INDONESIAN JOURNAL OF MULTIDISCIPLINARY SCIENCE

P-ISSN: 2808-5957
E-ISSN: 2808-6724

Comparative studies and risk analysis of heavy metal contaminants in *Solanum tuberosum* (Irish Potato) and *Daucus carota* (Carrot) in Bokkos LGA of Plateau State, Nigeria

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Keywords:

Bokkos

Daucus carota

heavy metal contaminants

risk analysis

Solanum tuberosum

ABSTRACT

The study aims to compare and analyze the levels of heavy metal contaminants in Solanum tuberosum (Irish Potato) and Daucus carota (Carrot) in Bokkos Local Government Area Plateau State, Nigeria, assessing potential health risks associated with consuming these crops. The research was focused to five heavy metals (Cd, Cr, Cu, Ni, and Pb) in Irish potato and carrot sample from five different farms. The concentrations of these metals were gotten in decreasing order as follows: (DIM) Irish potato (A) Cd > Pb > Cr > Ni; (EDI) Irish potatoes (C) Cu > P B > Cr B > Ni B > Cd; (DI) carrot (A), Cu > B > Cu B > P Ni; and (DIMA) carrot(A) Pb Cd Cu Pb. The health risk assessment indices for the populations through the consumption of contaminated fish were estimated based on the daily intake of metals relative to the reference oral dose (RfD) for each metal. The mean concentration of Pb, Cd, Ni and Cd in tubers was less than the recommended values of FAO/WHO. The risk analysis factors considered were transfer factor (TF), EDI, DIM, bioaccumulation factor (BF), target hazard quotient (THQ), and Health risk index (HRI) evaluated for this study showed moderate to less high risk levels with respect to human exposure through consumption of the vegetables and not the soil as may be indicate in transfer factor. It is therefore recommended to monitor periodically the agricultural farmlands using a different analysis techniques with a view for possible remediation.

INTRODUCTION

Consumption of tubers directly affects human health either positive or negative. Both old and young require tubers for proper and healthy living. The use of dumpsites as farm lands is a common practice in urban and sub-urban centers in Nigeria because of the fact that decayed and composted wastes enhance soil fertility. Generally, farmers are not bothered about the environmental effects or human hazards associated with irrigation of vegetables with waste water or cultivating around sewage dumpsite, rather they are primarily interested in the increase of yields and profits. Unfortunately, most of these tubers may be cultivated in soil rich in toxic elements, Microbial contamination, and anti-nutrients contaminated by sewage (Khalid et al., 2018; Shuaibu et al., 2013; Wilberforce & Nwabue, 2012). The Potentially toxic Element (PTEs) pollute the soil and mix with soil solution which enter into the plant body and hence can be accumulated at high levels in the edible parts of vegetables, even low levels in soil. Sewage consists of domestic effluent made up of black water (excreta, urine and associated sludge) and grey water (kitchen and bathroom wastewater) and also containing mineral and organic matter. Some potentially toxic elements (PTEs) are very useful if present in the soil at the right proportion. If these metals are however present at levels higher than the WHO standard, they become very toxic to man with very serious health implications (Shahid et al., 2018).

Waste water contains a lot of nutrients, which increase crop yields without use of fertilizer. However, it contains a variety of chemical substances from domestic and industrial sources. Wastewater contains potentially toxic elements (PTEs) such as zinc, chromium, copper, iron, cadmium, nickel, lead, mercury, microbial loads and parasitic worms, which can induce severe risks to the human health and the environment (Mark et al., 2019; Udofia et al., 2016). Soil in and around dumpsite is usually nutrient rich, which improve soil properties such as organic matter, and nutrients, which increases plant productivity, supply of macronutrients (N, P, and K) and can reduce the crop production cost (Okoro & Tarinabo, 2017). Thus despite their important and yield benefits, outbreaks of human infections and environmental hazard is associated with the consumption of vegetables grown on sewage dumpsite. In Nigeria, it is consumed as a leafy vegetable and constituent of sauces (or vegetable soups). Nutritionally, it is a good source of some minerals (e.g., calcium, magnesium, and potassium) and vitamins (e.g., ascorbic acid and pyridoxine). These nutrients help to repair worn out tissues, reduce cancer risks, lower cholesterol levels, normalize digestion time, improve vision, fight free radicals, and boost immune system activity. The vegetables also act as antioxidants that help to protect human body from oxidative stress, cardiovascular diseases and cancers (Santhakumar et al., 2018).

