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The Carcinogenic and Non-Carcinogenic Health Risks of Metals Bioaccumulation in Different Vegetables Cultivated in District Shikarpur, Sindh, Pakistan

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Abstract

Contaminated irrigation water from untreated municipal effluents poses a significant threat to vegetable farming in Shikarpur, Sindh. The current investigation shows the accumulation of HMs for instance Fe, Zn, Mn, Cu, Sn, Co, Ni, Cd, Cr, Pb and as in 15 varieties of locally grown vegetables. ICP – OES analysis declared that Cd, As and Cr exceeded the WHO/FAO limit, while other elements remained below the permissible limit. Seven vegetable species were observed to contain higher Cd content, and four species possessed higher as guideline. Cr was found in higher level than allowable level only in two varieties. Health risk assessments showed that each vegetable variety possessed Health Index (HI) greater than 1.0, ranging from 3.993 – 7.302, suggesting noteworthy non – carcinogenic hazards. Moreover, the Total Carcinogenic Risk $(\sum_{i=1}^{n} CRi)$ for entire vegetable samples enhanced the allowable permissible limit of 1.0×10^{-4}, with Cr and Cd recognized as the main conductors of cancer risk. These findings declare a severe public health alarm and a dire need for soil treatment and water irrigation management in the study area.

Keyword: HMs, Accumulation, Shikarpur, Vegetable, Public Health, Hazard Index (HI), ICP-OES, Contaminated Irrigation Water.

Introduction

The farming of vegetables in the district Shikarpur, Sindh, Pakistan represents a key connection of public health safety and agricultural productivity. District Shikarpur, by tradition noted for its green plains and a variety of agricultural products is extremely dependent on irrigation systems that are increasingly under risk from human activity (Hussain, et al., 2025). By development of industrialization and urbanization in the region, untreated municipal wastewater as well as industrial effluents is more and more being released into local bodies of water (Nazir, et al., 2025; Tariq, and Mushtaq, 2023; Khanam, et al., 2022). When this contaminated water is used for irrigation, it introduces a combination of heavy metals into the soil, containing Pb, Cd, Cr and As (Xu, et al., 2024; Jagaba, et al., 2024). Contrasting organic pollutants, these metals are not biodegradable and persist in the ecosystem for long periods of time, ultimately being absorbed by the vegetable crops through complicated physiological processes (Rashid, et al., 2023; Zeb, et al., 2022). Bioaccumulation takes place when plants build up metals from soil and water at rapidity that surpasses their ability to be metabolized or expelled. Different species of vegetables have different metal buildup capacity; for instance, leafy vegetables such as spinach commonly have larger number of heavy metals as compared to fruiting plants like peppers or tomatoes (Nnaji, et al., 2023; Edo, et al., 2024; Manwani, et al., 2023; Kaur, et al., 2025). Since vegetables are an essential source of vitamins and minerals for the people of Shikarpur, this accumulation is particularly concerning. Nevertheless, these crops become a major vector for human health hazards when they serve as a conduit for hazardous materials (Angon, et al., 2024). The socioeconomic aspects of the area make the issue worse because localized farming usually evades strict quality control measures, exposing the final consumer to silent toxicity (Osei-et al., 2024). The health concerns connected with eating metal-laden vegetables are divided into two categories: non-carcinogenic and carcinogenic (Adesida, and Alimba, 2025). Non-carcinogenic dangers include a variety of systemic malfunctions, such as neurological diseases, renal damage, gastrointestinal discomfort, and immune system impairment. These effects are frequently assessed using the Hazard Quotient and Hazard Index, which calculate the ratio of exposure to reference dosage (Budi, et al., 2024). Even at low concentrations, prolonged exposure to metals such as cadmium can cause bone mineralization difficulties, and lead exposure has been related to cognitive developmental abnormalities in children and hypertension in adults (Ciosek, et al., 2023). Because many Shikarpur inhabitants rely on locally grown vegetables for their daily calorie intake, the cumulative daily consumption of heavy metals frequently surpasses the safety limits set by international organizations, for example the World Health Organization. Beyond systemic toxicity, the potential for cancer of some metals is still the most concerning part of bioaccumulation in the food chain. The International Agency for Research on Cancer classifies arsenic, hexavalent chromium, and cadmium as Group 1 carcinogens. Extended disclosure to these metals through contaminated vegetables may cause oxidative suffering, unrestrained cell propagation, and DNA damage, all of which may cause cancers of skin, bladder and lung (Chauhan, et al., 2025). In study area of Shikarpur, where healthcare skills are poor, and the durable trouble of cancer caused by food disclosure creates a serious risk to the health of community. Consequently, a thorough assessment of both carcinogenic and non-carcinogenic concerns is necessary to follow the scope of the hazard and found methods for soil remediation as well as safer farming practices.

Study Area

The district Shikarpur lies strategically in northern Sindh and provides as a fundamental geographical rlation between Sindh, Punjab and Balochistan. The district Shikarpur is divided into four administrative talukas: Garhi Yasin, Lakhi Ghulam Shah, Khanpur and Shikarpur and the district covers the area of around 2,512 km^2. Previously known as an important trading hub near the Bolan Pass, the study area is illustrated by fertile floodplains of the Indus River basin. The ecosystem is characterized by high drought, with scorching summer temperatures that frequently increase 45 ºC and less annual rainfall, forcing a main dependence on river irrigation systems fed by the Sukkur and the Guddu Barrages. Agriculture is the heart of local economy, with the bulk of the inhabitants laboring to produce rice, wheat and wide range of seasonal vegetables. Shikarpur is also recognized for its prehistoric cottage industries, particularly its famous pickle product. Although, the area has considerable current problems, while urban development and poor waste management systems have contaminated irrigation supplies. Unprocessed urban wastewater is normally mixed with agricultural waste sources, producing a high-risk circumstances for soil worsening. This junction of severe farming and environmental degradation provides a significant structure for studying heavy metal buildup in the local food chain as well as the health cost for the society (Figure:1) (Chauhan, et al., 2025).

