and foreign materials such as gravel, pebbles, roots, and stones were removed. The composite sample was then reduced to about 0.5 kg by quartering, packed in a clean paper bag and labeled appropriately. From the field, the composite samples were taken to the laboratory where they were air dried for 1 week [37].

Control samples of oranges (n = 3) and mango fruits (n = 3) and their corresponding soils were obtained from orchards 5 km away from the Highway *i.e.*, in Agogomit and Awoja villages in Mukura and Aukot Sub-Counties. All the fruit and soil sample were taken on the same day.

2.3. Sampling Preparation

Mango fruits were peeled using a clean stainless-steel knife to obtain the pulp and the seeds were discarded. Each sample (300 g) was oven-dried for 24 hours at 105˚C [38]. The dried samples were then ground into a powder using a porcelain pestle and mortar. The powdered samples (0.2 g) were placed in a digestion tube to which aqua regia (6 mL of 37% hydrochloric acid and 6 mL of 65% nitric acid) were added. For orange samples, fruits were peeled and the peel was discarded. From the remaining portions, juice (150 mL) was squeezed into 250 mL beakers, filtered and then kept in a refrigerator. The sample juice (4 mL) was placed into a digestion tube and then 12 mL of 65% nitric acid was added. All the mixtures were heated at 105˚C on a hot plate for 30 minutes [37]. The resultant solutions were filtered into 50 mL volumetric flasks through Whatman filter no. 42 paper and the volume topped the mark with deionized water. Soil samples were ground and then sieved through a 0.15-mm mesh. Thereafter, samples (0.2 g) were transferred into Teflon tubes, and then aqua regia was added. The tubes were transferred onto a hot plate at 105˚C for 30 minutes for the samples to digest [37]. The digestates were then filtered using Whatmann Grade 1 filter papers into a 50 mL volumetric flask. These were topped with deionized water to the mark.

2.4. Instrumental Analysis, Quality Control and Assurance

The concentration of Cu, Zn, Pb, and Cd in soil and fruit samples was established using an inductively coupled plasma-optical emission spectrometer (ICP-OES; Optima 7000 DV, Perkin Elmer Inc., Waltham, USA) used in our previous studies [15] [39]. The instrument detection limits were 0.003, 0.005, 0.005, and 0.001 ppm for Cu, Zn, Pb, and Cd respectively as described in US EPA 200.7 [40]. The specific wavelengths used for the HMs were 224.700 nm, 206.200 nm, 220.353 nm and 214.440 nm, respectively. Quantitation was performed using calibration curves constructed from working standard solutions, which were prepared from 1000 mg/L stock solutions of the individual HMs' nitrate or chloride salt [15].

To ensure confidence in the data obtained, all reagents and chemicals used were all of analytical grade. Other quality control measures involved analyzing blanks and spiked samples for every 10 sample runs, which gave satisfactory recoveries (98.4% - 101.2%). Analytical method precision, expressed as relative standard deviations of runs, was below 5% (3.2% - 4.7%). To avoid batch-specific errors, each sample was analyzed in triplicate under the same standard conditions.

2.5. Health Risks Due to Consumption of Fruits

The health risks associated with consuming the fruits, as recommended by the US

EPA [41], are categorized into cancer and non-cancer risks for both children and adults. Assessing these risks requires determining the estimated daily intake (EDI, mg/kg/day) of HMs in the edible fruit parts. The EDI can be calculated using Equation 1 [42] [43]. The variables in the equation and their corresponding values are provided in **Table 1**.

$$\text{EDI} = \frac{C_{HM} \times \text{IngR} \times \text{EXF} \times \text{EXD}}{W_{ab} \times T_{aet}} \tag{1}$$

The non-cancer health risks were assessed using the hazard quotient (HQ) method (Equation (2)). Given that HMs exhibit additive toxicity, the hazard index (HI) was determined by summing the HQ values of the individual HMs (Equation (3)) [44].

$$\text{HQ} = \frac{\text{EDI}}{\text{RF}} \tag{2}$$

$$\text{HI} = \sum\nolimits_i^n \text{HQ} \tag{3}$$

In Equation (2), RF is the oral reference dose of the specific heavy metal, with values of 0.04, 0.006, 0.14 and 0.01 $\text{mg}\cdot\text{kg}^{-1}$ for Cu, Zn, Pb and Cd, respectively [44]-[46]. Ultimately, cancer risk (CR) was evaluated based on the incremental lifetime cancer risk for ingestion of carcinogenic HMs (Pb and Cd) in the edible fruit parts (Equation (4)) [47].

$$\text{CR} = \text{EDI} \times \text{CSF} \tag{4}$$

where CSF is the ingestion cancer slope factor = 8.5×10^{-3} and 5.01×10^{-1} mg/kg/day for Pb and Cd [47].

Table 1. Exposure factors used in health risk assessments due to heavy metals in fruits from orchards along the Mbale-Soroti Highway, Uganda.

Factor	Description (units)	Children	Adults
C_{HM}	Heavy metal concentration (mg/kg)	This study	This study
IngR	Fruit ingestion rate (kg/person/day)	0.04526	0.04526 [1]
EXF	Exposure frequency (days/year)	350	350
EXD	Exposure duration (years)	6	30
W_{ab}	Body weight (kg)	15	60 [2]
T_{aet}	Average time (days)	Non-carcinogenic metals: EXD × 365 days/year; carcinogenic metals: 60 years × 365 days/year	

2.6. Evaluation of Soil Heavy Metal Pollution Levels

Several pollution indices are available for the evaluation of HMs pollution of soils. In this study, we adopted two indices namely the contamination factor (Equation (5)) [48], and geoaccumulation index, an empirical metric that compares the concentration of HMs to their normalized geochemical backgrounds (Equation (6))

[49].

$$\text{Contamination factor (CF)} = \frac{C_{HM}}{C_{PIC}} \tag{5}$$

$$\text{Geoaccumulation index } (I_{\text{geo}}) = \log_2 \frac{C_{HM}}{1.5C_{PIC}} \tag{6}$$

In the foregoing equations, C_{PIC} represents the preindustrial concentration of the respective element in soils. These were taken to be the metal concentrations from the control sites since they were lower than those for Cu (12.5 mg/kg) and Zn (70.0 mg/kg) for the average shale [50] and 19.88 mg/kg and 0.13 mg/kg for Pb and Cd in soils from an uncontaminated site in Mbarara (Uganda) [15]. The constant of 1.5 serves as a background matrix correction factor to account for anticipated lithological variations [51] [52].

The cumulative pollution load in the soils was evaluated based on the pollution load index method (Equation (7)) [44].

$$\text{Pollution load index (PLI)} = (\text{CF}_{\text{Cu}} \times \text{CF}_{\text{Zn}} \times \text{CF}_{\text{Pb}} \times \text{CF}_{\text{Cd}})^{1/4} \tag{7}$$

The potential ecological risk index (RI) was employed to assess any harmful effects that could arise due to HMs pollution of the soils (Equations (8) and (9)) [48].

$$\text{Ecological risk coefficient } (E_i) = T_i \times \text{CF} \tag{8}$$

$$\text{RI} = \sum_{i=1}^{n=4} E_i \tag{9}$$

The toxic response factor (T_i) for a heavy metal indicates its toxic and ecological sensitivity levels, and its values for Cu = Pb = 5, Zn = 1 and Cd = 30 [48]. The criteria for classification of the different ecological and pollution indices are given in **Table 2**.

Table 2. Classification values of pollution and risk indices used in the study of heavy metals in soils from orchards along the Mbale-Soroti Highway, Uganda.

