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ASSESSMENT OF HEAVY METAL CONTAMINATION AND ASSOCIATED HUMAN HEALTH RISKS VIA VEGETABLE CONSUMPTION IN JACOBABAD, SINDH, PAKISTAN

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Article Info

Abstract

This study addresses the significant global concern regarding health risks from consuming heavy metal-contaminated vegetables. We utilized ICP-OES to quantify the concentrations of Fe, Zn, Mn, Cu, Sn, Co, Ni, Cd, Cr, Pb, and As in frequently consumed vegetables from District Jacobabad and subsequently estimated the associated human health risks. The maximum permissible limits (MPL) established by the FAO/WHO for these metals in vegetables were utilized for comparison. Fe, Zn and Cu were found below MPL in all vegetable samples, whereas no limit was suggested for Mn, Sn and Co. the level of Cd was exceeded in Capsicum (0.19 mg/kg), Tomato (0.09 mg/kg), Brinjal (0.09 mg/kg), Cauliflower (0.15 mg/kg), Green Chilli (0.19 mg/kg), Fennel (0.21 mg/kg) and Cluster Beans (0.12 mg/kg). Samples in which Cr was higher than MPL were Bitter Gourd and Methi with concentration of 2.57 mg/kg and 2.42 mg/kg respectively. Spinach, Lotus, Mustard and Green Chilli showed higher concentration of 0.16 mg/kg, 0.139 mg/kg, 0.133mg/kg and 0.122 mg/kg respectively. The Estimated Daily Intake (EDI) was calculated for all metals in each vegetable. Non-carcinogenic risk was evaluated using the Target Hazard Quotient (THQ), with results aggregated into the Hazard Index (HI). The values for most samples were greater than 1, with the highest value of 5.6 observed in the Tomato sample (Tm). The carcinogenic risk was quantified through the Incremental Lifetime Cancer Risk (ILCR), specifically for As, Cd, Cr, Ni, and Pb. The range total cancer risk (ΣILCR) was found as 1.036×10^{-3} to 1.157×10^{-2} which surpassed the acceptable limit of 1×10^{-4}, showing significant health risk to inhabitants of the area. Therefore, it is strongly recommended that strict regulatory control may be implemented over the safety of vegetables grown in the study area.

Keywords:

health risks, maximum permissible limits (MPL), Target Hazard Quotient (THQ)

INTRODUCTION

Ecological contamination due to heavy metals and consequential food safety concerns symbolize a considerable problem all over the world (Sarker, et al., 2022). When these metals accumulated in the body at higher levels than required may pose a severe health hazard to entire living organisms, especially humans (Munir, et al., 2021). It is well – established that consumption and demand of vegetables are sharply increasing all over the world, because of they are vital component of human diet and nutrition (de Steenhuijsen Piters, et al., 2021; Fanzo, and Davis, 2021). Literature reveals that residential and commercial growth of vegetables take place normally in urban settings, where they are exposed to anthropogenic pollution from different sources (Engel-Di Mauro, 2021). Such sources consist of urban and industrial waste, as well as metallurgical, smelting and mining operations. Therefore, food protection troubles and health hazards have become a noteworthy public matter across the world, establishing it as one of the most serious ecological concerns (Boahen, 2024; Munshed, 2025).

HMs are just one of the numerous important groups of pollutants that can be determined both on the surface and within the tissues of fresh vegetables (Munir, et al., 2021). Moreover, it has been recognized that the rate of urbanization and industrialization in developing countries has contributed to the enhanced level of HMs in the urban ecosystem (Li, et al., 2022). Soil contamination with HMs is an extensive problem; this soil may provide a major basis of metals for crops, potentially becoming the main corridor for human experience to these lethal metals (Islam, et al., 2024). Many scientific publications have constantly acknowledged HMs as foremost contaminants in vegetables cultivated in and around urban centers worldwide (Angon, et al., 2024; Adewumi, and Ogundele, 2024; Joshi, and Gururani, 2024). HM pollution in the ecosystem corresponds to a momentous and rising worry for universal food protection and public health. The introduction of these continual and potentially fatal elements into agricultural systems mainly takes place through anthropogenic behavior, for instance industrial discharge, the use of pesticides and fertilizers, inappropriate discarding of electronic and municipal waste, and irrigation with polluted wastewater (Mititelu, et al., 2025; Munir, et al., 2021). Vegetables, being a basic constituent of the human diet, are mainly susceptible to the uptake and buildup of HMs from polluted water and soil. Contrasting organic contaminants, HMs are non-biodegradable and may continue in the ecosystem for extensive periods, leading to their ongoing climax in the food chain (Ali, et al., 2021).

The growth of vegetables in such compromised ecosystems causes a direct hazard to human health, as continuing dietary intake of HMs such as Pb, Cd, As, and Hg has been connected to a spectrum of poor health impacts (Rilwanu, 2021). These consist of increased risks of various cancers, heart diseases, renal dysfunction and neurotoxicological disorders. As a result, the observing of HMs in frequently used vegetables has become a dangerous feature of food quality control and ecological observation (Sharma, and Kumar, 2025).

Though, only measuring the total content of HMs in a vegetable sample is inadequate for a wide-ranging health risk evaluation. Consequently, an organized risk assessment is very important to determine the potential hazards caused to consumers (Sadee, and Ali, 2023). This assessment generally consists of calculating specific indices, like Estimated Daily Intake (EDI), which contrasts the content of exposure to establish safe reference values (Demir, and Ağaoğlu, 2023). Moreover, targeted hazard quotient (THQ) is used to assess the non-cancer risks related with individual metals, whereas hazard index (HI) evaluates the cumulative non-cancer risk from disclosure to a combination of metals (Ain, et al., 2023). For identified carcinogens such as As and Pb, the ILCR presents an estimate of the chance of an individual developing cancer over a lifetime of exposure (Samaila, et al., 2021; Shi, et al., 2025). This integrated advance of pollution analysis and thorough risk assessment presents a technical base for regulatory bodies to establish safety standards, implement remediation strategies, and finally protect consumer health from the risk of heavy metal pollution in the food supply (Fayshal, et al., 2023).