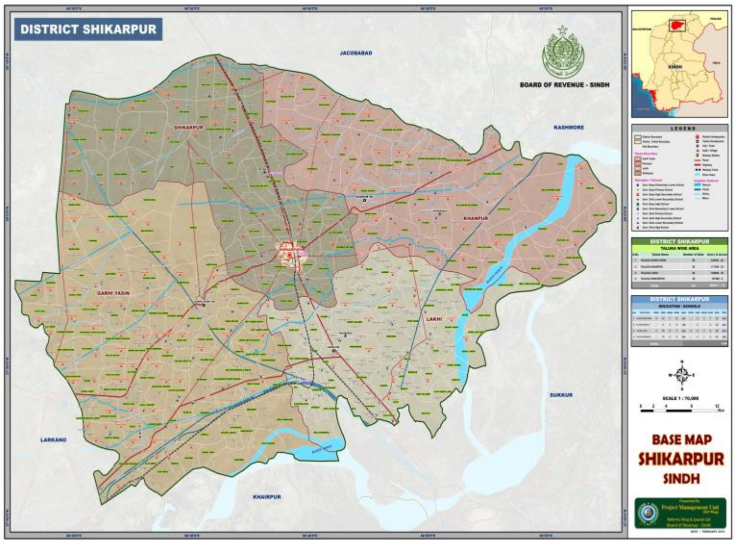

Figure: 1 Map of study area of vegetable collection (district Shikarpur)

Samples Collection and Preparation

The vegetable samples, that are, Peas, Capsicum, Spinach, Tomato, Sweet potato, Brinjal, Cauliflower, Lotus, Bitter Gourd, Mustard, G. Chilli, Fennel, Sunflower, Cluster Beans and Methi, were collected from five randomly chosen sub-sampling locations within the research area to accomplish a representative distribution. About 1.0 kg of each vegetable sample was collected and mixed to produce a composite sample for each variety, which was then sealed in pre-cleaned, sterilized polyethylene bags for quick shifting to the research laboratory, Institute of Chemistry Shah Abdul Latif University Khairpur Mir's, Sindh, Pakistan. As received, samples were subjected to a systematic clean-up method, starting with removal of any decaying pieces.

To eliminate surface contaminants, dirt as well as air particles, the vegetable samples were treated with a 0.01% HCl acid solution, then carefully rinsed with tap water and then with distilled water. To diminish metal cross – contamination, the uncontaminated edible pieces were cut into small bits with the help of a plastic knife before processing. These pieces were dried in an oven at 50 ºC – 60 ºC for 24 hours until they achieve a constant mass, representing that all moisture has been eliminated. The dehydrated vegetable samples were then crushed into a fine powder with a mortar and pestle and put through a 2 mm mesh filter to make sure regular particle size. These processed samples were finally stored in polyethylene bags and sustained within desiccators to avoid rehydration and maintain sample degradation until the digestion and ICP–OES analysis steps were commenced (Al-Juhaimi, et al., 2023).

Metals Quantification

Heavy metal determination using ICP-OES is an extremely sensitive analytical technique that uses the activation of atoms and ions within high temperature plasma to generate light at element specific wavelengths. A peristaltic pump draws the prepared vegetable sample solution into a nebulizer, where it is altered into a thin aerosol before being propelled into the center of the argon plasma. The plasma, which usually attains the temperature range of 6000 – 10,000 Kelvin, effectively dissolves, atomizes, and ionizes the sample constituents. Electromagnetic radiations are emitted from metals, as the electrons return from excited state to the ground state. Each metal in the prepared vegetable sample produces light at certain wavelengths, which are then divided by the instrument's optical system, which often uses grating or a prism. Beer – Lambert Law states that, the intensity of eliminated light at a certain wavelength is directly proportional to the concentration of metal present in the solution. To achieve accurate quantitative analysis, the instrument is calibrated using a series of multi – element standard solutions to construct a linear calibration graph. The program measures the quantity of metals in unknown vegetable samples by comparing their emission intensities to the predefined graph. Analytical strictness was retained by observing internal standards, for instance, Scandium which was introduced to each sample to report for physical interferences or fluctuations in plasma constancy. Moreover, the detection and quantification limits were strongly set so that the trace quantities of bio-accumulated metals in vegetable samples of district Shikarpur may be reported with high statistical accuracy and precision (Khan, et al., 2022).

Estimated Daily Intake (EDI)

The estimated Daily Intake (EDI) of HMs from different varieties of vegetable intake in study area is determined with the help of standardized mathematical models. Besides the metal concentration observed in vegetable samples, this approach regards as the physical characteristics as well as consumption patterns of the local people. The EDI provides an exact outline that can be weighed against international safety standards by regulating consumption based on body weight (Kumar, et al., 2023).

The formula for calculating the Estimated Daily Intake (EDI) is expressed as:

$$EDI = \frac{C \times IR \times EF \times ED}{BW \times AT} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(i)}$$

The variables within this equation are defined as follows:
C = Heavy metal concentration in vegetable samples measured in mg/kg
IR = Ingestion Rate of vegetables measured in kg/day
EF = Exposure Frequency measured as 365 days per year
ED = Exposure duration is often set at 70 Years in adults
BW = Average body weight of the consumer, measured in kilograms (kg).
AT = Average Time, which is the product of ED×365 days for non-carcinogenic risk assessment.