Pollution and risk indicators	Classification values	Description
Contamination factor (CF) [3]	CF < 1	Low contamination
	1 ≤ CF < 3	Moderate contamination
	3 ≤ CF < 6	Considerable contamination
	CF > 6	Very high contamination
Geo-accumulation index (I_{geo}) [4]	$I_{\text{geo}} < 0$ (class 0)	Practically uncontaminated
	$0 < I_{\text{geo}} < 1$ (class 1)	Low to median contamination
	$1 < I_{\text{geo}} < 2$ (class 2)	Median contamination
	$2 < I_{\text{geo}} < 3$ (class 3)	Median to strong contamination
	$3 < I_{\text{geo}} < 4$ (class 4)	Serious contamination
	$4 < I_{\text{geo}} < 5$ (class 5)	Serious to extreme contamination

Continued

	$I_{geo} > 5$ (class 6)	Extreme contamination
Pollution Load index (PLI) [2]	PLI < 1	Unpolluted
	PLI > 1	Polluted
Ecological risk (E_i and RI) [3]	$E_i < 40$; RI < 95	Low contamination
	$40 \le E_i \le 80$; $95 \le$ RI ≤ 190	Moderate contamination
	$80 \le E_i \le 160$; $190 \le$ RI ≤ 380	Considerable contamination
	$160 \le E_i \le 320$; RI ≥ 380	High contamination
	$320 \le E_i$	Very high contamination

2.7. Data Analysis

Analytical data were inspected, and their normality was determined using Shapiro-Wilk Test. Subsequently, One-Way Analysis of Variance was used to determine statistically significant differences in the mean concentrations of HMs in fruits and soils. Tukey's post hoc test was applied for multiple comparisons where statistical differences were detected at $p < 0.05$. The mean concentrations of the HMs were compared with the acceptable limits given by the World Health Organization and/or Food and Agricultural Organization of the United Nations (WHO/FAO) [53] [54]. Pearson's correlation analysis was performed to assess the relationships between HMs concentrations in fruits and soil samples. The analyses as well as data visualizations proceeded in Origin Pro 2025a (Origin Lab Corporation, Northampton, MA).

3. Results

3.1. Concentration of Heavy Metals in Orchard Fruits

The concentration of Cu in mangoes ranged from 1.49 ± 0.26 mg/kg to 1.81 ± 0.37 mg/kg. On the other hand, orange juice samples had Cu between 0.05 ± 0.01 mg/kg and 0.10 ± 0.02 mg/kg (**Table 3**). Similar to the observation with Cu, the concentrations of Zn varied between 2.41 ± 2.18 mg/kg to 8.11 ± 1.2 mg/kg in the fruit samples. In mangoes, the concentration of Zn ranged from 1.81 ± 0.37 mg/kg to 5.76 ± 1.30 mg/kg. In the orange juice samples, Zn was from 0.04 ± 0.03 mg/kg to 0.100 ± 0.010 mg/kg. Cadmium was below the limit of detection (<0.001 mg/kg) in all the fruit samples, while the concentration of Pb varied from 0.01 ± 0.00 mg/kg to 0.06 ± 0.03 mg/kg. In all the fruit pulps, mean total metal concentrations followed the chemical sequence Zn > Cu > Pb > Cd.

3.2. Distribution of HMs in Orchard Soil Samples

The concentration of HMs in the soil samples ranged from <0.001 - 0.44 ± 0.21 mg/kg for Cd to 20.15 ± 1.52 - 40.03 ± 7.30 mg/kg for Zn (**Figure 2**). Soil samples from orchards where oranges are cultivated had comparatively higher concentrations of all the HMs. The concentration of Zn was highest at 10 m for both mango

Table 3. Mean concentration of heavy metals (mg/kg) in fruits from orchards along Mbale-Soroti Highway, Uganda.

Distance from highway (m)	Heavy metal	Mangoes	Oranges
10	Cu	1.67 ± 0.41^{a}	0.10 ± 0.02^{a}
	Zn	5.76 ± 1.30^{b}	0.10 ± 0.01^{a}
	Pb	0.45 ± 0.24^{a,f}	0.06 ± 0.03^{b}
	Cd	<0.001	<0.001
100	Cu	1.49 ± 0.26^{a,c,d,e}	0.07 ± 0.02^{c}
	Zn	2.39 ± 0.47^{a,g}	0.06 ± 0.01^{b}
	Pb	0.11 ± 0.01^{c}	0.02 ± 0.004^{d}
	Cd	<0.001	<0.001
300	Cu	1.81 ± 0.37^{a,c}	0.06 ± 0.03^{b}
	Zn	1.90 ± 0.63^{a}	0.07 ± 0.03^{c}
	Pb	0.10 ± 0.04^{c,d}	0.03 ± 0.05^{e}
	Cd	<0.001	<0.001
5000 (control)	Cu	1.70 ± 0.66^{a}	0.05 ± 0.01^{f}
	Zn	2.41 ± 0.18^{a,h}	0.04 ± 0.03^{g}
	Pb	0.06 ± 0.20^{c,e,f}	0.01 ± 0.00^{h}
	Cd	<0.001	<0.001

Note: Values are presented as mean ± standard deviation of replicates (*n* = 3). Means carrying different letters in a column are statistically different as per Tukey test ($p < 0.05$).