The term "Toxic element or heavy metals" has been defined as metals which have specific weights more than 5 g cm-3 (Hezbullah et al., 2016; Udofia et al., 2016). In vegetables, these heavy metals can accumulate in edible parts (leaves). Heavy metals are generally more mobile at pH less than 7 and les mobile at pH greater than 7 (Fonge et al., 2017). Heavy metals are ubiquitous in the environment, as a result of both natural and anthropogenic activities, and humans are exposed to them; therefore, they tend to bio-accumulate, thus causing an increase in their concentration in a biological system (Woldetsadik et al., 2017). Heavy metals contribute significantly to a reduction in environmental quality. Heavy metals can originate from both natural and anthropogenic sources (Nagajyoti et al., 2010). Due to their potential toxicity, persistent and irreversible characteristic heavy metals such as Cd, Cr, As, Hg, pb, cu, Zn, and Ni have been listed as a priority control pollutant (Chen et al., 2014; Udofia et al., 2016).

The bio-accumulation of heavy metals may interact directly with biomolecules, disrupting critical biological processes, which result in toxicity and the concomitant transfer of these metals through the food chain and ultimately pose risk to human life (Latif et al., 2018; Udofia et al., 2016). These toxic effects can manifest as oxidative stress, enzyme inhibition, and damage to cellular components such as membranes, proteins, and DNA. Prolonged exposure to heavy metals such as lead, mercury, cadmium, and arsenic has been linked to a variety of health conditions, including neurological disorders, cardiovascular diseases, kidney damage, and cancer. Moreover, their persistent nature in the environment ensures that even low-level exposure can accumulate over time, amplifying the health risks to humans and wildlife. As these metals cycle through ecosystems, they not only threaten individual organisms but also destabilize entire food webs, making remediation and prevention efforts critical for environmental and public health.

The research aims to compare and analyze the levels of heavy metal contaminants in *Solanum tuberosum* (Irish Potato) and *Daucus carota* (Carrot) in Bokkos LGA, Plateau State, Nigeria, assessing potential health risks associated with consuming these crops. By identifying and quantifying specific heavy metals such as lead, cadmium, and mercury, the study seeks to provide insights into food safety and the health implications for local consumers. This comparative analysis contributes to understanding the differential accumulation of metals between crops, offering valuable data for public health risk assessments, agricultural management, and food safety standards, with implications that can be applied to other regions facing similar contamination challenges.

METHOD

Sampling

Irish Potato

Irish potato sample was collected in a clean polythene bag from five different farmland where each soil sample was collected and has joined together to form one sample (A) and likewise in the same manner in farm B, C, D, and E.

Carrot

It was collected in a clean polythene bag from five different farm with it soil sample joined together to form sample (A) and likewise the same manner with B, C, D, and farm E.

Soil

Soil sample for each of carrot and Irish potato farm were collected in a clean polythene bag from different points at the surface and 15cm beneath the surface.

Sample Pretreatment

The collected Irish potato and carrot samples were brought to the laboratory and were thoroughly washed under a running tap water to remove dust, dirt and possible parasite or their eggs. Then 1% nitric acid solution was use to remove surface contaminants, and then rinsed with double distilled water. Each sample was chopped into small pieces using a clean stainless table knife and afterward dried to a constant mass in an oven at 80°C for 72 h. The dried sample of Irish potato and carrot were pulverized to fine powder using a porcelain mortar and pestle. Particle sizes of 0.05 to 0.2 mm were obtained using laboratory sieves (Sobukola et al., 2010). The powders were kept for digestion. Soil sample was brought in to the laboratory and air dried and afterward was pulverized to fine powder using pulverizing machine and was kept for digestion.

Sample Digestion

A 1 g sample of each carrot, Irish potato and the soil sample was weighed using a Metler analytical balance and transferred into a digestion tube. 10ml of HNO_3, 2ml of H_2SO_4 and 2ml of $HClO_4$ were added into the digestion tube and heated using water bath at a constant of 80^0 C with periodic swirl until the color was transparent. Each digested sample was then cool and filtered through a separate Whatman no.42 filter paper. The filtrate was made up to 50ml using a volumetric flask cylinder thereby transferred into clean sampling bottle. The filtrate obtained was analyzed for Pb, Cu, Ni, Cd and Cr using Atomic Absorption Spectrophotometer (AAS).

RESULTS AND DISCUSSION

Results

Levels of heavy metal in of Irish potato and carrot sample from five different farms in Bokkos Local Government Area Plateau state.

Table 1. Mean Concentration of Elements in Potato Samples

Sample Matrix	Sample Station	Concentration of Elements (mgL^{-1})				
		Cd	**Cr**	**Cu**	**Ni**	**Pb**
	C1	0.009±0.018	0.000±0.000	0.171±0.014	0.009±0.003	0.005±0.003
	C2	0.003±0.000	0.001±0.001	0.332±0.014	0.077±0.014	0.016±0.003
	C3	0.004±0.001	0.001±0.001	0.334±0.028	0.079±0.001	0.021±0.002
	C4	0.006±0.001	0.003±0.001	0.386±0.085	0.020±0.001	0.026±0.001
	C5	0.007±0.001	0.003±0.001	0.417±0.027	0.121±0.001	0.031±0.002
	Mean Average	**0.006±0.0042**	**0.0016±0.000**	**0.328±0.033**	**0.061±0.004**	**0.019±0.002**
Soil	**Mean**	**0.008±0.000**	**0.007±0.000**	**0.482±0.006**	**0.039±0.002**	**0.030±0.002**