Non-Carcinogenic Risk

2.5.1 Target Hazard Quotient

The target hazard quotient (THQ) values were computed to assess non-carcinogenic human health hazards associated with the intake of heavy metal-contaminated leafy greens. It was calculated as the ratio of average daily metal ingestion to an oral reference dosage of each metal (Navaretnam, et al., 2023) and may be represented using the following equation:

$$THQ = \frac{EDI}{RfD} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(ii)}$$

Where EDI is the population's average daily metal consumption in mg/day/kg body weight, and RfD is the oral reference dosage (mg/kg/day) for each metal of concern. The RfD values for Cd, Pb, As Cr, Ni, Co, Fe, Zn, Mn, Cu, and Sn were 0.001, 0.004, 0.0003, 0.5, 0.11, 0.0003, 0.7, 0.3, 0.014, 0.04 and 0.6 mg/kg/day, respectively (Fekadu Demsie, et al., 2025). If the THQ < 1, it is normally believed to be secure for the danger of non-carcinogenic consequences; if the THQ > 1, the possibility of non-carcinogenic effects increases as the value rises.

Hazard Index

The metals overall human risk, the hazard index (HI) is calculated as the sum of all THQs estimated for specific heavy metals.

$$TCR = \sum_{n=1}^{i} HQi \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(iii)}$$

Where HI is the sum of various metal hazards, there is no apparent health impact if HI < 1. An HI > 1.0, on the other hand, indicates the possibility of an adverse health effect. HI > 10 has been linked to a severe chronic health impact

2.5.3 Carcinogenic Risk

The cancer risk (CR) presented to human health by individual potential carcinogenic metals was calculated. Then, the cumulative cancer risk (TCR), which may promote carcinogenic effects depending on exposure dose, was then calculated from ingestion of metals (Cr, Ni, As, Pb, and Cd).

$$CR = EDI \times CSF \text{ ……………………..(iv)}$$

$$TCR = \sum_{i=1}^{n} CRi \text{ …………………..…..(v)}$$

where CR cancer risk over a lifetime by individual heavy metal ingestion, EDI estimated daily metal intake of the population in mg/day/kg bodyweight, CSF oral cancer slope factor in (mg/kg/day), and n is the number of heavy metals considered for cancer risk calculation. The CSF values of Cr, Ni, As, Pb, and Cd were 0.5, 1.7, 1.5, 0.38, and 0.01 mg/kg/day, respectively [24]. For single carcinogenic metals and multi carcinogenic metals, the permissible limits are 10^{-6} and $< 10^{-4}$, respectively (Tepanosyan, et al., 2017).

Statistical Analysis

The effects of local farm location (15 sites), vegetable varieties, and their interactions on the metal concentrations were examined using the correlation coefficient indicated significant effects at the level of $p < 0.05$. The Pearson correlation coefficient among heavy metals determined from different varieties of vegetables was measured using SPSS software version 18 installed in laptop computer. The relationship of elemental concentrations in plant samples was investigated by the means of principal component analysis (PCA). All observation data were mean-centered and standardized prior to PCA, and only principal components with eigenvalues > 1were considered.

Table: 1: Mean concentration (mg/kg) of heavy metals in vegetables collected from Shikarpur, Sindh

Vegetables	Fe	Zn	Mn	Cu	Sn	Co	Ni	Cd	Cr	Pb	As
Peas	1.2	1.396	3.288	0.988	0.107	0.025	1.196	0.055	2.543	0.033	0.027
Capsicum	0.392	2.786	2.318	1.058	0.065	0.137	2.636	0.329	2.243	0.031	0.027
Spinach	0.982	2.346	2.218	0.295	0.033	0.024	2.316	0.063	0.983	0.034	0.081
Tomato	1.218	3.696	3.278	1.181	0.087	0.035	3.166	0.075	1.533	0.045	0.047
Sweet potato	0.188	1.406	4.958	1.301	0.033	0.047	1.406	0.089	1.213	0.047	0.034
Brinjal	1.259	5.776	7.108	1.018	0.028	0.022	4.706	0.092	1.513	0.042	0.014
Cauliflower	0.336	3.256	2.048	1.288	0.042	0.024	4.806	0.33	1.213	0.024	0.121
Lotus	0.95	5.166	3.278	1.113	0.033	0.024	3.266	0.051	1.043	0.025	0.132
Bitter Gard	0.899	6.166	9.368	2.08	0.121	0.031	4.366	0.046	1.633	0.044	0.053
Mustard	0.472	1.276	3.078	1.198	0.023	0.072	1.246	0.34	1.093	0.029	0.118
G. Chilli	0.998	3.286	1.258	1.091	0.023	0.023	3.256	0.302	0.963	0.033	0.108
Fennel	0.967	2.196	3.248	1.385	0.042	0.039	2.216	0.376	1.023	0.043	0.04
Sunflower	0.477	1.396	8.558	1.093	0.047	0.026	0.416	0.226	2.313	0.036	0.023
Cluster Beans	0.55	4.286	2.278	1.191	0.102	0.022	4.246	0.336	1.343	0.039	0.047
Methi	0.524	3.266	4.218	2.155	0.097	0.042	3.186	0.066	1.403	0.048	0.048