The main objective of the present work was to measure the level of HMs (Fe, Zn, Mn, Cu, Sn, Co, Ni, Cd, Cr, Pb & As) in different vegetable samples grown in the study area. The core objective was to establish a logical basis for public health concern by measuring the ΣILCR values and compare them with WHO/EPA limit and HI values in samples compared to the safety threshold of 1, thus highlighting the requisite for the urgent involvement and mitigation approach.

Materials and Methods

Study Area

District Larkana belongs to Sindh province has a hot desert climate with extreme temperatures and minimal rainfall. Summer remains from April to September, with temperatures commonly exceeding from 45 ºC and sometime reaching 50 ºC. It is considered as hottest areas of South Asia causing high rates of water evaporation. Winters are mild and short running from November – February, with cold nights but rare frost. Area receives little rain yearly, with most happening randomly during the weak monsoon season from July – September. This inadequate rainfall makes agriculture completely reliant on irrigation from Indus River. The climate of study area is also illustrated by hot, dry summer winds that enhance temperature strain. In real meaning the severe heat infertility and dependence on managed irrigation are the defining features that shape Larkana’s agriculture and ecosystem (Khoso, et al., 2025).

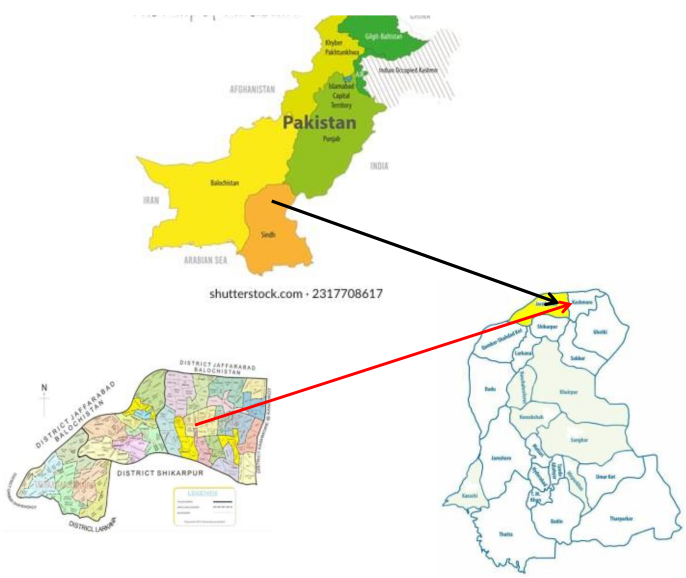

Figure: Map of Study Area of District Larkana, Sindh

Samples Collection and Preparation

For collection of vegetable samples, their edible portions were besieged. Five random sub-sampling sites were selected to collect vegetable samples. One kg of each sample was collected and mixed into separate, pre-cleaned and sterilized polyethylene bags to make composite sample. Any rotten material was removed from the samples, then immediately transported to the laboratory for further processing. In the laboratory, samples were initially treated with 0.01% HCl and then washed thoroughly with tap water and double-distilled water. Vegetable samples were dried, cleaned and chopped into small pieces using a knife. Subsequently, samples were air dried in a hot air oven at 50 – 60 ºC for 24 hours until constant mass. Finally, dried samples were ground into a fine powder with mortar and pestle, passed through 2 mm sieve and stored the resulting powder in polyethylene bags within desiccators until digestion and analysis (El Hosry, et al., 2023).

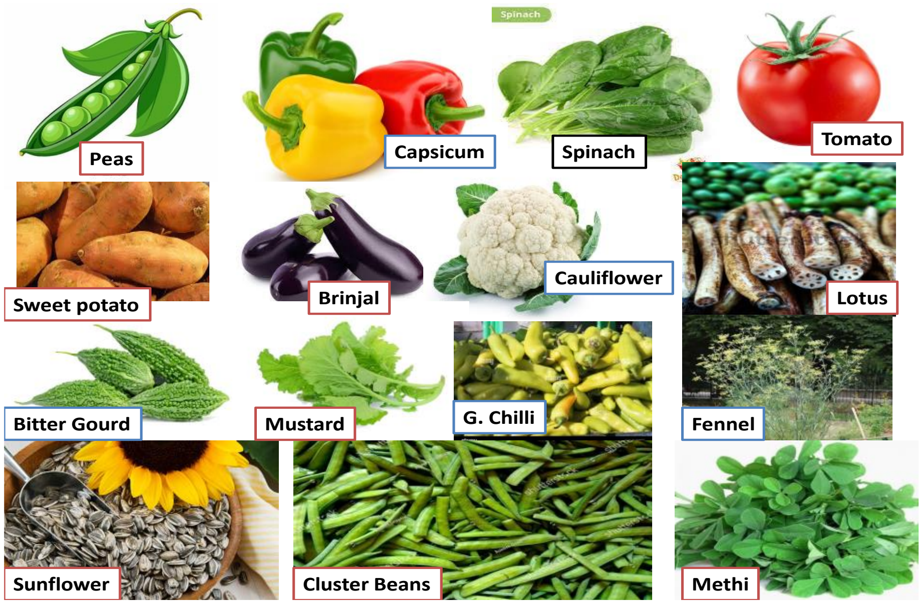

Figure: 1 Image of Vegetables Cultivated in District Jacobabad, Sindh, Pakistan

Table: 1 List of Vegetables, their Probable Scientific Name, Plant Family and Approximate Daily Intake

Common Name	Probable Scientific Name	Plant Family	Approx. Daily Intake (g)
Peas	Pisum sativum	Fabaceae (Legume)	100 g
Capsicum	Capsicum annuum	Solanaceae (Nightshade)	150 g
Spinach	Spinacia oleracea	Amaranthaceae	90 g
Tomato	Solanum lycopersicum	Solanaceae (Nightshade)	150 g
Sweet Potato	Ipomoea batatas	Convolvulaceae (Morning Glory)	130 g