Table 2. Mean Concentration of Elements in carrot Samples

Sample Matrix	Sample Station	Concentration of Elements (mgL^{-1})				
		Cd	**Cr**	**Cu**	**Ni**	**Pb**
	C1	0.006±0.000	0.004±0.001	0.665±0.089	0.032±0.001	0.030±0.002
	C2	0.009±0.000	0.004±0.001	0.544±0.010	0.048±0.001	0.042±0.001
	C3	0.004±0.001	0.001±0.001	0.757±0.174	0.069±0.001	0.044±0.002
	C4	0.010±0.001	0.006±0.001	0.573±0.048	0.069±0.001	0.047±0.000
	C5	0.006±0.001	0.001±0.001	0.243±0.050	0.069±0.001	0.002±0.002
	Mean Average	**0.007±0.000**	**0.003±0.001**	**0.557±0.074**	**0.057±0.001**	**0.033±0.0014**
Soil	**Mean**	**0.006±0.001**	**0.006±0.001**	**0.442±0.050**	**0.188±0.001**	**0.009±0.000**

The health risk factors were computed using the formulae below (Adamu et al., 2023; El-Zeiny & Abd El-Hamid, 2022; Haseeb et al., 2022; Hassaan et al., 2016; Huang et al., 2019; Kaba et al., 2023; Najy et al., 2023; Ntakirutimana et al., 2013):

$$\textbf{Transfer Factor (TF)} = \frac{Conc. of\ metal\ in\ edible\ portion\ (\frac{mg}{kg})}{Conc. of\ metal\ in\ sediment\ (\frac{mg}{kg})} \quad \ldots\ldots \quad (1)$$

$$\textbf{Hazard Quotient (HQ)} = \frac{Exposure\ Dose\ (\frac{mg}{kg}/day)}{Reference\ Dose\ (\frac{mg}{kg}/day)} \quad \ldots\ldots \quad (2)$$

$$\textbf{Target Hazard Quotient (THQ)} = \sum(\frac{Exposure\ Dose}{Reference\ Dose}) \quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

The daily intake of metals (DIM) was calculated to estimate the daily loading of metals into the body system (via the consumption of fish meal) of a specified body weight of a consumer. This would entail the relative bioavailability of the studied metals in this study. The daily intake of metals (DIM) was determined by the following

Health Risk Index (HRI)

The health risk index (HRI) for the populations through the consumption of contaminated fish was assessed based on the daily intake of metals (DIM) relative to the reference oral dose (RfD) for each metal. This is an index justifying an individual's risk of heavy metals. The HRI value of less than one implies safe tread and is considered acceptable; otherwise, the fish may pose heavy metals risk. The following formula was used for the calculation of HRI (Adamu et al., 2023; El-Zeiny & Abd El-Hamid, 2022; Haseeb et al., 2022; Hassaan et al., 2016; Huang et al., 2019; Kaba et al., 2023; Najy et al., 2023; Ntakirutimana et al., 2013):

$$HRI = DIM/R_fD \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \quad \textbf{(4)}$$

$$\textit{Estimated Daily Intake (EDI)} = \frac{E_F\ x\ E_D\ x\ F_{IR}\ x\ C_F\ x\ C_M}{W_{AB}\ x\ T_A}\ x\ 10^{-3} \quad \ldots\ldots.. \quad (5)$$

E_F = exposure frequency 365 days/year
E_D = Exposure Duration equivalent to verge lifetime (65 years for adults, and 12 years for children)
F_{IR} = Food ingestion rate (g/person/day)
C_F = Conversion Factor = 0.208
C_M = Metal concentration in food (mg/kg)
W_{AB} = Average body weight (taken as 65 kg for adults, and 15 kg for children)
T_A = Average Exposure over time for none Carcinogens (E_F x E_D)

$$\textit{Target Hazard Quotient (THQ)} = \frac{EDI}{RFD} \quad \ldots\ldots\ldots\ldots\ldots \quad (6)$$

R_FD = Reference dose (mg/kg/day)

Table 3. Risk Analyses Parameters of Heavy Metals

Risk Parameter	Sample Matrix	Elements				
		Cd	Cr	Cu	Ni	Pb
TF Potato	Irish Potato	0.625	0.142	0.680	1.564	0.633
TF Carrot	Carrot	1.166	0.500	1.260	0.303	3.666
EDI Potato						
Adult	Irish potato	8.40E-06	1.60E-06	5.50E-04	1.00E-04	3.10E-05
Children		1.40E-05	2.80E-06	9.10E-04	1.70E-04	5.30E-05
EDI Carrot	Carrot					
Adult		1.10E-05	5.00E-06	9.30E-04	9.50E-05	5.50E-05
Children		1.90E-05	8.40E-06	1.50E-03	1.50E-04	9.20E-05
BF						
Potato	Irish Potato	0.625	0.142	0.680	1.564	0.633
Carrot	Carrot	1.166	0.500	1.260	0.303	3.666
DIM Potato	Irish Potato					
Adult		1.20E-05	2.40E-06	7.90E-04	1.40E-04	4.60E-05