Results and Discussion

Metals Concentrations in the Vegetables

The provided results reveal the quantity of various HMs in selected vegetable samples, providing a thorough evaluation of their outline when compared to the WHO/FAO global guidelines. Entire investigated samples possessed the contents of Fe, Mn, and Cu that were considerably within the allowable limits of 425, 99.4, 500 and 73.3 mg/kg respectively. The contents of Pb, Ni, Co and Sn were also within permissible levels. The Pb contents did not exceed 0.048 mg/kg, which were much less than the 0.3 mg/kg level acceptable for safe intake, whereas Ni levels were found to contain below the permissible limit of 67 mg/kg. This shows that when consumed these vegetables, these individual metals do not cause a severe toxicity risk. Although, Cd contamination is the most common metal in this work to violate safety standards, the work elevates grave concerns. Out of 15 vegetable varieties analyzed, seven varieties capsicum, cauliflower, mustard, green chilli, fennel, sunflower, and cluster beans declared Cd level above WHO/FAO level of 0.2 mg/kg. Maximum level of 0.376 mg/kg of Fennel, approximately double the permissible limit. Cd is a very dangerous non-essential metal that can accumulate in the body over time and cause renal failure and bone demineralization. In addition to Cd, As and Cr present localized concerns in specific samples. Four vegetables—cauliflower, mustard, and green chilli—have levels of As above the 0.1 mg/kg limit, with lotus having the highest level at 0.132 mg/kg. At 2.543 mg/kg and 2.313 mg/kg, respectively, peas and sunflowers greatly exceed the standard safety limit of 2.3 mg/kg for Cr concentrations, which is normally below this limit. Although the majority of the vegetables in the study are safe in terms of a number of factors, the frequent exceeding of Cd and As limits in common dietary staples like mustard, cauliflower, and green chilli points to a possible long-term health risk for the population being consumed and the necessity of environmental monitoring of the soil and water sources used in cultivation (Table: 1, Figure: 2).

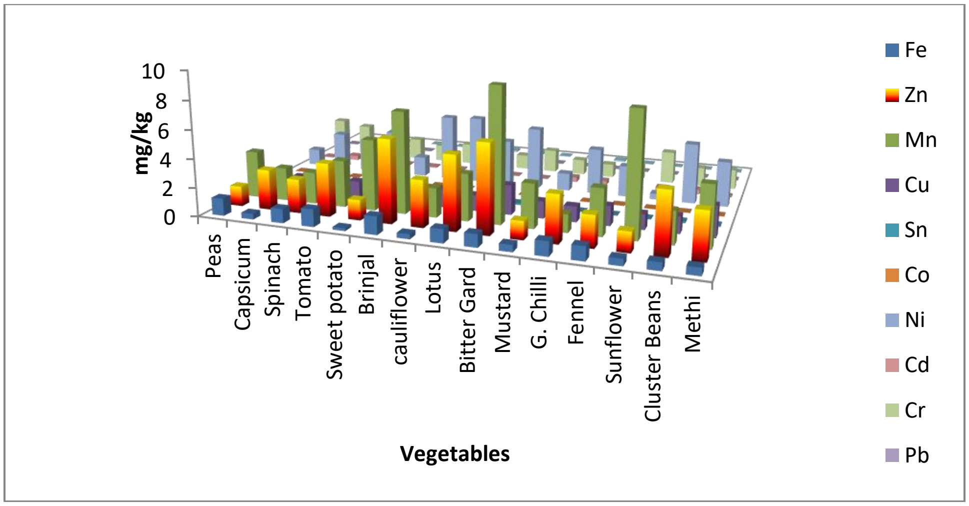

Figure: 2 Variation of different metals in varieties of vegetables collected from Shikarpur

Principal Components Analysis of Metals Concentrations in the Vegetables

The PCA biplot of contaminants in Shikarpur vegetables depicts the correlations between various metallic pollutants and their concentrations in different vegetable samples. The horizontal axis, Principal Component 1 (PC1), represents 29.54% of the overall variance, whereas the vertical axis, Principal Component 2 (PC2), describes 22.73%, for a total explained variance of 52.27%. Individual heavy metals are represented by the red vectors originating from the center, with the length of the vector indicating its effect on the main components and the angle between vectors indicating the degree of association. The positive PC1 quadrant shows an intense cluster of vectors that consist of Mn, Pb, and Sn. This recommends that these metals are notably positively related and almost certainly share geogenic or anthropogenic origins in the region. Blue dots show that the spatial display of vegetables, which exemplifies how distinct metal profiles distinguish various product species. Mustard for example, is observed in the positive PC2 and negative PC1 quadrants and is very much correlated with the Cd vector, recommending that Shikarpur Mustard samples are greatly correlated with higher Cd content. Correspondingly, vegetables such as, tomatoes and brinjal are more strongly correlated with Zn and Fe in the lower – right quadrant, whereas sunflower and peas are in the upper – right quadrant and possess strong correlation with Cr. An elevated attraction for As is specified by the content of cauliflower, green chili and lotus in the lower – left quadrant. This spatial grouping efficiently identified which crops may cause the maximum risk of contact to particular harmful metals by categorizing vegetables according to their exceptional metal buildup models (Figure: 3).