Brinjal (Eggplant)	Solanum melongena	Solanaceae (Nightshade)	100 g
Cauliflower	Brassica oleracea var. botrytis	Brassicaceae (Mustard)	100 g
Lotus	Nelumbo nucifera	Nelumbonaceae	100 g
Bitter Gourd	Momordica charantia	Cucurbitaceae (Gourd)	100 g
Mustard	Brassica juncea or Sinapis alba	Brassicaceae (Mustard)	90 g
Green Chilli	Capsicum annuum or Capsicum frutescens	Solanaceae (Nightshade)	15 g
Fennel (Herb/Saunf)	Foeniculum vulgare	Apiaceae (Carrot)	15 g
Sunflower	Helianthus annuus	Asteraceae (Daisy)	30 g
Cluster Beans	Cyamopsis tetragonoloba	Fabaceae (Legume)	100 g
Methi (Fenugreek)	Trigonella foenum-graecum	Fabaceae (Legume)	100 g

Microwave-Assisted Digestion and Metal Analysis

Analytical Reagent grade HCl, HNO_3 and HF acids were used to prepare samples for microwave-assisted digestion with all glassware pre-cleaned. The process of digestion was carried out in a CEM MARS 6 Microwave Digestion System following a controlled temperature program. The resultant digests were then cooled filtered and volume made up to 150 mL in measuring flasks. Quantity of metals was analyzed by Inductively Coupled Plasma–Optical Emission Spectroscopy (ICP-OES) using a Thermo Scientific iCAP 7000 Series spectrometer and an ASX-280 autosampler. To ensure analytical quality and validity, the method included a thorough quality control procedure. This included the use of a certified reference material, yielding percent recoveries from 94.5% to 102%; reagent blanks that registered below the detection limit; and laboratory duplicates demonstrating excellent reproducibility (Gazulla, et al., 2022).

Table: 2 Maximum Permissible Limits (MPL) for Heavy Metals (Mg/Kg) in Vegetables, As Established by the FAO/WHO

Vegetables	Fe (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	Ni (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	Pb (mg/kg)	As (mg/kg)
WHO/EPA Limit	425.5	99.4	73.3	67.9	0.2	2.3	0.3	0.1
Peas	425.5	99.4	73.3	67.9	0.1	2.3	0.2	0.1
Capsicum	425.5	99.4	73.3	67.9	0.05	2.3	0.1	0.1

Spinach	425.5	99.4	73.3	67.9	0.2	2.3	0.3	0.1
Tomato	425.5	99.4	73.3	67.9	0.05	2.3	0.1	0.1
Sweet Potato	425.5	99.4	73.3	67.9	0.1	2.3	0.2	0.1
Brinjal	425.5	99.4	73.3	67.9	0.05	2.3	0.1	0.1
Cauliflower	425.5	99.4	73.3	67.9	0.05	2.3	0.3	0.1
Lotus	425.5	99.4	73.3	67.9	0.1	2.3	0.2	0.1
Bitter Gourd	425.5	99.4	73.3	67.9	0.05	2.3	0.1	0.1
Mustard	425.5	99.4	73.3	67.9	0.2	2.3	0.3	0.1
G. Chilli	425.5	99.4	73.3	67.9	0.05	2.3	0.1	0.1
Fennel	425.5	99.4	73.3	67.9	0.2	2.3	0.3	0.1
Sunflower	425.5	99.4	73.3	67.9	0.2	2.3	0.3	0.1
Cluster Beans	425.5	99.4	73.3	67.9	0.1	2.3	0.2	0.1
Methi	425.5	99.4	73.3	67.9	0.2	2.3	0.3	0.1

Note: No limit is suggested by WHO/FAO for Mn, Sn and Co for vegetables

Risk Assessment

Human health risk assessment from vegetable consumption is a scientific process used to evaluate the potential for adverse health effects caused by consuming vegetables contaminated with toxic substances, such as, EDI of HMs, THQ, TTHQ, HI, and TCR.

Estimated Daily Intake (EDI) of Heavy Metals

The Estimated Daily Intake (EDI) of metals from food consumption is calculated using a standard formula in environmental and health risk assessments. This formula relates the concentration of the metal in the food to the amount of that food consumed and the body weight of the consumer.

The most common formula is:

$$\text{EDI (mg/kg body weight/day)} = \frac{C \times IR}{BW}$$

Table: 3 Description of the formula to calculate Estimated Daily Intake (EDI)

Variable	Description	Units
EDI	Estimated Daily Intake	mg/kg body weight/day
C	Concentration of the Metal in Food	mg/kg (of food)
IR	Ingestion Rate or Food Consumption Rate	kg/person/day
BW	Body Weight	kg

Target Hazard Quotient (THQ)

The THQ was evaluated using the formula given below:

$$THQ = \frac{EF \times ED \times FIR \times CM}{BW \times AT \times RfD} \times 10 - 3$$

In this study, EF = Exposure Frequency (365 days/year),

ED = Exposure Duration (70 Years), as indicated by (Mehri, et al., 2024).

CM = Heavy Metal Concentration (mg/kg),

BW = Average Body Weight (60 kg),

AT = Average Exposure Time (EF × ED), ($AT = 25{,}550$ days)

RfD = Reference dose of Metals, (Cd = 0.001mg/kg/day, Cr = 1.5mg/kg/day, Ni = 0.02 mg/kg/day, Pb = 0.0035 mg/kg/day),

FIR = Food Ingestion Rate (g/person/day) (Mehri, et al., 2024).