Children		1.30E-05	2.60E-06	8.60E-04	1.50E-04	4.90E-05
DIM Carrot	Carrot					
Adult		1.60E-05	7.20E-06	1.30E-03	1.30E-04	8.00E-05
Children		1.80E-05	7.80E-06	1.40E-03	1.40E-05	4.90E-05
THQ potato	Irish Potato					
Adult		0.012	1.60E-06	0.019	7.00E-03	0.328
Children		0.013	1.70E-06	0.021	7.50E-03	0.350
THQ Carrot	Carrot					
Adult		0.016	4.80E-06	0.032	6.50E-03	0.571
Children		0.018	5.20E-06	0.035	7.00E-03	0.614
HRI Potato	Irish potato					
Adult		0.012	0.000	0.000	0.007	0.011
Children		0.015	0.000	0.021	0.007	0.012
HRI carrot	Carrot					
Adult		0.016	0.000	0.032	0.006	0.02
Children		0.018	0.000	0.350	0.007	0.021

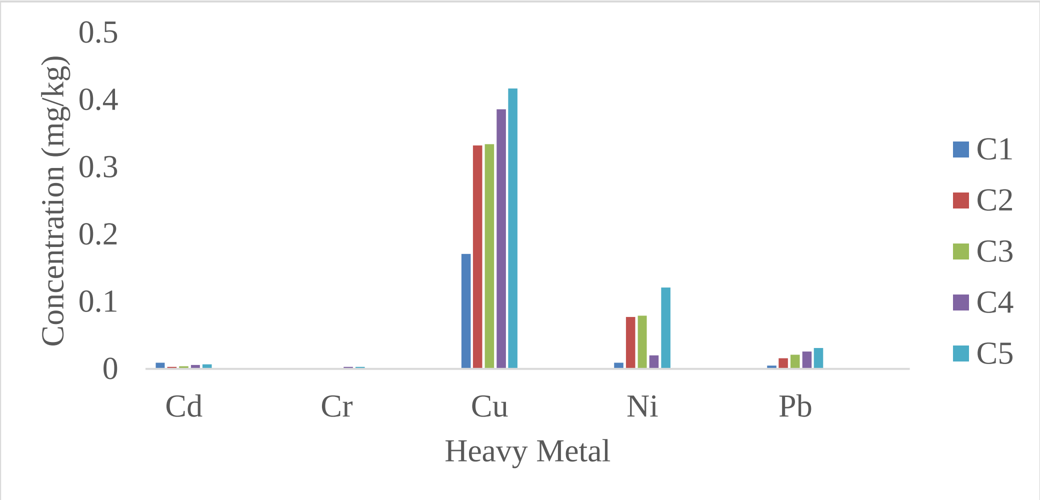

Figure 1. Bar Chart for Heavy Metals Mean Concentration in *Solanum tuberosum*

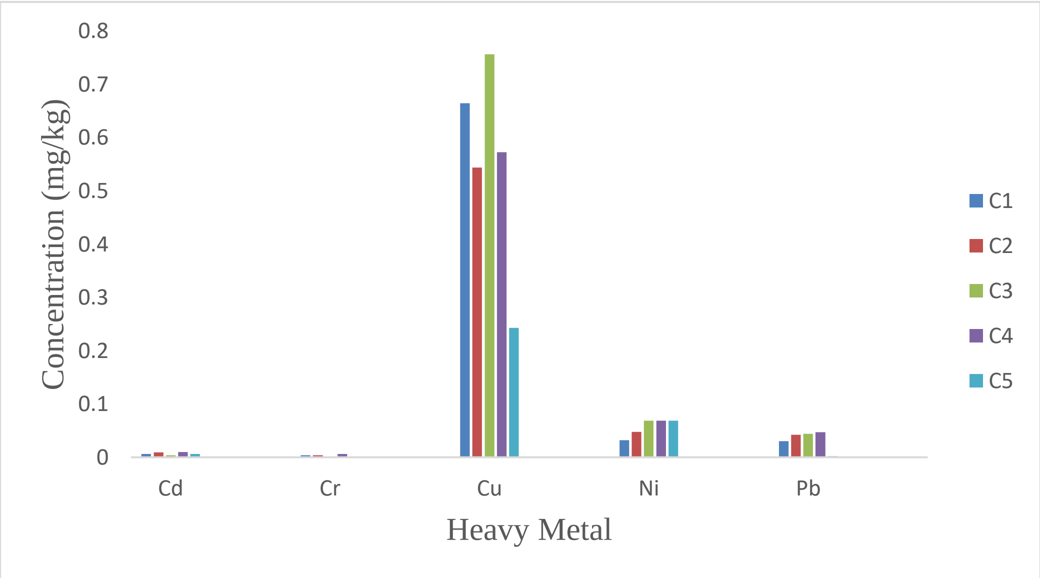

Figure 2. Bar Chart for Heavy Metals Mean Concentration in *Daucus carota*

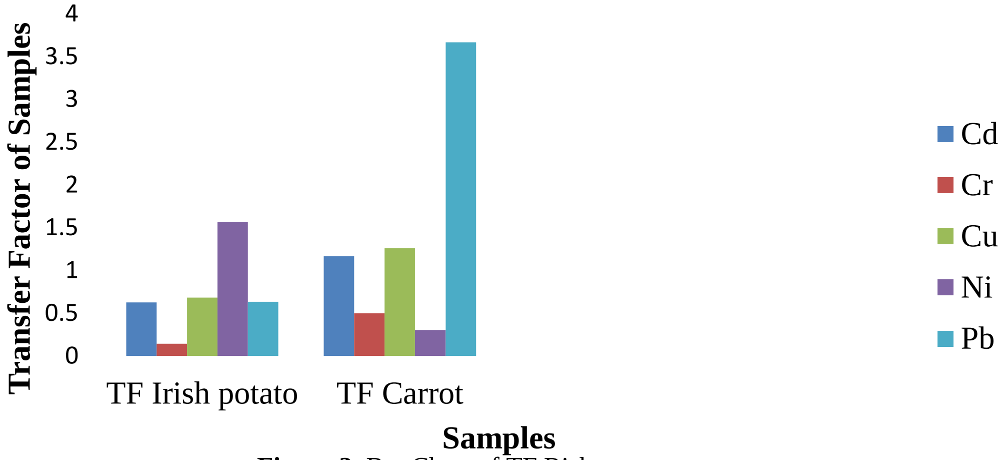

Figure 3. Bar Chart of TF Risk parameter