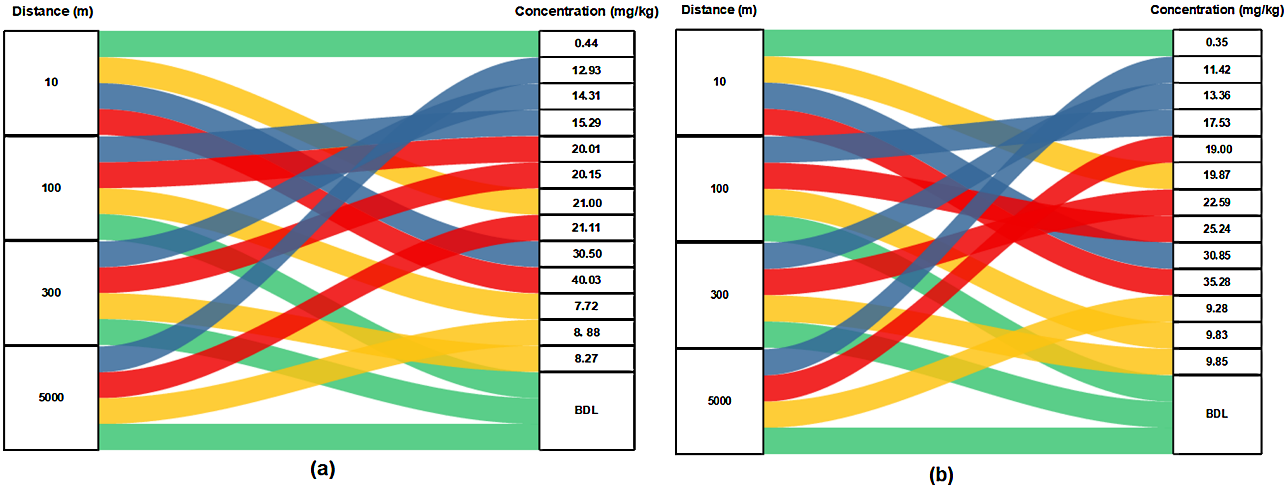


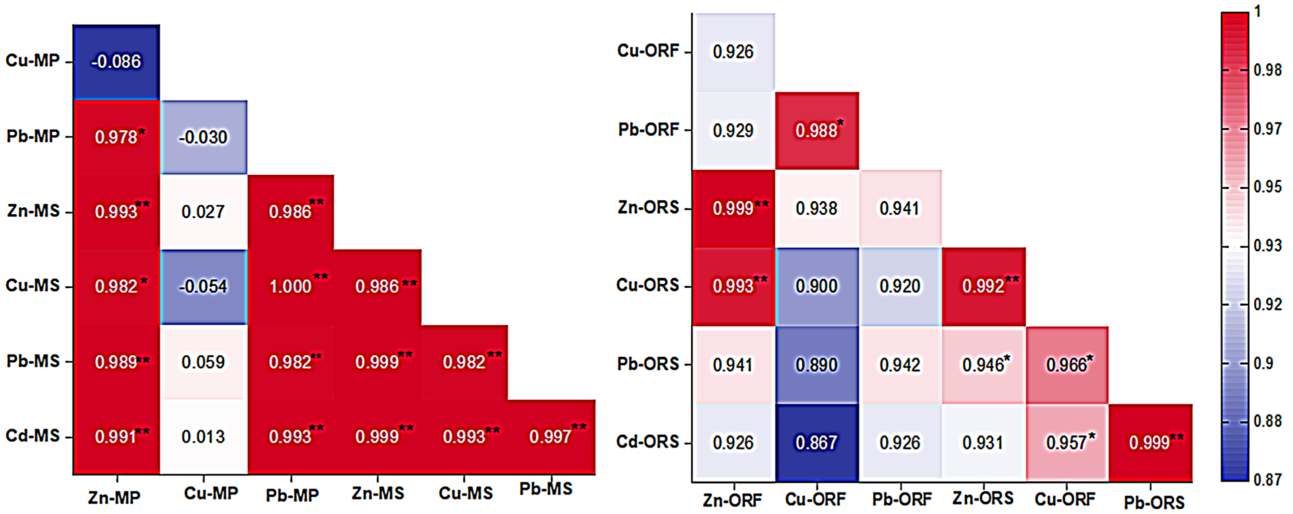
Figure 2. Alluvial plot of mean metal concentration in soils from: (a) mango, and (b) orange orchards. The heavy metals are colour coded: Cu (blue), Zn (red), Pb (yellow) and Cd (green). BDL = Below detection limit of 0.001 mg/kg.

(40.03 ± 7.30 mg/kg) and orange (35.28 ± 4.07 mg/kg) orchards, decreasing with distance from the road ($p < 0.05$). Background values at 5 km showed lower Zn levels (21.11 ± 3.34 mg/kg for mango and 19.00 ± 1.30 mg/kg for orange orchards). For Cu, a similar trend was observed where its concentrations were high near the road at 10 m (30.50 ± 3.62 mg/kg in mango orchards and 30.85 ± 5.97 mg/kg in orange orchards) and decreased steadily with distance. Only Zn and Cd in mango orchard soils within 10 m radius were statistically different ($p < 0.05$).

Lead concentrations were highest at 10 m (21.00 ± 3.13 mg/kg in mango orchards and 19.87 ± 2.71 mg/kg in orange orchards) and dropped significantly ($P < 0.05$) at 100 m and 300 m. Background Pb concentrations were relatively low (8.88 ± 0.10 mg/kg and 9.28 ± 0.40 mg/kg for mango and orange orchards, respectively), emphasizing road-associated Pb contamination. Lastly, Cd was detectable only at 10 m in both mango and orange orchards, with concentrations of 0.44 ± 0.21 mg/kg (mango) and 0.35 ± 0.19 mg/kg (orange). Cd was below detection limits (<0.001 mg/kg) beyond 100 m and at the control distance (5 km). In all the samples, mean metal concentrations decreased in the order Zn > Cu > Pb > Cd.

3.3. Correlation of HMs Concentrations in Fruits with Those in the Soil Samples

Inter-metal correlation analysis showed that in both soils and mango fruits, there were weak to very strong positive correlations between HM pairs (**Figure 3(a)**). However, except for Cu in mangoes that had a negative correlation with Zn ($r = -0.086$, $p > 0.05$) and Pb ($r = -0.030$, $p > 0.05$) in the mango pulps, and Cu in the soils ($r = -0.054$, $p > 0.05$). On the other hand, Pearson's correlation analysis showed that in soils and oranges, there were very strong positive correlations between metal pairs (**Figure 3(b)**). However, some associations, especially for Cu and Pb in oranges were not statistically significant ($p < 0.05$).



(a) (b)

Figure 3. Pearson's bivariate correlation matrix plot for the heavy metals in orchard soils and (a) mango pulps, (b) orange juices. Legend: MP means mango pulp, and MS means mango orchard soil, OR means orange fruit, and ORS means orange orchard soil. Cadmium was not detected in the fruits and it was therefore, not shown in the correlation matrixes. *Significant at the 0.05 level (2-tailed), **also significant at the 0.01 level.

3.4. Health Risks from Dietary Intake of HMs in Fruits

The EDI calculated for mangoes ranged from 1.74×10^{-5} mg/kg/day for Pb (at

5000 m) in children to 6.67×10^{-2} mg/kg/day for Zn at 10 m in adults (Table 4). For oranges, the EDI were 2.89×10^{-6} mg/kg/day for Pb (at 5000 m) in children to 1.16×10^{-3} mg/kg/day for Zn at 10 m in adults. The hazard quotients were 1.24×10^{-4} for Pb (at 5000 m) in children to 1.11×10^{1} for Zn at 10 m in adults for mango pulps, and 2.07×10^{-5} to 1.93×10^{-1} in orange juices, respectively. The corresponding hazard indices were from 1.08×10^{-1} at 100 m in children to 5.24×10^{-1} at 300 m in adults for mango pulps, and 1.45×10^{-2} in adults (at 5000 m) to 7.23×10^{-3} at 10 m in children for orange juices.

Table 4. Health risk indices for consumption of fruits from orchards along Mbale-Soroti Highway, Uganda.

Age group	Distance from highway (m)	Heavy metal	Estimated daily intake (Mangoes)**	Estimated daily intake (Oranges) **	Hazard quotient (Mangoes)	Hazard quotient (Oranges)	Hazard index (Mangoes)	Hazard index (Oranges)
Children	10	Cu	4.83E−03	2.89E−04	1.21E−01	7.23E−03	1.21E−01	7.23E−03
		Zn	1.67E−02	2.89E−04	2.78E+00	4.82E−02		
		Pb	1.30E−04	1.74E−05	9.30E−04	1.24E−04		
	100	Cu	4.31E−03	2.03E−04	1.08E−01	5.06E−03	1.08E−01	5.06E−03
		Zn	6.92E−03	1.74E−04	1.15E+00	2.89E−02		
		Pb	3.18E−05	5.79E−06	2.27E−04	4.13E−05		
	300	Cu	5.24E−03	1.74E−04	1.31E−01	4.34E−03	1.31E−01	4.34E−03
		Zn	5.50E−03	2.03E−04	9.16E−01	3.38E−02		
		Pb	2.89E−05	8.68E−06	2.07E−04	6.20E−05		
	5000 (control)	Cu	4.92E−03	1.45E−04	1.23E−01	3.62E−03	1.23E−01	3.62E−03
		Zn	6.97E−03	1.16E−04	1.16E+00	1.93E−02		
		Pb	1.74E−05	2.89E−06	1.24E−04	2.07E−05		
Adults	10	Cu	1.93E−02	1.16E−03	4.83E−01	2.89E−02	4.83E−01	2.89E−02
		Zn	6.67E−02	1.16E−03	1.11E+01	1.93E−01		
		Pb	5.21E−04	6.94E−05	3.72E−03	4.96E−04		
	100	Cu	1.72E−02	8.10E−04	4.31E−01	2.03E−02	4.31E−01	2.03E−02
		Zn	2.77E−02	6.94E−04	4.61E+00	1.16E−01		
		Pb	1.27E−04	2.31E−05	9.09E−04	1.65E−04		
	300	Cu	2.09E−02	6.94E−04	5.24E−01	1.74E−02	5.24E−01	1.74E−02
		Zn	2.20E−02	8.10E−04	3.66E+00	1.35E−01		
		Pb	1.16E−04	3.47E−05	8.27E−04	2.48E−04		
	5000 (control)	Cu	1.97E−02	5.79E−04	4.92E−01	1.45E−02	4.92E−01	1.45E−02
		Zn	2.79E−02	4.63E−04	4.65E+00	7.72E−02		
		Pb	6.94E−05	1.16E−05	4.96E−04	8.27E−05		

Note: **Calculated in mg/kg/day.