Although there is a possible health risk and related treatments and protective measures must be implemented, exposed customers are not to suffer any detrimental healthiness risks if the THQ is less than 1 (Ahmadi-Jouibari, et al., 2023). According to USEPA Region III Risk-based Concentration, formula used to estimate THQ was computed as below (Chowdhury, et al., 2024);

Total Targeted Hazard Quotient (TTHQ)

The TTHQ for each individual from THQs as described by following equation: (Chowdhury, et al., 2024).

$$\mathrm{TTHQ} = \mathrm{THQ(Fe)} + \mathrm{THQ(Zn)} + \mathrm{THQ(Mn)} + \mathrm{THQ\ (Cu)} + \mathrm{THQ\ (Sn)} + \mathrm{THQ\ (Co)} + \mathrm{THQ\ (Ni\ )} + \mathrm{THQ\ (Cd)} + \mathrm{THQ\ (Cr)} + \mathrm{THQ\ (Pb)} + \mathrm{THQ\ (As)}$$

Hazard Index (HI)

To calculate the total risk of non-carcinogenic health risks from consuming many metals, HI is evaluated as below (Li, et al., 2024).

$$\mathrm{HI} = \mathrm{TTHQ(Food1)} + \mathrm{TTHQ(Food2)} + \mathrm{TTHQ(Food3)} + \mathrm{TTHQ(Food4)} \ldots\ldots\ldots \mathrm{n}$$

Carcinogenic Risk Assessment

Targeted Cancer Risk (TCR)

TCR can be calculated by using the following formula;

$$\mathrm{TCR} = \mathrm{EDI} \times \mathrm{CPSo}$$

Where,

EDI = Estimated Daily Intake,

CPSo = Carcinogenic Potency Slope, As = 1.5 $(mg/kg\cdot day)^{-1}$ (Antoine, et al., 2017), Cd = 6.1 $(mg/kg\cdot day)^{-1}$ (Lee, et al., 2023), Cr = 0.5 $(mg/kg\cdot day)^{-1}$ (Chang, et al., 2014), Ni = 0.84 $(mg/kg\cdot day)^{-1}$ (Lee, et al., 2023), Pb = 0.0085 $(mg/kg\cdot day)^{-1}$ (Javed, and Usmani, 2016). Generally speaking, a CR value below 1.0E-06 is regarded as insignificant, one beyond 1.0E-04 as unsatisfactory, and one falling between 1.0E-06 and 1.0E-04 as a normal range (Chang, et al., 2014).

Results and Discussions

Heavy Metals

The provided data details the concentrations (mg/kg) of eleven heavy metals determined from various vegetable samples cultivated in District Jacobabad, Sindh. When comparing these measured concentrations with the Maximum Permissible Limits (MPL) established by the FAO/WHO, it becomes evident that while most metals are within acceptable ranges, Cadmium (Cd) is a major concern, and Arsenic (As) also shows exceedances for certain vegetables.

For the metals Iron (Fe), Zinc (Zn), Copper (Cu), and Nickel (Ni), the concentrations in all tested vegetable samples were significantly lower than the respective FAO/WHO values. For instance, the highest concentration was 1.13 mg/kg in Brinjal, which is far below the MPL of 425.5 mg/kg. Similarly, Zn, Cu, and Ni concentrations across all vegetables remained well within their generous MPL of 99.4 mg/kg, 73.3 mg/kg, and 67.9 mg/kg, respectively.

Lead (Pb) and Chromium (Cr) concentrations in all vegetables were also found to be safely below their respective MPL. The highest Pb concentration was 0.037 mg/kg in Sweet Potato, which is less than the most stringent vegetable-specific MPL of 0.1 mg/kg (for Capsicum, Tomato, Brinjal, Bitter Gourd, and G. Chilli) and the WHO/EPA limit of 0.3 mg/kg,Cr concentrations, with a maximum of 2.57 mg/kg in Bitter Gourd, did not exceed the common of 2.3 mg/kg.

However, the concentration of Cadmium (Cd) exceeded its in several samples. For instance, Capsicum and Green Chilli had a concentration of 0.19 mg/kg, significantly exceeding their specific MPL of 0.05 mg/kg. Peas, Lotus, and Cluster Beans, with an MPL of 0.1 mg/kg, had levels of 0.16 mg/kg, 0.05 mg/kg, and 0.12 mg/kg, respectively, indicating excess in Peas and Cluster Beans. Furthermore, Cauliflower, Mustard, Fennel, and Sunflower all exceeded their specific for Cd. For Arsenic (As), while most vegetables were below the 0.1 mg/kg or 0.1 mg/kg MPL, Spinach (0.16 mg/kg), Lotus (0.139 mg/kg), Mustard (0.133 mg/kg), and Green Chilli (0.122 mg/kg) all exceeded the 0.1 mg/kg limit. Notably, Manganese (Mn), Tin (Sn), and Cobalt (Co) were determined in the samples, but no MPL is suggested by FAO/WHO for these elements in vegetables (Table: 4 and Figures 2a & 2b).

Table: 4 Concentration (Mg/Kg) Of heavy Metals Determined from Selected Vegetables Cultivated in District Jacobabad, Sindh

Vegetables	Fe (mg/kg)	Zn (mg/kg)	Mn (mg/kg)	Cu (mg/kg)	Sn (mg/kg)	Co (mg/kg)	Ni (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	Pb (mg/kg)	As (mg/kg)
Peas	0.91	1.61	6.8	0.289	0.041	0.062	1.02	0.16	2.29	0.025	0.038
Capsicum	0.18	2.33	1.04	0.48	0.069	0.152	2.13	0.19	1.22	0.013	0.038
Spinach	0.81	3.2	2.22	0.99	0.052	0.094	4.55	0.08	1.3	0.028	0.16
Tomato	0.96	2.34	3.23	1.95	0.051	0.055	2.16	0.09	2.29	0.023	0.076
Sweet Potato	0.1	3.25	4.16	0.97	0.071	0.047	1.19	0.02	1.36	0.037	0.026
Brinjal	1.13	4.72	7.06	0.84	0.041	0.016	2.35	0.09	1.45	0.031	0.037
Cauliflower	0.02	2.18	4.16	0.48	0.053	0.048	2.35	0.15	1.11	0.032	0.099
Lotus	0.56	1.52	3.06	0.93	0.033	0.028	3.2	0.05	1.09	0.018	0.139
Bitter Gard	0.519	3.73	5.23	0.95	0.033	0.08	2.58	0.04	2.57	0.02	0.027
Mustard	0.74	3.29	2.13	0.94	0.048	0.094	2.26	0.12	0.96	0.023	0.133
G. Chilli	0.71	3.11	2.28	0.902	0.063	0.013	4.31	0.19	1.21	0.034	0.122
Fennel	0.41	3.31	8.29	1.06	0.053	0.022	3.11	0.21	1.97	0.034	0.037
Sunflower	0.34	2.35	4.87	0.96	0.056	0.023	0.66	0.12	1.23	0.036	0.035