TF Irish potato: Transfer factor of Irish potato sample
TF Carrot: Transfer factor of carrot sample

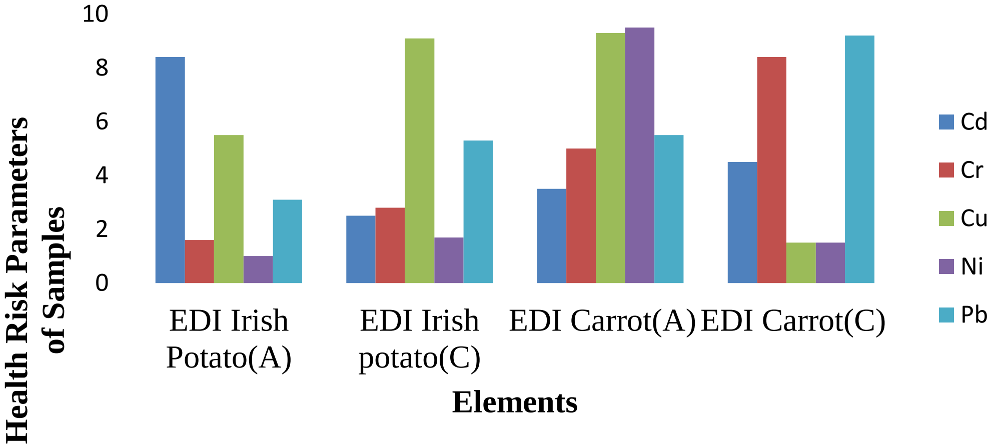

Figure 4. Bar Chart of EDI Risk parameters

EDI Irish potato (A): Estimated daily intake of heavy metal for adult in Irish potato sample
EDI Irish potato (C): Estimated daily intake of heavy metal for children in Irish potato sample
EDI carrot (A): Estimated daily intake of heavy metal for adult in carrot sample
EDI carrot (C): Estimated daily intake of heavy metal for children in carrot sample

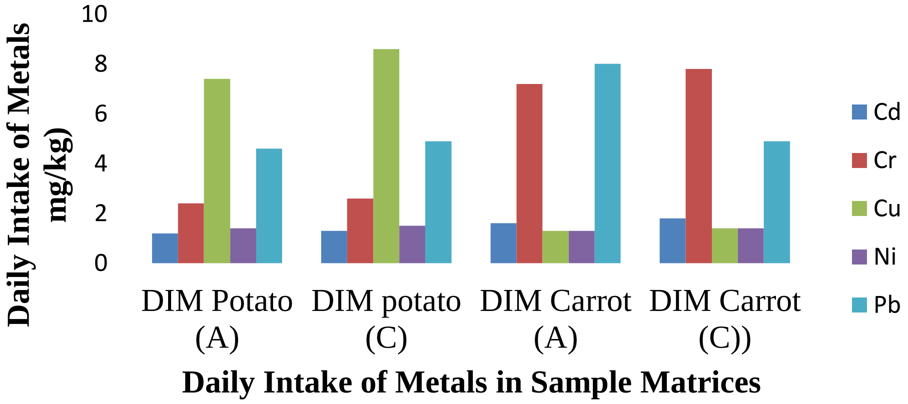

Figure 5. Bar Chart of DIM risk parameters

DIM Irish potato (A): Daily intake of metal for adult in Irish potato sample
DIM Irish potato (C): Daily intake of metal for children in Irish potato sample
DIM carrot (A): Daily intake of metal for adult in carrot sample
DIM carrot (C): Daily intake of metal for children in carrot sample