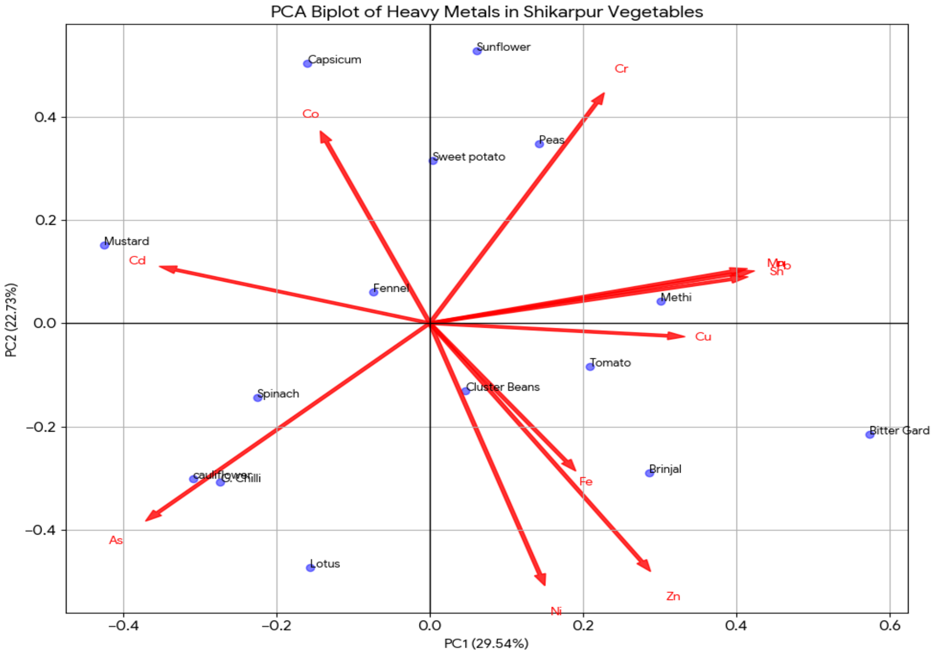

Figure: 3 Principal Component Analysis of Metals Concentrations in Vegetables of Shikarpur, Sindh

Estimated Daily Intake

Fifteen varieties of vegetables' Estimated Daily Intake (EDI) values expose a range of metal buildup and consumption risk patterns. While comparing to other essential metals Fe range from 9.30×10^{-4} to 6.21×10^{-3} in SP and Br respectively, showing modest consumption limits. With a peak in BG at 3.04 ×10-2 and Br at 2.85 ×10-2, zinc (Zn) consumption is noticeably higher across many samples, indicating that these vegetables are important sources of daily zinc intake. Manganese (Mn) has the greatest EDI values in BG (4.22×10^{-2}) and SF (4.22×10^{-2}), but lowest in GC (6.20×10^{-2}). Copper (Cu) intake is largely steady, with Mt consumption accounting for the maximum intake (1.06×10^{-2}). In comparison, the EDI for minor or hazardous metals is often substantially smaller. Tin (Sn) consumption is below 6.00×10^{-4} in all samples, with the greatest levels found in BG. Cobalt (Co) levels are low in the 10^{-4} range, with the highest identified in Cp at 6.70×10^{-4}. Nickel (Ni) intake is highly varied and substantial; with an upper limit of 2.37×10^{-2} in CF. Cadmium (Cd) consumption is maximum in Fl (1.85×10^{-3}), and lowest in BG (2.30×10^{-4}). Chromium (Cr) has higher EDI values than other hazardous metals, with a peak documented in Ps at 1.25×10^{-2}. Lead (Pb) and Arsenic (As) have the lowest daily intakes, peaking at 2.40×10^{-4} in Mt and 6.50×10^{-4} in Lt (Table: 2).

Table: 2 Estimated Intake (EDI) of heavy metals in vegetable varieties collected from Shikarpur

ID	**Fe**	**Zn**	**Mn**	**Cu**	**Sn**	**Co**	**Ni**	**Cd**	**Cr**	**Pb**	**As**
Ps	5.91×10^{-3}	6.88×10^{-3}	1.62×10^{-2}	4.87×10^{-3}	5.30×10^{-4}	1.20×10^{-4}	5.89×10^{-3}	2.70×10^{-4}	1.25×10^{-2}	1.60×10^{-4}	1.30×10^{-4}
Cp	1.93×10^{-3}	1.37×10^{-2}	1.14×10^{-2}	5.21×10^{-3}	3.20×10^{-4}	6.70×10^{-4}	1.30×10^{-2}	1.62×10^{-3}	1.11×10^{-2}	1.50×10^{-4}	1.30×10^{-4}
Sp	4.84×10^{-3}	1.16×10^{-2}	1.09×10^{-2}	1.45×10^{-3}	1.60×10^{-4}	1.20×10^{-4}	1.14×10^{-2}	3.10×10^{-4}	4.85×10^{-3}	1.70×10^{-4}	4.00×10^{-4}
Tm	6.00×10^{-3}	1.82×10^{-2}	1.62×10^{-2}	5.82×10^{-3}	4.30×10^{-4}	1.70×10^{-4}	1.56×10^{-2}	3.70×10^{-4}	7.56×10^{-3}	2.20×10^{-4}	2.30×10^{-4}
SP	9.30×10^{-4}	6.93×10^{-3}	2.44×10^{-2}	6.41×10^{-3}	1.60×10^{-4}	2.30×10^{-4}	6.93×10^{-3}	4.40×10^{-4}	5.98×10^{-3}	2.30×10^{-4}	1.70×10^{-4}
Br	6.21×10^{-3}	2.85×10^{-2}	3.50×10^{-2}	5.02×10^{-3}	1.40×10^{-4}	1.10×10^{-4}	2.32×10^{-2}	4.50×10^{-4}	7.46×10^{-3}	2.10×10^{-4}	7.00×10^{-5}
CF	1.66×10^{-3}	1.61×10^{-2}	1.01×10^{-2}	6.35×10^{-3}	2.10×10^{-4}	1.20×10^{-4}	2.37×10^{-2}	1.63×10^{-3}	5.98×10^{-3}	1.20×10^{-4}	6.00×10^{-4}
Lt	4.68×10^{-3}	2.55×10^{-2}	1.62×10^{-2}	5.49×10^{-3}	1.60×10^{-4}	1.20×10^{-4}	1.61×10^{-2}	2.50×10^{-4}	5.14×10^{-3}	1.20×10^{-4}	6.50×10^{-4}
BG	4.43×10^{-3}	3.04×10^{-2}	4.62×10^{-2}	1.03×10^{-2}	6.00×10^{-4}	1.50×10^{-4}	2.15×10^{-2}	2.30×10^{-4}	8.05×10^{-3}	2.20×10^{-4}	2.60×10^{-4}
Ms	2.33×10^{-3}	6.29×10^{-3}	1.52×10^{-2}	5.90×10^{-3}	1.10×10^{-4}	3.50×10^{-4}	6.14×10^{-3}	1.68×10^{-3}	5.39×10^{-3}	1.40×10^{-4}	5.80×10^{-4}
GC	4.92×10^{-3}	1.62×10^{-2}	6.20×10^{-3}	5.38×10^{-3}	1.10×10-4	1.10×10^{-4}	1.61×10^{-2}	1.49×10^{-3}	4.75×10^{-3}	1.60×10^{-4}	5.30×10^{-4}
Fl	4.77×10^{-3}	1.08×10^{-2}	1.60×10^{-2}	6.83×10^{-3}	2.10×10^{-4}	1.90×10^{-4}	1.09×10^{-2}	1.85×10^{-3}	5.04×10^{-3}	2.10×10^{-4}	2.00×10^{-4}
SF	2.35×10^{-3}	6.88×10^{-3}	4.22×10^{-2}	5.39×10^{-3}	2.30×10^{-4}	1.30×10^{-4}	2.05×10^{-3}	1.11×10^{-3}	1.14×10^{-2}	1.80×10^{-4}	1.10×10^{-4}
CB	2.71×10^{-3}	2.11×10^{-2}	1.12×10^{-2}	5.87×10^{-3}	5.00×10^{-4}	1.10×10^{-4}	2.09×10^{-2}	1.66×10^{-3}	6.62×10^{-3}	1.90×10^{-4}	2.30×10^{-4}
Mt	2.58×10^{-3}	1.61×10^{-2}	2.08×10^{-2}	1.06×10^{-2}	4.80×10^{-4}	2.10×10^{-4}	1.57×10^{-2}	3.30×10^{-4}	6.91×10^{-3}	2.40×10^{-4}	2.40×10^{-4}