Cluster Beans	0.73	3.11	3.19	1.19	0.154	0.049	3.2	0.12	2.16	0.014	0.027
Methi	0.37	4.23	1.17	2.04	0.031	0.021	4.19	0.031	2.42	0.023	0.077

Estimated Daily Intake (EDI)

Estimated Daily Intake (EDI) was measured for 11 various heavy metals from 15 distinct vegetable samples, with all values expressed in mg/kg/day. The EDI is critical parameter in health risk assessment, showing the daily amount of a pollutant ingested per unit of body weight. Analytical results reveal that Mn consistently had the highest EDI values across about all samples. Comparative EDI values for Mn were found in Brinjal (Br) and Peas (Ps) as 1.2×10^{-2} and 1.1×10^{-2} mg/kg/day respectively. Cr and Ni also showed higher EDI values with Cr maximum at 5.7×10^{-3} and 7.0×10^{-3} mg/kg/day in tomato and methi respectively. On the other hand the EDI values for Pb and As were among the lowest across all samples usually determined in the 10^{-5} range. The minimum EDI value for Fe in cauliflower was found as 3.3×10^{-5} mg/kg/day. Overall, the pattern of EDI suggests that Mn, Cr, and Ni were the primary contributors to the daily intake of heavy metals through the consumption of these vegetables (Table: 5).

Table: 5 Estimated Daily Intake (EDI) for each Vegetable (mg/kg/day) Cultivated in District Jacobabad, Sindh

Sample	As	Cd	Co	Cr	Cu	Fe	Mn	Ni	Pb	Sn	Zn
Ps	6.3×10^{-5}	2.7×10^{-4}	1.0×10^{-4}	3.8×10^{-3}	4.8×10^{-4}	1.5×10^{-3}	1.1×10^{-2}	1.7×10^{-3}	4.2×10^{-5}	6.8×10^{-5}	2.7×10^{-3}
Cm	9.5×10^{-5}	4.8×10^{-4}	3.8×10^{-4}	3.1×10^{-3}	1.2×10^{-3}	4.5×10^{-4}	2.6×10^{-3}	5.3×10^{-3}	3.2×10^{-5}	1.7×10^{-4}	5.8×10^{-3}
Sp	2.4×10^{-4}	1.2×10^{-4}	1.4×10^{-4}	1.9×10^{-3}	1.5×10^{-3}	1.2×10^{-3}	3.3×10^{-3}	6.8×10^{-3}	4.2×10^{-5}	7.8×10^{-5}	4.8×10^{-3}
Tm	1.9×10^{-4}	2.2×10^{-4}	1.4×10^{-4}	5.7×10^{-3}	4.9×10^{-3}	2.4×10^{-3}	8.1×10^{-3}	5.4×10^{-3}	5.8×10^{-5}	1.3×10^{-4}	5.8×10^{-3}
S.P	5.6×10^{-5}	4.3×10^{-5}	1.1×10^{-4}	2.9×10^{-3}	2.1×10^{-3}	2.2×10^{-4}	9.0×10^{-3}	2.6×10^{-3}	8.0×10^{-5}	1.5×10^{-4}	7.0×10^{-3}
Br	6.2×10^{-5}	1.5×10^{-4}	2.7×10^{-5}	2.4×10^{-3}	1.4×10^{-3}	1.9×10^{-3}	1.2×10^{-2}	3.9×10^{-3}	5.2×10^{-5}	6.8×10^{-5}	7.9×10^{-3}
Cf	1.6×10^{-4}	2.5×10^{-4}	8.0×10^{-5}	1.8×10^{-3}	8.0×10^{-4}	3.3×10^{-5}	6.9×10^{-3}	3.9×10^{-3}	5.3×10^{-5}	8.8×10^{-5}	3.6×10^{-3}
Lt	2.3×10^{-4}	8.3×10^{-5}	4.7×10^{-5}	1.8×10^{-3}	1.6×10^{-3}	9.3×10^{-4}	5.1×10^{-3}	5.3×10^{-3}	3.0×10^{-5}	5.5×10^{-5}	2.5×10^{-3}
BG	4.5×10^{-5}	6.7×10^{-5}	1.3×10^{-4}	4.3×10^{-3}	1.6×10^{-3}	8.6×10^{-4}	8.7×10^{-3}	4.3×10^{-3}	3.3×10^{-5}	5.5×10^{-5}	6.2×10^{-3}
Md	2.0×10^{-4}	1.8×10^{-4}	1.4×10^{-4}	1.4×10^{-3}	1.4×10^{-3}	1.1×10^{-3}	3.2×10^{-3}	3.4×10^{-3}	3.4×10^{-5}	7.2×10^{-5}	4.9×10^{-3}
GC	3.1×10^{-5}	4.8×10^{-5}	3.2×10^{-6}	3.0×10^{-4}	2.3×10^{-4}	1.8×10^{-4}	5.7×10^{-4}	1.1×10^{-3}	8.5×10^{-6}	1.6×10^{-5}	7.8×10^{-4}
Fl	9.2×10^{-6}	5.2×10^{-5}	5.5×10^{-6}	4.9×10^{-4}	2.7×10^{-4}	1.0×10^{-4}	2.1×10^{-3}	7.8×10^{-4}	8.5×10^{-6}	1.3×10^{-5}	8.3×10^{-4}