For cancer risks, the estimation was only done due to Pb ingestion since Cd was not detectable in the fruits (**Table 5**). In mangoes, the cancer risks ranged from 1.476 × 10^{-7} in children consuming mangoes grown within 5000 m radius of the highway to 44.27 × 10^{-7} for adults consuming mangoes grown within 10 m radius from the highway. For oranges, the cancer risks ranged from 0.246 × 10^{-7} for fruits grown 5000 m away from the highway (consumed by children) to 5.9 × 10^{-7} for fruits grown at 10 m away from the highway that are consumed by adults.

Table 5. Cancer risk values (1 × 10^{-7}) for consumption of lead in fruits from orchards.

Age group	Distance (m)	Mangoes	Oranges
Children	10	11.070	1.48
	100	2.705	0.492
	300	2.459	0.738
	5000	1.476	0.246
Adults	10	44.27	5.9
	100	10.82	1.97
	300	9.837	2.95
	5000	5.902	0.984

3.5. Soil Pollution Assessment Indices

The potential effects of highway traffic on orchard soil pollution were assessed. The CF, I_{geo} and pollution load indices were calculated. The CF showed that the values lied in the classification of 1 ≤ CF ≤ 3 and 3 ≤ CF < 6 for Cu, Zn, Pb and Cd in mango orchards within 10 m radius. Beyond this distance, the CF were generally about 1 or less. In orange orchards, the same trend was observed and Cd was the major contributor to pollution (**Table 6**). For the PLI, the values were from 0.99 to 1.81, with the highest values for soils taken from within 10 m radius of the orchard soils. For index of geoaccumulation (I_{geo}) in soils from orchards within 10 m radius, values were generally less than 1 for both mango and orange orchard soils. These were thus classified under class 1 ($0 < I_{geo} < 1$) for Cu, Pb and Zn (**Table 2**; **Table 6**). For this index, the HMs showed an order: Cu > Pb > Zn > Cd.

Table 6. Contamination and geoaccumulation indices of heavy metals in orchard soils, Uganda.

Contamination index	Distance from highway (m)	Mango orchards				Orange orchards			
		Cu	Zn	Pb	Cd	Cu	Zn	Pb	Cd
Contamination factor (CF)	10	2.36	1.89	2.37	–	2.70	1.86	2.14	–
	100	1.18	0.95	0.87	–	1.36	1.33	1.11	–
	300	1.11	0.95	0.93	–	1.17	1.19	1.06	–

Continued

Geoaccumulation index (I_{geo})	10	0.93	0.33	0.94	–	1.09	0.31	0.70	–
	100	−0.22	−0.65	−0.76	–	0.02	−0.42	−0.35	–
	300	−0.31	−0.63	−0.50	–	−0.18	−0.22	−0.23	–
Ecological risk coefficient (E_i)	10	1.90	11.80	11.85	–	13.50	1.86	10.70	–
	100	0.95	5.90	4.35	–	6.80	1.33	5.55	–
	300	0.95	5.55	4.65	–	5.85	1.19	5.30	–
Pollution load index (PLI)	10	1.80				1.81			
	100	0.99				1.19			
	300	0.99				1.10			
Potential ecological risk index (RI)	10	25.55				26.06			
	100	11.20				13.68			
	300	11.15				12.34			

The ecological risk coefficients were from 0.95 to 11.85 and 1.19 (for Zn) to 13.50 for Cu at 10 m (**Table 6**). In order of severity, the risk coefficients could be arranged as Pb > Cu > Zn for mango orchard soils, and Cu > Pb > Zn for orange orchard soils. The potential ecological risk index ranged from 11.15 to 26.06 for soils from all orchards.

4. Discussion

4.1. Concentration of HMs in Fruits as Compared to Permissible Limits

The present findings indicated varying concentrations of Cu, Zn, Pb and Cd in mangoes and oranges obtained along Mbale-Soroti highway. The levels of all the metals detected in fruits were below the regulatory international limit of 40, 1.5, 0.50 and 0.02 mg/kg, respectively [53], which suggested minimal health risks associated with the consumption of the fruits. The distribution pattern of metals observed could show the influence of both environmental and plant-specific factors. The significant differences of Cu in the fruit samples suggest uniform deposition or minimal soil-to-fruit transference of the metal although Cu is essential in the plant metabolism, there could have been a strong physiological regulation in Cu uptake and translocation across the plant tissues [55], leading to the observed variability. Relatedly, significant differences in Zn levels between mango pulp and orange juice ($p < 0.05$) suggested possible varying species-specific translocation dynamics or external deposition rates between the fruits. The distribution of zinc tends to vary with the fruit skin permeability, physiology, juice content, and the fruit surface area for dust adherence and the subsequent penetration into edible fruit tissues [56].

Compared to previous studies, the levels of Cu, Zn, Pb, and Cd reported in mangoes and oranges from Uganda as per the current study were generally lower (**Table 7**). Few studies conducted in Ethiopia [57], Nepal [58] and India [59] reported even lower HM levels although the samples were taken from orchards near highways. In contrast, higher levels win HMs were observed in fruits grown along highways in Turkey [60], where there are high traffic density along the highways, industrial emissions could contribute to the elevated dust load and hence metal contamination.

Factors such as antagonism, soil pH, organic matter, nature of the plant, and the chemical form could suggest why cadmium was not detectable in fruits [61]. Cadmium uptake can also be competitively inhibited by the presence of Zn since they are chemically similar, a mechanism of antagonism reported in plant systems [61]. Other factors like root barrier mechanisms, restricted xylem intake could further hinder the translocation of Cd.

Table 7. Comparison of heavy metal content (mg/kg) of mangoes and sweet oranges from fruit orchards along Mbale-Soroti Highway, Uganda with previous studies.

Country	Fruit	Cu	Zn	Pb	Cd	Reference
Uganda	Mangoes	1.70 - 1.67	2.41 - 5.76	0.06 - 0.45	<0.001	Present study
	Oranges	0.05 - 0.10	0.04 - 0.10	0.01 - 0.06	<0.001	
	Mangoes	–	–	0.32	0.40	Muhwezi *et al.* [62]
Ethiopia	Mangoes	0.019 - 0.198	0.134 - 0.321	0.035 - 0.097	0.193	Ezez and Belew [57]
Democratic Republic of the Congo		22.0 - 29.3	9.5 - 13.3	0.31 - 2.20	0.09 - 0.19	Langunu *et al.* [63]
Nigeria		1.5 - 8.0	–	1.5 - 40.0	–	Chata *et al.* [64]
Sierra Leone		25.47	11.88	10.65	–	Egbenda *et al.* [65]*
Iran		–	–	0.08 - 0.50	0.02 - 0.14	Rahimzadeh and Rastegar [66]*
India		–	–	0.02 - 0.15	0.01 - 0.08	Širić *et al.* [67]
Bangladesh		7.891	0.604	0.642	0.005	Shaheen *et al.* [38]
China		–	–	0.0008 - 0.209	0.0003 - 0.0042	Bi *et al.* [68]
Nepal		–	0.510	BDL	–	Pant *et al.* [58]
Malaysia		5.74	12.22	1.64	0.12	Ang *et al.* [69]
India	Oranges	–	–	0.002	0.001	Mawari *et al.* [59]
China		–	–	0.028 - 0.067	0.001 - 0.005	Cheng *et al.* [70]
		0.204 - 0.334	0.380 - 0.661	0.001 - 0.050	0.001 - 0.002	Li *et al.* [71]
Pakistan		–	–	5.25	2.15	Ullah *et al.* [72]

Note: – means Not reported. BDL = Below detection limit; *These values were converted to mg/kg to allow for comparison.

4.2. Enrichment of HMs in Orchard Soils

Uganda does not have set permissible limits for HMs in agricultural soils.