Health Risk Assessment

Non-Carcinogenic Risk

Target Hazard Quotient

According to the Target Hazard Quotient (THQ) for specific metals, Chromium (Cr), Cadmium (Cd), and Arsenic (As) are the most significant contributions to non-carcinogenic health concerns in the examined vegetables. In practically all samples, chromium consistently has the highest THQ values, reaching a peak of 4.2 in peas (Ps) and 3.8 in sunflower (SF). The THQ of As was observed as 2.2 in Lotus and value of 1.9 and 1.7 for Cd in Fennel and Mustard was a major concern. The enormously low THQ values of other metals such as, Fe, Zn, Mn, and Sn, usually ranged from 10^{-2} to 10^{-4} suggested that these metals do not pose a personal health hazard to consumers (Table: 3).

Table: 3 THQ and HI of metals under study in various vegetable species collected from Shikarpur

ID	Fe	Zn	Mn	Cu	Sn	Co	Ni	Cd	Cr	Pb	As	(HI)
Ps	8.4×10^{-3}	2.3×10^{-2}	1.2×10^{-1}	1.2×10^{-1}	8.8×10^{-4}	6.0×10^{-3}	2.9×10^{-1}	2.7×10^{-1}	4.2	4.6×10^{-2}	4.3×10^{-1}	**5.910**
Cp	2.8×10^{-3}	4.6×10^{-2}	8.2×10^{-2}	1.3×10^{-1}	5.3×10^{-4}	3.4×10^{-2}	6.5×10^{-1}	1.6	3.7	4.3×10^{-2}	4.3×10^{-1}	**7.151**
Sp	6.9×10^{-3}	3.9×10^{-2}	7.8×10^{-2}	3.6×10^{-2}	2.7×10^{-4}	6.0×10^{-3}	5.7×10^{-1}	3.1×10^{-1}	1.6	4.9×10^{-2}	1.3	**4.136**
Tm	8.6×10^{-3}	6.1×10^{-2}	1.2×10^{-1}	1.5×10^{-1}	7.2×10^{-4}	8.5×10^{-3}	7.8×10^{-1}	3.7×10^{-1}	2.5	6.3×10^{-2}	7.7×10^{-1}	**5.080**
SP	1.3×10^{-3}	2.3×10^{-2}	1.7×10^{-1}	1.6×10^{-1}	2.7×10^{-4}	1.2×10^{-2}	3.5×10^{-1}	4.4×10^{-1}	2.0	6.6×10^{-2}	5.7×10^{-1}	**3.993**
Br	8.9×10^{-3}	9.5×10^{-2}	2.5×10^{-1}	1.3×10^{-1}	2.3×10^{-4}	5.5×10^{-3}	1.2	4.5×10^{-1}	2.5	6.0×10^{-2}	2.3×10^{-1}	**5.011**
CF	2.4×10^{-3}	5.4×10^{-2}	7.2×10^{-2}	1.6×10^{-1}	3.5×10^{-4}	6.0×10^{-3}	1.2	1.6	2.0	3.4×10^{-2}	2.0	**7.302**
Lt	6.7×10^{-3}	8.5×10^{-2}	1.2×10^{-1}	1.4×10^{-1}	2.7×10^{-4}	6.0×10^{-3}	8.1×10^{-1}	2.5×10^{-1}	1.7	3.4×10^{-2}	2.2	**5.414**
BG	6.3×10^{-3}	1.0×10^{-1}	3.3×10^{-1}	2.6×10^{-1}	1.0×10^{-3}	7.5×10^{-3}	1.1	2.3×10^{-1}	2.7	6.3×10^{-2}	8.7×10^{-1}	**5.808**
Ms	3.3×10^{-3}	2.1×10^{-2}	1.1×10^{-1}	1.5×10^{-1}	1.8×10^{-4}	1.8×10^{-2}	3.1×10^{-1}	1.7	1.8	4.0×10^{-2}	1.9	**6.152**
GC	7.0×10^{-3}	5.4×10^{-2}	4.4×10^{-2}	1.3×10^{-1}	1.8×10^{-4}	5.5×10^{-3}	8.0×10^{-1}	1.5	1.6	4.6×10^{-2}	1.8	**5.986**
Fl	6.8×10^{-3}	3.6×10^{-2}	1.1×10^{-1}	1.7×10^{-1}	3.5×10^{-4}	9.5×10^{-3}	5.5×10^{-1}	1.9	1.7	6.0×10^{-2}	6.7×10^{-1}	**5.253**
SF	3.4×10^{-3}	2.3×10^{-2}	3.0×10^{-1}	1.3×10^{-1}	4.0×10^{-4}	6.5×10^{-3}	1.0×10^{-1}	1.1	3.8	5.1×10^{-2}	3.7×10^{-1}	**6.034**
CB	3.9×10^{-3}	7.0×10^{-2}	8.0×10^{-2}	1.5×10^{-1}	8.3×10^{-4}	5.5×10^{-3}	1.0	1.7	2.2	5.4×10^{-2}	7.7×10^{-1}	**6.084**
Mt	3.7×10^{-3}	5.4×10^{-2}	1.5×10^{-1}	2.7×10^{-1}	8.1×10^{-4}	1.1×10^{-2}	7.9×10^{-1}	3.3×10^{-4}	2.3	6.9×10^{-2}	8.0×10^{-1}	**4.618**