Sf	1.8×10^{-5}	6.0×10^{-5}	1.2×10^{-5}	6.1×10^{-4}	4.8×10^{-4}	1.7×10^{-4}	2.4×10^{-3}	3.3×10^{-4}	1.8×10^{-5}	2.8×10^{-5}	1.2×10^{-3}
CF	4.5×10^{-5}	2.0×10^{-4}	8.2×10^{-5}	3.6×10^{-3}	2.0×10^{-3}	1.2×10^{-3}	5.3×10^{-3}	5.3×10^{-3}	2.3×10^{-5}	2.6×10^{-4}	5.2×10^{-3}
Mt	1.3×10^{-4}	5.2×10^{-5}	3.5×10^{-5}	4.0×10^{-3}	3.4×10^{-3}	6.2×10^{-4}	2.0×10^{-3}	7.0×10^{-3}	3.8×10^{-5}	5.2×10^{-5}	7.1×10^{-3}

Targeted Hazard Quotient (THQ)

The table presents the Targeted Hazard Quotient (THQ) values for eleven heavy metals in various vegetable samples, alongside the overall Hazard Index (HI) which represents the cumulative non-carcinogenic health risk from metal ingestion. The general guideline for non-carcinogenic risk states that if the HI exceeds 1, there is a potential for adverse health effects on the exposed population. The majority of the vegetable samples exhibited HI values significantly greater than 1, indicating a high likelihood of cumulative non-carcinogenic health risks for the consumers. Particularly, the highest HI value of 5.6 was determined in tomato while Capsicum, Bitter Gourd and Methi showed HI values of 4.4, 3.9 and 3.8 respectively. Three samples, Green Chilli, Fennel and sunflower showed HI values less than safety threshold limit of 1 as 0.4, 0.5 and 0.6 respectively. Determination of individual THQ reveals that Cr was the primary driver of the mostly risk in the most of the samples. The THQ for Cr ranged from 2.02×10^{-1} to 3.82×10^{0} in G. Chilli and Tomato respectively. Co and As also showed the higher HI values of 1.27×10^{0} and 8.00×10^{-1} in Capsicum and Spinach respectively. For the most of the samples, the THQ values for Fe, Sn, Pb, and Cu were in the range 10^{-4} to 10^{-2}, signifying they contributed less to the overall non-carcinogenic risk (Table: 6).

Table: 6 THQ values of each Vegetable Cultivated in District Jacobabad, Sindh and HI = sum of THQs per sample.

Sample	As	Cd	Co	Cr	Cu	Fe	Mn	Ni	Pb	Sn	Zn	HI
Ps	2.11×10^{-1}	2.67×10^{-1}	3.44×10^{-1}	2.55×10^{0}	1.20×10^{-2}	2.17×10^{-3}	8.09×10^{-2}	8.50×10^{-2}	1.19×10^{-2}	1.14×10^{-3}	8.94×10^{-3}	3.6
Cm	3.17×10^{-1}	4.75×10^{-1}	1.27×10^{0}	2.03×10^{0}	3.00×10^{-2}	6.43×10^{-4}	1.86×10^{-2}	2.66×10^{-1}	9.29×10^{-3}	2.88×10^{-3}	1.94×10^{-2}	4.4
Sp	8.00×10^{-1}	1.20×10^{-1}	4.70×10^{-1}	1.30×10^{0}	3.71×10^{-2}	1.74×10^{-3}	2.38×10^{-2}	3.41×10^{-1}	1.20×10^{-2}	1.30×10^{-3}	1.60×10^{-2}	3.1
Tm	6.33×10^{-1}	2.25×10^{-1}	4.58×10^{-1}	3.82×10^{0}	1.22×10^{-1}	3.43×10^{-3}	5.77×10^{-2}	2.70×10^{-1}	1.64×10^{-2}	2.12×10^{-3}	1.95×10^{-2}	5.6
S.P	1.88×10^{-1}	4.33×10^{-2}	3.39×10^{-1}	1.97×10^{0}	5.26×10^{-2}	3.11×10^{-4}	6.44×10^{-2}	1.29×10^{-1}	2.29×10^{-2}	2.56×10^{-3}	2.35×10^{-2}	2.8
Br	2.06×10^{-1}	1.50×10^{-1}	8.89×10^{-2}	1.61×10^{0}	3.50×10^{-2}	2.69×10^{-3}	8.41×10^{-2}	1.96×10^{-1}	1.48×10^{-2}	1.14×10^{-3}	2.62×10^{-2}	2.4
Cf	5.50×10^{-1}	2.50×10^{-1}	2.67×10^{-1}	1.23×10^{0}	2.00×10^{-2}	4.76×10^{-5}	4.95×10^{-2}	1.96×10^{-1}	1.52×10^{-2}	1.47×10^{-3}	1.21×10^{-2}	2.6
Lt	7.72×10^{-1}	8.33×10^{-2}	1.56×10^{-1}	1.21×10^{0}	3.88×10^{-2}	1.33×10^{-3}	3.64×10^{-2}	2.67×10^{-1}	8.57×10^{-3}	9.17×10^{-4}	8.44×10^{-3}	2.6
BG	1.50×10^{-1}	6.67×10^{-2}	4.44×10^{-1}	2.85×10^{0}	3.96×10^{-2}	1.24×10^{-3}	6.23×10^{-2}	2.15×10^{-1}	9.52×10^{-3}	9.17×10^{-4}	2.07×10^{-2}	3.9
Md	6.65×10^{-1}	1.80×10^{-1}	4.70×10^{-1}	9.60×10^{-1}	3.52×10^{-2}	1.59×10^{-3}	2.28×10^{-2}	1.69×10^{-1}	9.86×10^{-3}	1.20×10^{-3}	1.64×10^{-2}	2.5