However, the WHO target values for unpolluted soils are 36, 50, 85 and 0.8 mg/kg for Cu, Zn, Pb and Cd respectively [54]. In the current study, HM levels in the orchard soil were all below the WHO threshold target values, as well as the control site, and the global average levels in the upper continental crust (38.9, 64.0, 27.0 and 0.40 mg/kg for Cu, Zn, Pb and Cd, respectively) [73] [74]. These findings show that there is minimal degree of contamination of the orchard soils along the Mbale-Soroti Highway. This observation suggests that vehicular activities could not be the sole contributing factor of HMs in such areas. Some of the HMs detected, such as Cu and Zn in orchard soils might be accumulating in such soils due to agricultural inputs as the possible sources. The application of fertilizers and fungicides containing the HM salts could have enriched the soils with these metals [75]. The presence of these metals in soil reflects their persistence in soils, accumulation due to the agricultural activities, and limited atmospheric deposition from the traffic load. The low levels of Pb and Cd could be ascribed to low emissions from limited leaded petrol traffic on the highway and the low industrial activity in the study area.

In comparison with related studies in other countries, HM levels reported in the current study were quite lower than those reported elsewhere. For example, Egbenda *et al.* [65] quantified mean Cu, Zn and Pb in mango orchard soils as 40.85, 11.10 and 2.565 mg/kg. Similarly, da Silva *et al.* [75] reported Cu (2.26 - 40.10 mg/kg), Zn (0.20 - 102.87 mg/kg) and Pb (undetected - 9.29 mg/kg) in mango orchard soils of Pernambuco, Brazil. Cheng *et al.* [70] found Pb (3.58 - 213 mg/kg) and Cd (0.05 - 12.9 mg/kg) in orange orchard soils of China. Another study reported the respective mean concentration of 90.5, 159, 21.8, and 0.94 mg/kg for Cu, Zn, Pb and Cd in orange orchard soils from Korea [76]. In Perlis, Malaysia, mango orchard soils contained Pb (0.32 - 0.42 mg/kg) and Cd (0.26 - 0.98 mg/kg) [77]. However, Bi *et al.* [68] previously reported exceptionally low levels of Pb (0.0008 - 0.063 mg/kg) and Cd (0.000019 - 0.00021 mg/kg) in mango orchard soils from the relatively pristine area of Hainan Island, China.

These marked differences in the HM levels reflect the importance of local factors shaping soil HM contamination. The geographical location, physicochemical properties and nature of anthropogenic activities may enrich the soil contamination with HMs [78]. For instance, pH, organic matter, and clay content strongly influence the retention, mobility, and bioavailability of HMs. Acidic soils increase the solubility of Cd and Pb, while organic matter can immobilize Cu and Zn via complexation. Environmental factors such as rainfall via surface run-off and wind, alters the extent of atmospheric deposition, while anthropogenic activities such as pesticide use, vehicular density enrich soils with HMs.

Therefore, the observed pattern of HMs in the orchard soils along the Mbale-Soroti highway shows that these soils are relatively uncontaminated. The Cu and Zn levels reflect agricultural inputs, while the low Pb and Cd levels could be due to limited atmospheric deposition. The comparatively lower levels than those reported elsewhere are indicative of combined effects of soil chemistry, traffic intensity, and land-use practices.

4.3. Soil-to-Fruit Transfer of HMs and Associated Health Risks

Correlation analysis gave an insight into how HMs can be transferred between soils and fruits. In mango fruits, Cu metal showed either very weak positive correlations or negative correlations with Cu in the soils and other metals in both matrices. The observed weak associations proposed distinct origins and limited soil-to-fruit transfer of Cu, probably due to the strong binding to the soil organic matter, clay soil particles, which in turn restrict mobility and hence plant uptake. The significant positive correlations between metal pairs suggest a common or combined source, probably agricultural inputs like Cu- and Zn-containing fungicides and fertilizers, or atmospheric deposition due to vehicular emissions [79]. Additionally, strong correlations of metals may also indicate similar retention mechanisms, like co-precipitation with carbonates, sorption to oxides, comparable geochemical behaviours in solid matrices. It also indicates that the metals entered into the environment through anthropogenic contributions [80]. When the same metal exhibits a positive soil-fruit relationship, it indicates accumulation from the soil into the edible tissues as a result of active uptake and translocation [6] [71] [81], and the absence of such a pattern shows limited bioavailability in soils.

The EDI calculated values of Cu, Zn, Pb, and Cd for both mangoes and oranges, all were lower than the oral reference doses established by international agencies. Subsequently, the hazard quotients and hazard indices for both adults and children did not surpass 1. This observation suggested a negligible risk of non-carcinogenic effects expected in individuals due to regular consumption of mango and orange pulps from the orchards. On the other hand, the incremental cancer risk values were only calculated for Pb as the sole driver of carcinogenic health risks. The risk values calculated ranged from 0.246×10^{-7} to 44.27×10^{-7}. These values were within the acceptable risk range (10^{-4} to 10^{-6}) as per the US EPA, and the unacceptable value for the risks should be surpassing 10^{-4}. Therefore, for the current study, the cancer risk values confirmed that there is no significant carcinogenic risk for both adults and children due to Pb exposure through ingestion the fruits.

The pollution indices to substantiate the contamination status of orchard soils along the Mbale-Soroti Highway showed that the contamination factor (CF) values were within the “low contamination” category as per Hakanson’s classification [48], while the pollution load index (PLI < 1) denoted unpolluted soils [6] observed. The geo-accumulation index (I_{geo}) values were consistent with “unpolluted to low contamination” [49] soils. Relatedly, the ecological risk coefficients ($E_i < 40$ and RI < 95) showed low contamination indicative of low ecological risks [48]. These findings altogether suggested that there is low pollution of soils as well as ecological risks to the biodiversity in the orchard soils, which is similar to a previous observation in orange orchard soils reported by Xue *et al.* [82]. The findings thus demonstrated that orchard soils in the study area pose low ecological and health risks. The fruit contamination could be influenced by atmospheric deposition and agricultural practices than by direct soil-to-fruit transfer. This emphasizes the need to consider both environmental inputs and plant uptake mechanisms when assessing food safety near highways.

5. Conclusion

This study investigated the risks posed by HMs in soils, mangoes and oranges along the Mbale-Soroti Highway, an arterial stretch of the Pan-African Highway in Uganda. All the metals occurred at levels that never exceeded safety thresholds, posing no potential carcinogenic and non-cancer health risks. Metal concentrations were higher in soils than fruits and decreased with distance from the highway, with a strong soil-to-fruit transfer correlation. Establishing orchards at least 300 m from the highway is recommended to minimize possible contamination by HMs and safeguard food safety.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] United Nations Department of Economic and Social Affairs, Population Division (2024) World Population Prospects 2024: Summary of Results (UN DE-SA/POP/2024/TR/NO. 9). United Nations.

[2] van Dijk, M., Morley, T., Rau, M.L. and Saghai, Y. (2021) A Meta-Analysis of Projected Global Food Demand and Population at Risk of Hunger for the Period 2010-2050. *Nature Food*, **2**, 494-501. https://doi.org/10.1038/s43016-021-00322-9

[3] Oncini, F., Hirth, S., Mylan, J., Robinson, C.H. and Johnson, D. (2024) Where the Wild Things Are: How Urban Foraging and Food Forests Can Contribute to Sustainable Cities in the Global North. *Urban Forestry & Urban Greening*, **93**, Article ID: 128216. https://doi.org/10.1016/j.ufug.2024.128216

[4] Creţan, R., Chasciar, D. and Dragan, A. (2024) Forests and Their Related Ecosystem Services: Visitors' Perceptions in the Urban and Peri-Urban Spaces of Timişoara, Romania. *Forests*, **15**, Article 2177. https://doi.org/10.3390/f15122177

[5] Khan, M.M., Akram, M.T., Janke, R., Qadri, R.W.K., Al-Sadi, A.M. and Farooque, A.A. (2020) Urban Horticulture for Food Secure Cities through and Beyond Covid-19. *Sustainability*, **12**, Article 9592. https://doi.org/10.3390/su12229592