Hazard Index

In every vegetable sample examined, the Hazard Index (HI), which measures the overall non-carcinogenic exposure from all combined metals, is higher than the suitable cutoff of 1.0. Cauliflower (CF) has the highest value at 7.302, while sweet potatoes (SP) have the lowest at 3.993. Cluster beans (CB) at 6.084, mustard (Ms) at 6.152, and capsicum (Cp) at 7.151 are other vegetables with high contamination levels. Our results suggest that long-term consumption of these Shikarpur region vegetables may pose a serious collective health risk to the local population, as an HI greater than 1.0 suggests the potential for adverse health effects (Table: 3).

Carcinogenic Risk

The levels of chromium and cadmium are the main causes of the significant potential health problems revealed by the carcinogenic risk analysis for the tested vegetable samples. From 2.38×10^{-3} in GC to 6.25×10^{-3} in Ps, the data indicates that individual risk levels for chromium (Cr) are consistently high. While arsenic (As) risk levels are lower but still significant, ranging from 1.05×10^{-4} to 9.75×10^{-4}, cadmium (Cd) has a higher risk profile in some samples, with values as high as 1.13×10^{-2} in Fl and 1.02×10^{-2} in Ms. With risk levels usually in the $\times10^{-6}$ range, lead (Pb) has the least carcinogenic profile and is considered tolerable or negligible. A substantial lifetime risk of cancer is indicated by the total carcinogenic risk (sum CR) for all vegetable samples exceeding the safety threshold of 1.0×10^{-4}. At 1.56×10^{-2}, capsicum (Cp) poses the highest overall risk, followed by cluster beans (CB) at 1.38×10-2, cauliflower (CF), mustard (Ms), and fennel (Fl) at 1.41×10^{-2}. Yet vegetable samples with less cumulative risk such as, Lotus (5.07×10^{-3}) and Spinach (4.92×10^{-3}) exceeded the threshold limit. Major content of Cr and Cd are mainly accountable for these high levels, recommending that these two metals are the foremost providers to the carcinogenic hazard in local vegetables (Table: 4).

Table: 4 Carcinogenic risk and Total Carcinogenic risk (∑CR) of Cr, Cd, Pb and As in vegetable varieties collected from district Shikarpur

ID	Cr Risk (CSF=0.5)	Cd Risk (CSF=6.1)	Pb Risk (CSF=0.0085)	As Risk (CSF=1.5)	**Total Risk (∑CR)**
Ps	6.25×10^{-3}	1.65×10^{-3}	1.36×10^{-6}	1.95×10^{-4}	**8.09×10^{-3}**
Cp	5.55×10^{-3}	9.88×10^{-3}	1.28×10^{-6}	1.95×10^{-4}	**1.56×10^{-2}**
Sp	2.43×10^{-3}	1.89×10^{-3}	1.45×10^{-6}	6.00×10^{-4}	**4.92×10^{-3}**
Tm	3.78×10^{-3}	2.26×10^{-3}	1.87×10^{-6}	3.45×10^{-4}	**6.38×10^{-3}**
SP	2.99×10^{-3}	2.68×10^{-3}	1.96×10^{-6}	2.55×10^{-4}	**5.93×10^{-3}**
Br	3.73×10^{-3}	2.75×10^{-3}	1.79×10^{-6}	1.05×10^{-4}	**6.58×10^{-3}**
CF	2.99×10^{-3}	9.94×10^{-3}	1.02×10^{-6}	9.00×10^{-4}	**1.38×10^{-2}**
Lt	2.57×10^{-3}	1.53×10^{-3}	1.02×10^{-6}	9.75×10^{-4}	**5.07×10^{-3}**
BG	4.03×10^{-3}	1.40×10^{-3}	1.87×10^{-6}	3.90×10^{-4}	**5.82×10^{-3}**
Ms	2.70×10^{-3}	1.02×10^{-2}	1.19×10^{-6}	8.70×10^{-4}	**1.38×10^{-2}**
GC	2.38×10^{-3}	9.09×10^{-3}	1.36×10^{-6}	7.95×10^{-4}	**1.23×10^{-2}**
Fl	2.52×10^{-3}	1.13×10^{-2}	1.79×10^{-6}	3.00×10^{-4}	**1.41×10^{-2}**
SF	5.70×10^{-3}	6.77×10^{-3}	1.53×10^{-6}	1.65×10^{-4}	**1.26×10^{-2}**
CB	3.31×10^{-3}	1.01×10^{-2}	1.62×10^{-6}	3.45×10^{-4}	**1.38×10^{-2}**
Mt	3.46×10^{-3}	2.01×10^{-3}	2.04×10^{-6}	3.60×10^{-4}	**5.83×10^{-3}**