GC	1.02×10^{-1}	4.75×10^{-2}	1.08×10^{-2}	2.02×10^{-1}	5.64×10^{-3}	2.54×10^{-4}	4.07×10^{-3}	5.38×10^{-2}	2.43×10^{-3}	2.62×10^{-4}	2.59×10^{-3}	0.4
Fl	3.08×10^{-2}	5.25×10^{-2}	1.83×10^{-2}	3.28×10^{-1}	6.62×10^{-3}	1.46×10^{-4}	1.48×10^{-2}	3.89×10^{-2}	2.43×10^{-3}	2.21×10^{-4}	2.76×10^{-3}	0.5
Sf	5.83×10^{-2}	6.00×10^{-2}	3.83×10^{-2}	4.10×10^{-1}	1.20×10^{-2}	2.43×10^{-4}	1.74×10^{-2}	1.65×10^{-2}	5.14×10^{-3}	4.67×10^{-4}	3.92×10^{-3}	0.6
CF	1.50×10^{-1}	2.00×10^{-1}	2.72×10^{-1}	2.40×10^{0}	4.96×10^{-2}	1.74×10^{-3}	3.80×10^{-2}	2.67×10^{-1}	6.67×10^{-3}	4.28×10^{-3}	1.73×10^{-2}	3.4
Mt	4.28×10^{-1}	5.17×10^{-2}	1.17×10^{-1}	2.69×10^{0}	8.50×10^{-2}	8.81×10^{-4}	1.39×10^{-2}	3.49×10^{-1}	1.10×10^{-2}	8.61×10^{-4}	2.35×10^{-2}	3.8
TTHQ	5.260	2.270	4.760	25.600	0.581	0.018	0.589	2.860	0.158	0.022	0.221	42.3

Correlation Coefficient

The results shown in the Table: 7 demonstrate the correlation coefficient among studied heavy metals in the vegetable samples, which help in understanding the possible common origins or mutually dependent mobility of these metals within soil – plant system. A strong positive correlation (≤ +1) shows that the level of two metals increase or decrease simultaneously, likely pointing to a shared source or system of uptake, whereas a strong negative correlation (≤ −1) recommends opposed behavior in uptake. Focusing on statistically noteworthy correlation, a highly negative correlation was found between Mn and As with a coefficient of −0.51**, recommending that as the level of one metal enhances, the other tends to decline. The Co and Pb showed another highly significant negative correlation of −0.55**. On the other hand strong positive correlation of 0.58** was found between Ni and As which involves that these two pollutants have similar pathway into vegetables. The Pb and Mn showed positive correlation of 0.44* indicating that they may build up under similar conditions. The Cr and Cu displayed positive correlation of 0.46*, however, Cu and Cd declared a corresponding significant negative correlation of −0.46*. Furthermore, various pairs of metals declared positive as well as negative correlation coefficients such as Cr and As (−0.50*), Fe and Zn (0.19), Fe and Mn (0.19), Cd and Ni (−0.03). In general, correlation coefficient pattern shows that the heavy metal pollution in different vegetables is not only from a single source but is disposed by various complex geochemical and physiological mechanisms (Table: 7).

Table: 7 Correlation Coefficient Among Various Metals Present in Vegetables Cultivated in District Jacobabad, Sindh, Pakistan

	Fe	Zn	Mn	Cu	Sn	Co	Ni	Cd	Cr	Pb	As
Fe	1.00										
Zn	0.19	1.00									
Mn	0.19	0.08	1.00								
Cu	0.16	0.37	−0.30	1.00							
Sn	−0.03	−0.03	−0.15	−0.01	1.00						

Co	−0.13	−0.20	−0.41	−0.32	0.08	1.00					
Ni	0.17	0.36	−0.41	0.37	0.03	−0.11	1.00				
Cd	−0.01	−0.30	0.20	−0.46*	0.22	0.13	−0.03	1.00			
Cr	0.24	0.22	0.26	0.46*	0.03	−0.11	0.05	−0.20	1.00		
Pb	−0.15	0.18	0.44*	−0.09	−0.25	−0.55**	−0.18	0.09	−0.28	1.00	
As	0.17	−0.17	−0.51**	0.07	−0.29	0.05	0.58**	−0.05	−0.50*	−0.01	1.00

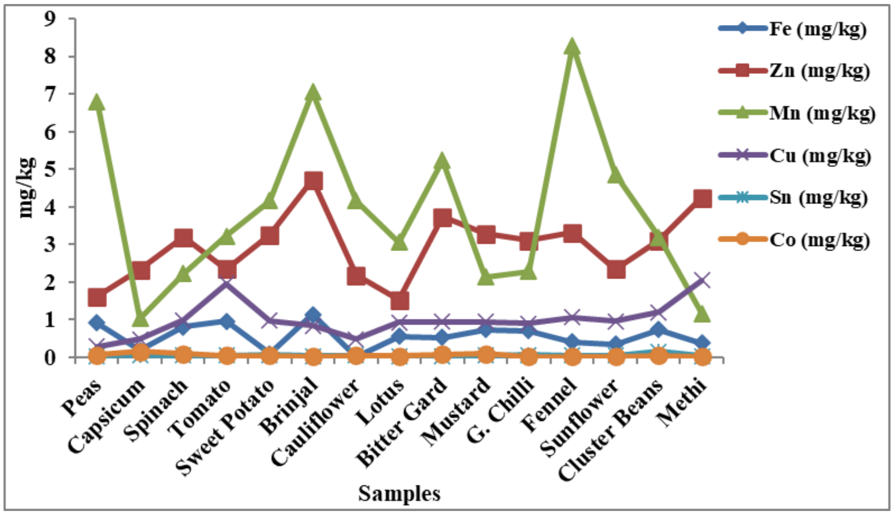

Figure: 2a Concentration of heavy Metals determined from Vegetables Cultivated in District Jacobabad, Sindh, Pakistan

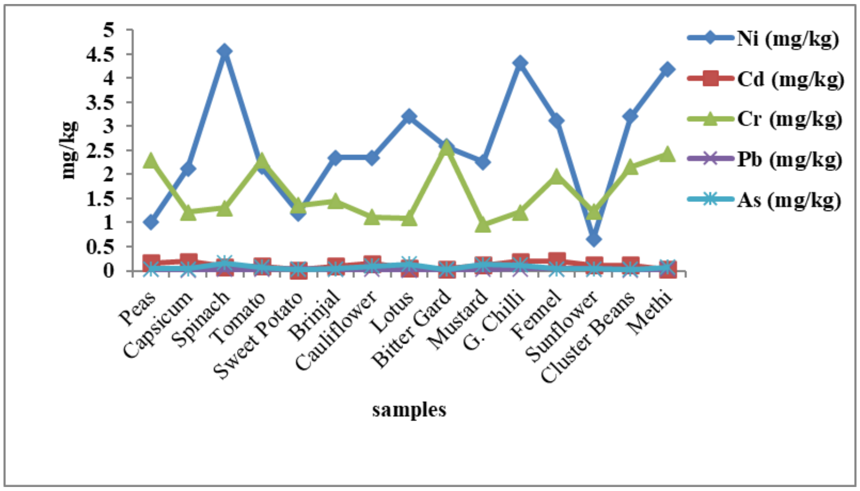

Figure: 2b Concentration of heavy metals determined from Vegetables cultivated in District Jacobabad, Sindh, Pakistan