[6] Rutehenda, D.R., Adaku, C., Omara, T., Angiro, C. and Ntambi, E. (2024) Enrichment, Bioaccumulation and Health Risks of Trace Metals in Soils and Leafy Vegetables Grown on the Banks of the Ugandan Lifeline River, River Rwizi. *World*, **5**, 136-154. https://doi.org/10.3390/world5010008

[7] Chatzistathis, T., Kavvadias, V., Sotiropoulos, T. and Papadakis, I.E. (2021) Organic Fertilization and Tree Orchards. *Agriculture*, **11**, Article 692. https://doi.org/10.3390/agriculture11080692

[8] Ritika,, Bora, B., Ismail, B.B., Garba, U., Mishra, S., Jha, A.K., *et al.* (2024) Himalayan Fruit and Circular Economy: Nutraceutical Potential, Traditional Uses, Challenges and Opportunities. *Food Production*, *Processing and Nutrition*, **6**, Article No. 71. https://doi.org/10.1186/s43014-023-00220-6

[9] Chamberlain, L.K., Scott, H., Beddoe, N. and Rintoul-Hynes, N.L.J. (2024) Heavy Metal Contamination (Cu, Pb, and Cd) of Washed and Unwashed Roadside Blackberries (*Rubus fruticose* L.). *Integrated Environmental Assessment and Management*, **20**, 2107-2115. https://doi.org/10.1002/ieam.4981

[10] Warczyk, A., Gruba, P., Józefowska, A., Wanic, T., Warczyk, A., Świątek, B., *et al.* (2024) Accumulation of Heavy Metals in Blueberry (*Vaccinium myrtillus* L.) and Dominant Mosses (*Pleurozium schreberi* (Willd. Ex Brid.) Mitt.) as Bioindicators of the Expressway Influence on Forest Ecosystems. *Atmosphere*, **15**, Article 971. https://doi.org/10.3390/atmos15080971

[11] Demirhan Aydın, Ş. and Pakyürek, M. (2020) Heavy Metal Accumulation Potential in Pomegranate Fruits and Leaves Grown in Roadside Orchards. *PeerJ*, **8**, e8990. https://doi.org/10.7717/peerj.8990

[12] Singh, N.B. and Susan, A.B.H. (2018) Polymer Nanocomposites for Water Treatments. In: Jawaid, M. and Khan, M.M., Eds., *Polymer-Based Nanocomposites for Energy and Environmental Applications*, Elsevier, 569-595. https://doi.org/10.1016/b978-0-08-102262-7.00021-0

[13] Tchounwou, P.B., Yedjou, C.G., Patlolla, A.K. and Sutton, D.J. (2012) Heavy Metal Toxicity and the Environment. In: Luch, A., Ed., *Molecular, Clinical and Environmental Toxicology*, Springer, 133-164. https://doi.org/10.1007/978-3-7643-8340-4_6

[14] Way, M., Willingham, J. and Goodall, R. (2019) Brazing Filler Metals. *International Materials Reviews*, **65**, 257-285. https://doi.org/10.1080/09506608.2019.1613311

[15] Nuwamanya, E., Byamugisha, D., Nakiguli, C.K., Angiro, C., Khanakwa, A.V., Omara, T., *et al.* (2024) Exposure and Health Risks Posed by Potentially Toxic Elements in Soils of Metal Fabrication Workshops in Mbarara City, Uganda. *Journal of Xenobiotics*, **14**, 176-192. https://doi.org/10.3390/jox14010011

[16] Li, J., Cao, D., Huang, Y., Chen, B., Chen, Z., Wang, R., *et al.* (2022) Zinc Intakes and Health Outcomes: An Umbrella Review. *Frontiers in Nutrition*, **9**, Article 798078. https://doi.org/10.3389/fnut.2022.798078

[17] Frugier, C. and Bégin, P. (2024) Food Toxins. In: Sicherer, S.H., Ed., *Encyclopedia of Food Allergy*, Elsevier, 814-827. https://doi.org/10.1016/b978-0-323-96018-2.00011-0

[18] WHO (2022) Lead in Drinking-Water: Health Risks, Monitoring and Corrective Actions. https://apps.who.int/iris/rest/bitstreams/1460455/retrieve

[19] WHO (2021) Exposure to Lead: A Major Public Health Concern, 2nd Edition. World Health Organization. https://www.who.int/publications/i/item/9789240037656

[20] Kim, H., Jang, T., Chae, H., Choi, W., Ha, M., Ye, B., *et al.* (2015) Evaluation and Management of Lead Exposure. *Annals of Occupational and Environmental Medicine*, **27**, Article No. 30. https://doi.org/10.1186/s40557-015-0085-9

[21] Eid, R., Arab, N.T.T. and Greenwood, M.T. (2017) Iron Mediated Toxicity and Programmed Cell Death: A Review and a Re-Examination of Existing Paradigms. *Biochimica et Biophysica Acta (BBA)—Molecular Cell Research*, **1864**, 399-430. https://doi.org/10.1016/j.bbamcr.2016.12.002

[22] Balali-Mood, M., Naseri, K., Tahergorabi, Z., Khazdair, M.R. and Sadeghi, M. (2021) Toxic Mechanisms of Five Heavy Metals: Mercury, Lead, Chromium, Cadmium, and Arsenic. *Frontiers in Pharmacology*, **12**, Article 643972. https://doi.org/10.3389/fphar.2021.643972

[23] Vodyanitskii, Y.N. (2010) Equations for Assessing the Total Contamination of Soils with Heavy Metals and Metalloids. *Eurasian Soil Science*, **43**, 1184-1188.

https://doi.org/10.1134/s106422931010011x

[24] Herlocker, D. (2024) Africa's Great North Road. https://storiesofeastafrica.com/2020/09/24/africas-great-north-road/

[25] Broeckx, J., Maertens, M., Isabirye, M., Vanmaercke, M., Namazzi, B., Deckers, J., *et al.* (2018) Landslide Susceptibility and Mobilization Rates in the Mount Elgon Region, Uganda. *Landslides*, **16**, 571-584. https://doi.org/10.1007/s10346-018-1085-y

[26] Opedes, H., Mücher, S., Baartman, J.E.M., Nedala, S. and Mugagga, F. (2022) Land Cover Change Detection and Subsistence Farming Dynamics in the Fringes of Mount Elgon National Park, Uganda from 1978-2020. *Remote Sensing*, **14**, Article 2423. https://doi.org/10.3390/rs14102423

[27] Nugent, P. and Soi, I. (2020) One-Stop Border Posts in East Africa: State Encounters of the Fourth Kind. *Journal of Eastern African Studies*, **14**, 433-454. https://doi.org/10.1080/17531055.2020.1768468

[28] Fitzmaurice, M. and Hartmann, O. (2025) Border Crossing Monitoring along the Northern Corridor. The International Bank for Reconstruction and Development/The World Bank. https://openknowledge.worldbank.org/server/api/core/bitstreams/da67157a-93ab-51a0-a6a3-7677f98dabd4/content

[29] Collins, T. (2020) East African Community Battles Trade Disruption. https://african.business/2020/08/trade-investment/east-african-community-battles-trade-disruption/

[30] Joshua (2022) Places to Visit in Eastern Uganda. https://toptenuganda.com/places-to-visit-in-eastern-uganda/

[31] Hong, S., Hwang, S., Adriko, J., Semalulu, O., Nampamya, D., Lee, J., *et al.* (2020) Effect of *Pseudocercospora* Spot Disease Control and Soil Moisture Management on Citrus Production in Teso Region, Uganda. *Journal of the Korean Society of International Agricultue*, **32**, 199-205. https://doi.org/10.12719/ksia.2020.32.3.199

[32] Kongai, H., Mangisoni, J., Elepu, G., Chilembwe, E. and Makoka, D. (2018) Analysis of Citrus Value Chain in Eastern Uganda. *African Crop Science Journal*, **26**, 417-431. https://doi.org/10.4314/acsj.v26i3.7

[33] Achuu, S.P., Nachuha, S., Nakizito, J., Musoke, S.H. and Opedes, H.E. (2022) Citrus Fruit Farmers' Adaptation Capacities to Climate Variability in Ngora District, Eastern Uganda. *Kabale University Interdisciplinary Research Journal*, **1**, 86-98.