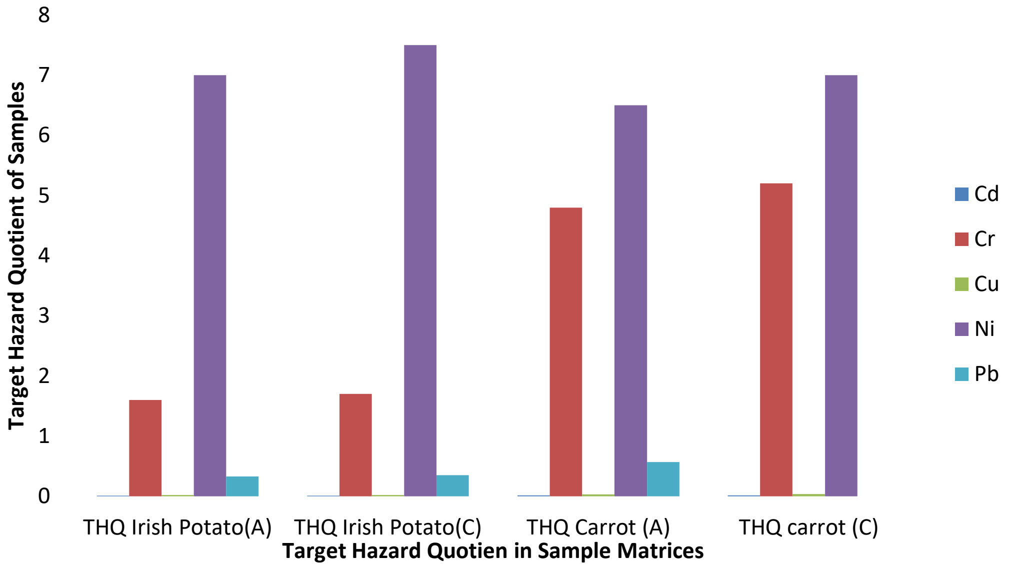

Figure 6. Bar Chart of THQ risk parameter

THQ Irish potato (A): Target hazard quotient for adult in Irish potato sample
THQ Irish potato (C): Target hazard quotient for children in Irish potato sample
THQ carrot (A): Target hazard quotient for adult in carrot sample
THQ carrot (C): Target hazard quotient for children in carrot sample