Statistical Analysis

According to the Pearson correlation matrix, there are so many remarkable correlations between metals observed in vegetable species. The strong positive correlation of 0.853 between Zn and Ni was found at the significant level of 0.01. This recommends that these two metals may be contaminated by same sources or show similar plant absorption patterns. Whereas negative correlation of -0.675 was observed between Fe and Cd since, Cr and as displayed negative correlation of -0.663 which were significant at 0.05 level. The negative correlations entail an inverse relation which shows that if concentration of one metal increases, then the other decreases (Table: 5).

Table: 5 Correlation Coefficient among heavy metals observed in different varieties of vegetables collected from district Shikarpur

Metals	**Fe**	**Zn**	**Mn**	**Cu**	**Sn**	**Co**	**Ni**	**Cd**	**Cr**	**Pb**	**As**
Fe	1	0.411	0.133	-0.096	0.331	-0.537	0.199	-.675*	0.419	0.288	-0.56
Zn		1	0.433	0.156	-0.084	-0.196	.853**	-0.219	-0.181	0.015	0.152
Mn			1	0.381	0.363	-0.255	0.279	-0.511	0.259	0.572	-0.42
Cu				1	0.418	0.088	0.11	-0.045	-0.135	0.539	-0.176
Sn					1	-0.104	-0.144	-0.268	0.496	0.246	-0.132
Co						1	0.003	0.295	-0.099	-0.018	-0.1
Ni							1	-0.024	-0.329	0.028	0.337
Cd								1	-0.309	-0.013	0.286
Cr									1	0.245	-.663*
Pb										1	-0.112
As											1

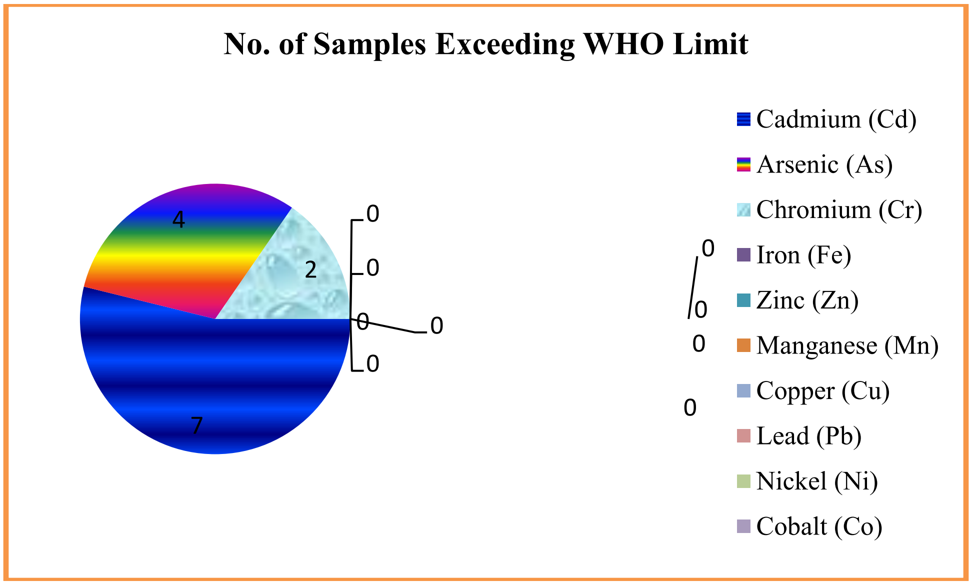

Figure: 4 Number of Vegetable Samples collected from District Shikarpur Exceeding the WHO/FAO recommended level

Conclusion

The detailed examination of heavy metal bioaccumulation in Shikarpur vegetables reveals that the local population's everyday diet poses serious health hazards. While necessary mineral concentrations are now below acceptable ranges, the frequent breach of international safety standards for deadly non-essential metals such as cadmium and arsenic is concerning. The overall non-carcinogenic Hazard Index and total carcinogenic risk values for each vegetable analyzed are both significantly higher than acceptable levels, indicating a substantial risk of ill health consequences and cancer after a lifetime of use. Statistical research using PCA and Pearson correlation indicates that many of these pollutants have similar anthropogenic origins, which are most likely related to the release of unprocessed waste into agricultural water resources. To protect community health, strict environmental monitoring must be implemented, as well as sustainable agriculture techniques that prevent harmful metals from entering the food chain.

Author Contributions

Tahmina Fakhr-u-Nisa Abbasi and Abdul Raheem Shar conceptualized, collected samples, designed experiments, Rabia Parveen Memon collected data and prepared the draft of the article Seema Sarwar Ghumro and Ammat-ur-Rehman Soomro interpreted the data Farzana Mangrio and Sahib Ghanghro, performed water analysis, Prof. Dr. Ghulam Qadir Shar Supervised the whole work. All authors read, revised, and approved the final version of the manuscript.

Conflict of Interest

The authors declare no conflict of interest

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