[34] Gumisiriza, M., Tadesse, T., Isubikalu, P., Kabirizi, J. and Zziwa, E. (2016) Perception on Climate Change and Climate Smart Agricultural Technologies among Small Holder Mixed Farmers in East Africa. *RUFORUM Working Document Series*, No. 14, 225-234.

[35] Office of the Prime Minister, G. O. U. (2016) Ngora District Hazard, Risk and Vulnerability Profile. https://www.necoc.opm.go.ug/HzEastern/Ngora%20District%20HRV%20Profile.pdf

[36] Akbar, K.F., Hale, W.H.G., Headley, A.D. and Athar, M. (2006) Heavy Metal Contamination of Roadside Soils of Northern England. *Soil and Water Research*, **1**, 158-163. https://doi.org/10.17221/6517-swr

[37] Wang, Q., Liu, J. and Cheng, S. (2014) Heavy Metals in Apple Orchard Soils and Fruits and Their Health Risks in Liaodong Peninsula, Northeast China. *Environmental Monitoring and Assessment*, **187**, Article No. 4178. https://doi.org/10.1007/s10661-014-4178-7

[38] Shaheen, N., Irfan, N.M., Khan, I.N., Islam, S., Islam, M.S. and Ahmed, M.K. (2016)

Presence of Heavy Metals in Fruits and Vegetables: Health Risk Implications in Bangladesh. *Chemosphere*, **152**, 431-438. https://doi.org/10.1016/j.chemosphere.2016.02.060

[39] Kaggwa, A., Byamugisha, D., Omara, T. and Ntambi, E. (2024) Assessment of Potentially Toxic Elements and Their Risks in Water and Sediments of Kitengure Stream, Buhweju Plateau, Uganda. *Earth*, **5**, 743-760. https://doi.org/10.3390/earth5040039

[40] U.S. Environmental Protection Agency (1994) Method 200.7: Determination of Metals and Trace Elements in Water and Wastes by Inductively Coupled Plasma-Atomic Emission Spectrometry. Revision 4.4.

[41] US EPA (2025) IRIS, Environmental Protection Agency Region I. https://cfpub.epa.gov/ncea/iris2/chemicalLanding.cfm?substance_nmbr=422

[42] Ordóñez, A., Álvarez, R., Charlesworth, S., De Miguel, E. and Loredo, J. (2011) Risk Assessment of Soils Contaminated by Mercury Mining, Northern Spain. *Journal of Environmental Monitoring*, **13**, 128-136. https://doi.org/10.1039/c0em00132e

[43] Omara, T., Karungi, S., Kalukusu, R., Nakabuye, B., Kagoya, S. and Musau, B. (2019) Mercuric Pollution of Surface Water, Superficial Sediments, Nile Tilapia (*Oreochromis nilotica* Linnaeus 1758 [Cichlidae]) and Yams (*Dioscorea alata*) in Auriferous Areas of Namukombe Stream, Syanyonja, Busia, Uganda. *PeerJ*, **7**, e7919. https://doi.org/10.7717/peerj.7919

[44] Opolot, M., Omara, T., Adaku, C. and Ntambi, E. (2023) Pollution Status, Source Apportionment, Ecological and Human Health Risks of Potentially (Eco)toxic Element-Laden Dusts from Urban Roads, Highways and Pedestrian Bridges in Uganda. *Pollutants*, **3**, 74-88. https://doi.org/10.3390/pollutants3010007

[45] US EPA (2011) Exposure Factors Handbook. National Centre for Environment Assessment.

[46] USEPA (2010) Risk-Based Concentration Table. United States Environmental Protection Agency, Washington, DC.

[47] Ajeh, E.A., Modi, F.J. and Omoregie, I.P. (2022) Health Risk Estimations and Geospatial Mapping of Trace Metals in Soil Samples around Automobile Mechanic Workshops in Benin City, Nigeria. *Toxicology Reports*, **9**, 575-587. https://doi.org/10.1016/j.toxrep.2022.03.021

[48] Hakanson, L. (1980) An Ecological Risk Index for Aquatic Pollution Control. A Sedimentological Approach. *Water Research*, **14**, 975-1001. https://doi.org/10.1016/0043-1354(80)90143-8

[49] Müller, G. (1981) Die Schwermetallbelastung der Sedimenten des Neckars und Seiner Nebenflüsse. *Chemiker-Zeitung*, **6**, 157-164.

[50] Taylor, S.R. (1964) Abundance of Chemical Elements in the Continental Crust: A New Table. *Geochimica et Cosmochimica Acta*, **28**, 1273-1285. https://doi.org/10.1016/0016-7037(64)90129-2

[51] Chen, C., Kao, C., Chen, C. and Dong, C. (2007) Distribution and Accumulation of Heavy Metals in the Sediments of Kaohsiung Harbor, Taiwan Region. *Chemosphere*, **66**, 1431-1440. https://doi.org/10.1016/j.chemosphere.2006.09.030

[52] Zhang, W., Feng, H., Chang, J., Qu, J., Xie, H. and Yu, L. (2009) Heavy Metal Contamination in Surface Sediments of Yangtze River Intertidal Zone: An Assessment from Different Indexes. *Environmental Pollution*, **157**, 1533-1543. https://doi.org/10.1016/j.envpol.2009.01.007

[53] FAO/WHO (2011) Joint FAO/WHO Food Standards Programme Codex Committee

on Contaminants in Foods, Food CF/5 INF/1. Fifth Session. The Hague.

[54] Denneman, C.A.J. and Robberse, J.G. (1990) Ecotoxicological Risk Assessment as a Base for Development of Soil Quality Criteria. In: Arendt, F., Hinsenveld, M. and Van Den Brink, W.J., Eds., *Contaminated Soil* '90, Springer Netherlands, 157-164. https://doi.org/10.1007/978-94-011-3270-1_28

[55] Xu, E., Liu, Y., Gu, D., Zhan, X., Li, J., Zhou, K., *et al.* (2024) Molecular Mechanisms of Plant Responses to Copper: From Deficiency to Excess. *International Journal of Molecular Sciences*, **25**, Article 6993. https://doi.org/10.3390/ijms25136993

[56] Rasheed, N., Maqsood, M.A., Aziz, T., Ashraf, M.I., Saleem, I., Ehsan, S., *et al.* (2024) Zinc Portioning and Allocation Patterns among Various Tissues Confers Variations in Zn Use Efficiency and Bioavailability in Lentil Genotypes. *Frontiers in Plant Science*, **14**, Article 1325370. https://doi.org/10.3389/fpls.2023.1325370

[57] Ezez, D. and Belew, M. (2023) Analysis of Physicochemical Attributes, Contamination Level of Trace Metals and Assessment of Health Risk in Mango Fruits from Southern Region Ethiopia. *Toxicology Reports*, **10**, 124-132. https://doi.org/10.1016/j.toxrep.2023.01.004

[58] Pant, N., Subedee, A., Gharti, R.B. and Shrestha, S. (2020) Spectrometric Determination of Heavy Metals Present in Mango Fruit of Nepali Origin. *Amrit Research Journal*, **1**, 72-77. https://doi.org/10.3126/arj.v1i1.32457

[59] Mawari, G., Kumar, N., Sarkar, S., Daga, M.K., Singh, M.M., Joshi, T.K., *et al.* (2022) Heavy Metal Accumulation in Fruits and Vegetables and Human Health Risk Assessment: Findings from Maharashtra, India. *Environmental Health Insights*, **16**, 1-10. https://doi.org/10.1177/11786302221119151