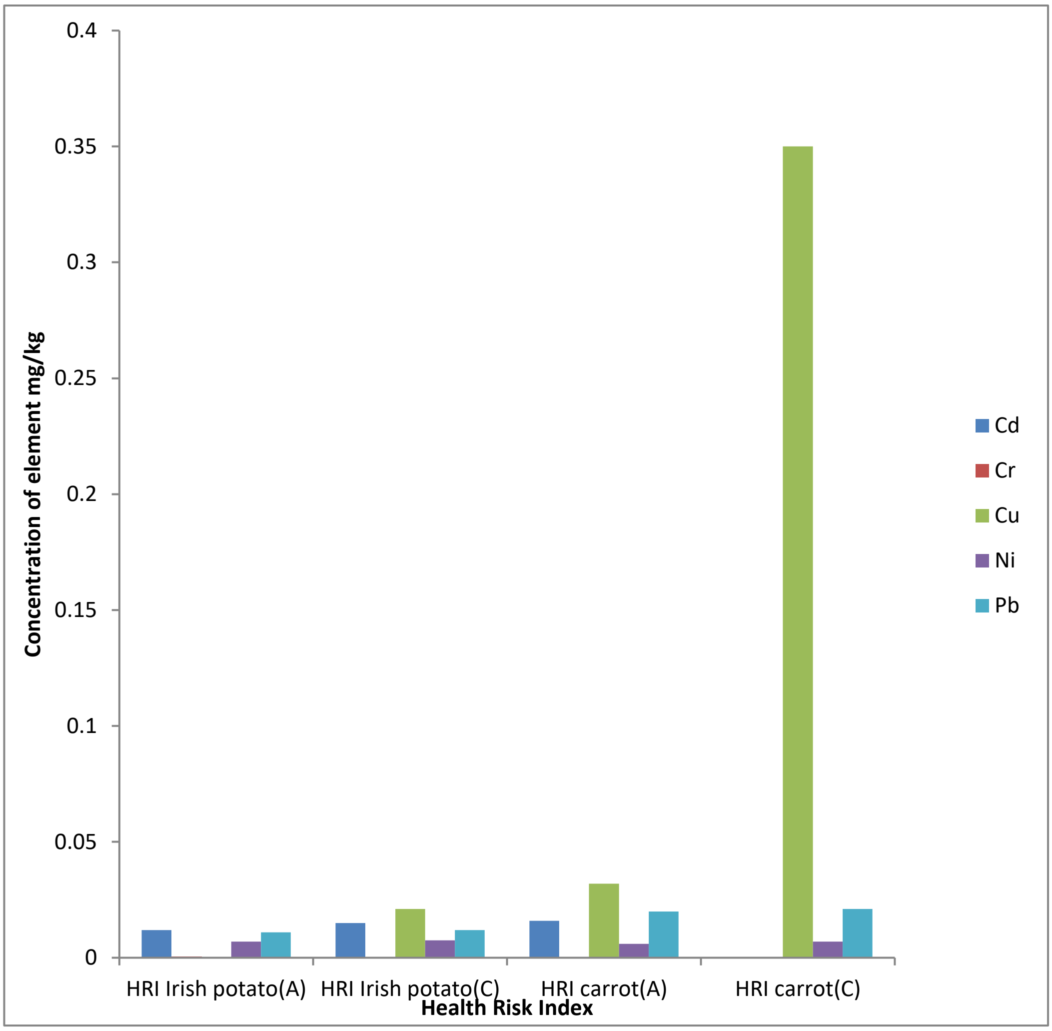

Figure 7. Bar Chart of HRI risk parameter

HRI Irish potato (A): Health risk index for adult in Irish potato sample
HRI Irish potato (C): Health risk index for children in Irish potato sample
HRI carrot (A): Health risk index for adult in carrot sample
HRI carrot (C): Health risk index for children in carrot sample

Discussion

The average concentrations of different heavy metals (Cr, Cd, Cu, Ni and Pb) in Irish potato and carrot cultivated around different locations of Kopmardarken, Feret, Murfet, Tangur and Matol have been represented in Table 1 and 2. The observed concentrations of metals were compared with the recommended limit as established by the joint WHO to assess the level of food contamination and the results are in line with the carried out by (Ladipo et al., 2011). Finding from the study reveal that the concentration of heavy most heavy metals were below the permissible limit.

Heavy Metal Bioaccumulation

1) Cr: The average concentration of chromium from the result in table 1 and table 2 were within the range of 0.00mg/L to 0.003 in Irish potato and 0.001 mg/L to 0.006mg/L in carrot. However the recommended maximum limit for chromium in vegetable by FAO/WHO (2011) is 2.3mg/kg. All samples were within the permissible limit.
2) Cu: The average concentration of copper from the result in table 1 and table 2 were within the range of 0.171mg/L to 0.417mg/L in Irish potato and 0.243mg/L to 0.757mg/L in carrot. However the recommended maximum limit for copper in tubers by FAO/WHO (2016) is 3.0mg/kg. All samples were within the permissible limit.
3) Cd: The average concentration of cadmium from the result in table 1 and table 2 were within the range of 0.003mg/L to 0.007mg/L in Irish potato and 0.004mg/L to 0.010mg/L in carrot. However

the recommended maximum limit for lead in tubers by FAO/WHO (2016) is 0.05mg/kg. All samples were within the permissible limit.

4) Ni: The average concentration of nickel from the result in table 1 and table 2 were within the range of 0.0201mg/L to 0.121mg/L in Irish potato and 0.032mg/L to 0.069mg/L in carrot. However the recommended maximum limit for nickel in vegetable by FAO/WHO 2016 is 1.63mg/kg. All samples were within the permissible limit and are safe for consumption.
5) Pb: The average concentration of lead from the result in table1 and table 2 were within the range of 0.005mg/L to 0.032mg/L in Irish potato and 0.002mg/L to 0.047mg/L in carrot. However the recommended maximum limit for lead in vegetable by FAO/WHO 2016 is 0.3mg/kg. All samples were within the permissible limit.

Risk Analysis

The risk analysis factors considered were transfer factor (TF), estimated daily intake (EDI), daily intake of metals (DIM), bioaccumulation factor (BF), target hazard quotient (THQ) and Health risk index (HRI) (Fonge et al., 2017; Khalid et al., 2018; Latif et al., 2018; Udofia et al., 2016; Woldetsadik et al., 2017)

Transfer Factor (TF)