Incremental Lifetime Cancer Risk (ILCR)

Incremental Lifetime Cancer Risk (ILCR) values for five carcinogenic heavy metals (As, Cd, Cr, Ni, and Pb) in different vegetable samples, and the corresponding Total Cancer Risk (ΣILCR) for each sample is shown in (Table: 7). The primary standard for satisfactory cancer risk is generally set as 1×10^{-4}. A technical estimation of the data reveals that the ΣILCR values for different vegetable samples notably surpassed the acceptable limit of 1×10^{-4}. Sunflower showed the ΣILCR value of 1.036×10^{-3} whereas; Tomato displayed the maximum value of 1.157×10^{-2} of ΣILCR, showing a high potential cancer risk related with the consumption of these vegetables. Upon the nearer assessment of the individual metal contributions, Cr and Ni were constantly the prevailing heavy metals driving the total carcinogenic risk. The tomato sample showed the maximum ILCR value of 5.700×10^{-3} for Cr. Likewise, the highest ILCR value of 7.000×10^{-3} for Ni was found in methi sample. On the other hand, the ILCR value for As, Cd, and Pb were one to two orders of magnitude lower as compared to those for Cr and Ni. Sweet potato showed the highest ILCR value of 8.000×10^{-5} for Pb. The elevated ΣILCR values highlight a severe public concern, suggesting that the consumption of these vegetables pose an improperly high risk of developing cancer over a lifetime for the population of District Jacobabad (Table: 8).

Table: 8 Calculated Incremental Lifetime Cancer Risk (ILCR) values for different heavy metals in various vegetable samples cultivated in District Jacobabad, Sindh, Pakistan

Sample	ILCR (As)	ILCR (Cd)	ILCR (Cr)	ILCR (Ni)	ILCR(Pb)	Total Cancer Risk (ΣILCR)
Ps	6.300×10^{-5}	2.700×10^{-4}	3.800×10^{-3}	1.700×10^{-3}	4.200×10^{-5}	5.875×10^{-3}
Cm	9.500×10^{-5}	4.800×10^{-4}	3.100×10^{-3}	5.300×10^{-3}	3.200×10^{-5}	9.007×10^{-3}
Sp	2.400×10^{-4}	1.200×10^{-4}	1.900×10^{-3}	6.800×10^{-3}	4.200×10^{-5}	9.102×10^{-3}
Tm	1.900×10^{-4}	2.200×10^{-4}	5.700×10^{-3}	5.400×10^{-3}	5.800×10^{-5}	1.157×10^{-2}
S.P	5.600×10^{-5}	4.300×10^{-5}	2.900×10^{-3}	2.600×10^{-3}	8.000×10^{-5}	5.679×10^{-3}
Br	6.200×10^{-5}	1.500×10^{-4}	2.400×10^{-3}	3.900×10^{-3}	5.200×10^{-5}	6.564×10^{-3}
Cf	1.600×10^{-4}	2.500×10^{-4}	1.800×10^{-3}	3.900×10^{-3}	5.300×10^{-5}	6.163×10^{-3}
Lt	2.300×10^{-4}	8.300×10^{-5}	1.800×10^{-3}	5.300×10^{-3}	3.000×10^{-5}	7.443×10^{-3}
BG	4.500×10^{-5}	6.700×10^{-5}	4.300×10^{-3}	4.300×10^{-3}	3.300×10^{-5}	8.745×10^{-3}
Md	2.000×10^{-4}	1.800×10^{-4}	1.400×10^{-3}	3.400×10^{-3}	3.400×10^{-5}	5.214×10^{-3}
GC	3.100×10^{-5}	4.800×10^{-5}	3.000×10^{-4}	1.100×10^{-3}	8.500×10^{-6}	1.488×10^{-3}

Fl	9.200×10^{-6}	5.200×10^{-5}	4.900×10^{-4}	7.800×10^{-4}	8.500×10^{-6}	1.340×10^{-3}
Sf	1.800×10^{-5}	6.000×10^{-5}	6.100×10^{-4}	3.300×10^{-4}	1.800×10^{-5}	1.036×10^{-3}
CF	4.500×10^{-5}	2.000×10^{-4}	3.600×10^{-3}	5.300×10^{-3}	2.300×10^{-5}	9.168×10^{-3}
Mt	1.300×10^{-4}	5.200×10^{-5}	4.000×10^{-3}	7.000×10^{-3}	3.800×10^{-5}	1.122×10^{-2}

Conclusion

It is concluded from the present work that consumption of vegetables grown in District Jacobabad, Sindh, poses a significant health risk to the local inhabitants because of heavy metals contamination. The non-carcinogenic risk, as illustrated by HI, showed that the most vegetables surpassed the safe limit of 1, involving a collective risk of non-carcinogenic health hazards from the accumulation of heavy metals. The sample tomato displayed the highest HI value of 5.6. Moreover, the cancer risk, measured by the Total Cancer Risk (ΣILCR), was observed to be inappropriately high through all vegetable samples. All values of ΣILCR ranged from 1.036×10^{-3} to 1.157×10^{-2} were found above the acceptable cancer threshold of 1×10^{-4}. The tomato displayed the highest cancer risk with a ΣILCR of 1.157×10^{-2}. These findings strongly suggest an urgent need for intervention measures to monitor and control heavy metal contamination in the agricultural practices of District Jacobabad to protect public health.

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