[60] Yildiz, E., Erkek, B., Yilmaz, K.U. and Yaman, M. (2022) Determination of the Effect of Distance to Highway on the Accumulation of Some Heavy Metals in Apple Orchards. *Current Trends in Natural Sciences*, **11**, 145-152. https://doi.org/10.47068/ctns.2022.v11i21.017

[61] Godfrey, M., Johnson, T. and Juliet, K. (2021) Assessment of Heavy Metal Concentrations in Mango Fruits Grown in Kasese District, Uganda. *African Journal of Environmental Science and Technology*, **15**, 451-456. https://doi.org/10.5897/ajest2021.3041

[62] Langunu, S., Imabo, P.M.I., Bibi Fwanda, B., Kilela Mwanasomwe, J., Colinet, G. and Ngoy Shutcha, M. (2023) Accumulation of Trace Metals in Fruits from Mango and *Syzygium guineense* Growing in Residential Households from a Contaminated District of Lubumbashi (DR Congo): Is Fruit Consumption at Risk? *Toxics*, **11**, Article 620. https://doi.org/10.3390/toxics11070620

[63] Yaman, M., and Dilgin, Y. (2002). AAS Determination of Cadmium in Fruits and Soils. *Atomic Spectroscopy*, **23**, 59-64.

[64] Chata, D., Iliya, A.Y., Chidawa, M.S., Emmanuel, M.B., Juliana, O.O. and Chibuzor, E.K. (2018) Determination of Heavy Metals in Four Mango Fruit Varieties Sold in Minna Modern Market, Niger State, Nigeria. *Journal of Biological and Environmental Engineering*, **1**, 24-29.

[65] P, O.E., F, T. and I, K. (2015) A Physico-Chemical Analysis of Soil and Selected Fruits in One Rehabilitated Mined Out Site in the Sierra Rutile Environs for the Presence of Heavy Metals: Lead, Copper, Zinc, Chromium and Arsenic. *African Journal of Pure and Applied Chemistry*, **9**, 27-32. https://doi.org/10.5897/ajpac2015.0606

[66] Rahimzadeh, M. and Rastegar, S. (2017) Heavy Metals Residue in Cultivated Mango Samples from Iran. *Journal of Food Quality and Hazards Control*, **4**, 29-31.

[67] Širić, I., Eid, E.M., El-Morsy, M.H.E., Osman, H.E.M., Adelodun, B., Abou Fayssal, S., *et al.* (2022) Health Risk Assessment of Hazardous Heavy Metals in Two Varieties of Mango Fruit (*Mangifera indica* L. Var. Dasheri and Langra). *Horticulturae*, **8**, Article 832. https://doi.org/10.3390/horticulturae8090832

[68] Bi, X., Ren, L., Gong, M., He, Y., Wang, L. and Ma, Z. (2010) Transfer of Cadmium and Lead from Soil to Mangoes in an Uncontaminated Area, Hainan Island, China. *Geoderma*, **155**, 115-120. https://doi.org/10.1016/j.geoderma.2009.12.004

[69] Ang, L.H. and Ng, L.T. (2000) Trace Element Concentration in Mango (*Mangifera indica* L.), Seedless Guava (*Psidium guajava* L.) and Papaya (*Carica papaya* L.) Grown on Agricultural and Exmining Lands of Bidor, Perak. *Pertanika Journal of Tropical Agricultural Science*, **23**, 15-22.

[70] Cheng, J., Ding, C., Li, X., Zhang, T. and Wang, X. (2015) Heavy Metals in Navel Orange Orchards of Xinfeng County and Their Transfer from Soils to Navel Oranges. *Ecotoxicology and Environmental Safety*, **122**, 153-158. https://doi.org/10.1016/j.ecoenv.2015.07.022

[71] Li, Q., Wei, C., Huang, Y., Wang, L. and Wang, D. (2010) A Study on the Characteristics of Heavy Metals in Orange Ecosystem. *Chinese Journal of Geochemistry*, **29**, 100-106. https://doi.org/10.1007/s11631-010-0100-3

[72] Ullah, H., Alam, Z., Shah, M., Ali, W., Ahmad, A. and Hadi, F. (2019) Investigation of Cadmium (Cd) and Lead (Pb) Contents in Soil, Orange Fruit and Its Accumulation in Human Blood. *International Journal of Agronomy & Agricultural Research*, **15**, 15-19.

[73] Kabata-Pendias, A. (2011) Trace Elements in Soils and Plants. In: Kabata-Pendias, A. and Pen-dias, H.K., Eds., *Trace Elements in Soils and Plants*, Taylor and Francis, 548.

[74] Xiao, X., Zhang, J., Wang, H., Han, X., Ma, J., Ma, Y., *et al.* (2020) Distribution and Health Risk Assessment of Potentially Toxic Elements in Soils around Coal Industrial Areas: A Global Meta-Analysis. *Science of the Total Environment*, **713**, Article ID: 135292. https://doi.org/10.1016/j.scitotenv.2019.135292

[75] Silva, J.P.S.D., Nascimento, C.W.A.D., Biondi, C.M. and Cunha, K.P.V.D. (2012) Heavy Metals in Soils and Plants in Mango Orchards in Petrolina, Pernambuco, Brazil. *Revista Brasileira de Ciência do Solo*, **36**, 1343-1354. https://doi.org/10.1590/s0100-06832012000400028

[76] Kang, T., Yang, H.J., Lee, W., Koo, B. and Park, W. (2023) Accumulation and Origin of Phosphorus and Heavy Metals in Citrus Orchard Soils in Jeju Island, South Korea: Potential Ecological Risks and Bioavailability. *Water*, **15**, Article 3951. https://doi.org/10.3390/w15223951

[77] Shareef, R.S., Mamat, A.S., Al-Shaheen, M.R. and Aslam, M.S. (2015) Study of Heavy Metals in Mango (*Mangifera indica* L) in Perlis, Malaysia. *Indian Journal of Pharmaceutical Sciences*, **7**, 299-303.

[78] Nazzal, Y., Ghrefat, H. and A. Rosen, M. (2014) Heavy Metal Contamination of Roadside Dusts: A Case Study for Selected Highways of the Greater Toronto Area, Canada Involving Multivariate Geostatistics. *Research Journal of Environmental Sciences*, **8**, 259-273. https://doi.org/10.3923/rjes.2014.259.273

[79] Ibrahim, M.I.A., Mohamed, L.A., Mahmoud, M.G., Shaban, K.S., Fahmy, M.A. and Ebeid, M.H. (2019) Potential Ecological Hazards Assessment and Prediction of Sediment Heavy Metals Pollution along the Gulf of Suez, Egypt. *Egyptian Journal of Aquatic Research*, **45**, 329-335. https://doi.org/10.1016/j.ejar.2019.12.003

[80] Xiang, Z., Wu, S., Zhu, L., Yang, K. and Lin, D. (2024) Pollution Characteristics and Source Apportionment of Heavy Metal(loid)s in Soil and Groundwater of a Retired

Industrial Park. *Journal of Environmental Sciences*, **143**, 23-34. https://doi.org/10.1016/j.jes.2023.07.015

[81] Lei, M., Wang, Y., Guo, G., Zhang, D. and Zhao, X. (2021) The Bio-Availability and Accumulation of the Trace Elements in Rock-Soil-Fruit System in Carbonatite Regions of Different Stratums: Critical Soil Factors and Transfer Models. *Science of the Total Environment*, **760**, Article ID: 143328. https://doi.org/10.1016/j.scitotenv.2020.143328

[82] Xue, J., Jiang, W., Gong, S., Fan, Y. and Li, X. (2013) An Evaluation of Heavy Metals Contamination in Soils from Ganzhou Navel Orange Orchards by Geoaccumulation Indexes and Statistical Analysis. *Chemistry and Ecology*, **29**, 586-594. https://doi.org/10.1080/02757540.2013.831078