Transfer factor refers to the ratio of the concentration of metals in plants to the total concentration in soil. However, the concentration value obtained in the present studies for TF potato in decreasing order; Ni > Cu > Pb > Cd > Cr showing nickel with the highest concentration value greater than one and TF carrot; Pb > Cu > Cd > Cr > Ni showing lead with the highest concentration value greater than one as both shown in table 3. When the transfer factor is less than one, it may also be a probability that soil is the main source of metals bioaccumulation in plants. However, it is more revealing that when the value is higher than one, plant is the main source of metals bioaccumulation (Adamu et al., 2023; Huang et al., 2019; Mwegoha & Kihampa, 2010). Therefore from the present studies of Irish potato Cd, Cr, Cu, and Pb are less than one and Ni greater than one. While for carrot sample, Cr and Ni are less than one and Cd, Cu and Pb are greater than one. This showed that Cd, Ni, Pb and Cu have higher ability of translocation to the vegetable sample species and that the source is as e result of anthropogenic pollution of the farmlands (Fonge et al., 2017; Khalid et al., 2018; Latif et al., 2018; Udofia et al., 2016; Wuana & Okieimen, 2011).

Estimated Daily Intake (EDI) of Metal

Estimated daily intake (EDI) were calculated for Irish potato and carrot for both adult and children and the concentration of heavy metals were gotten in decreasing order as follows: (EDI) Irish potato (A) Cd > Cu > Pb > Cr > Ni; (EDI) Irish potato (C) Cu > Cd > Cr > Pb > Ni; (EDI) carrot (A) Ni > Cu > Cd > Cr > Pb; (EDI) carrot(C) Pb > Cr > Cd > Cu ≥ Ni. Therefore Irish potato and carrot EDI concentration in adult and children show low metal intake in sample. Thus it is safe for consumption.

Daily Intake of Metal (DIM)

From the result in the present study, the concentrations of heavy metals were gotten in decreasing order as follows: (DIM) Irish potato (A) Cu > Pb > Cr > Ni > Cd; (DIM) Irish potato (C) Cu > Pb > Cr > Ni > Cd; (DIM) carrot (A) Pb > Cr > Cd > Cu ≥ Ni; (DIM) carrot (C) Cr > Pb > Cd > Cu ≥ Ni. This showed concordance with works of other researchers (Fonge et al., 2017; Latif et al., 2018; Liao et al., 2022; Udofia et al., 2016)

Comparing these result with the permissible limits of daily intake, all the investigated heavy metal concentration indicate low intake and thus the sample are safe for consumption. These shows some agreement with previous studies showing levels of heavy metals in edible part of food crops irrigated with wastewater (Fonge et al., 2017; Kaba et al., 2023; Liao et al., 2022; Udofia et al., 2016).

Target Hazard Quotient (THQ)

Target hazard quotient is the dimensionless index of risk associated with long term exposure to chemicals. From the result obtained in figure 6 and table 3, the concentrations of heavy metals were obtained for both children and adult as follows: (THQ) Irish potato (A) Ni > Cr > Pb > Cd ≥ Cu**;** (THQ) Irish potato (C) Ni > Cr > Pb > Cd ≥ Cu**;** (THQ) carrot (A) Ni > Cr > Pb > Cd ≥ Cu**;** (THQ) carrot (A) Ni > Cr > Cu ≥Pb > Cd, showing some level agreement the works of Latif et al. (2018), Udofia et al. (2016), and Adesuyi et al. (2015). However the concentration of Cu, Pb Ni, Cr and Cd in table 3 is less than one which is safe for consumption. These studies is related to Udofia et al. (2016), Adesuyi et al. (2015), Singh et al. (2010) which said that if the ratio is equal to or greater than one, an exposed population is a risk, but if the ratio is less than one, it is for consumption.

Health Risk Index (HRI)

From the result in table 3 and fig.7, the concentration of heavy metals in Irish potato and carrot for both adult and children are less than one indicating safe for consumers. It is given HRI (Liao et al., 2022; Mark et al., 2019). HRI greater than one for any metal in food crop means that the consumer population faces a health risk. For both sample matrices, the HRI is less than 1, indicating the safety of the vegetable upon consumption. This also indicated that the environmental pollution due to anthropogenic activities is minimal (Adesuyi et al., 2015; Kaba et al., 2023; Liao et al., 2022; Mark et al., 2019; Singh et al., 2010; Udofia et al., 2016)

CONCLUSION

The study found that root tubers from Feret, Mandarken, Tangur, Murfet, and Matol contain various concentrations of heavy metals, with Cu, Ni, Pb, Cd, and Cr being the most common. These metals are less than the recommended values of FAO/WHO. The health risk assessment indices showed moderate to less high risk levels due to human exposure through vegetable consumption. Regular monitoring of heavy metals in vegetables is recommended, and remediation strategies should be taken to reduce contamination sources. The research focused on five heavy metals in Irish potato and carrot samples. Farm sites with regular herbicide, fertilizer, and near-mining areas contribute to metal bioaccumulation. Farmers should use organometallic and organic fertilizers, while discouraged from using chemical fertilizers. Future research should explore a broader range of heavy metals, explore bioaccumulation pathways, assess remediation strategies, and track changes in contamination levels over time for deeper insights into long-term risks and mitigation strategies.

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