

Research Article

Lead Exceedance in Vegetables Grown on Guideline-compliant Soils: Heavy Metal Contamination and Human Health Risk in Cumilla, Bangladesh

Khandaker Nadia Anjum¹ , **Subrato Roy²**, **Most Zakiya Islam³**,
Md. Sajjad Hossain^{4,*}

¹Faculty of Agriculture, Sher-e-Bangla Agricultural University, Dhaka, Bangladesh

²Plant Protection Wing, Department of Agricultural Extension, Dhaka, Bangladesh

³Department of Agricultural Chemistry, Sher-e-Bangla Agricultural University, Dhaka, Bangladesh

⁴Department of Soil Science, Sher-e-Bangla Agricultural University, Dhaka, Bangladesh

Abstract

Cumilla district combines intensive year-round vegetable production with an export processing zone, dense brick-kiln clusters and heavily trafficked national highways, yet no systematic soil-vegetable survey of toxic metals has been reported for the district. This study quantified copper (Cu), chromium (Cr) and lead (Pb) in five widely grown vegetables (potato, tomato, chili pepper, cauliflower and cabbage) and their matched surface field soils (0–15 cm) across six upazilas spanning an industrial-to-rural gradient, and tested the hypothesis that crop contamination tracks soil contamination closely enough for soil monitoring to serve as a proxy for food safety screening. Thirty matched crop-soil pairs (60 composites) were digested in HNO₃: HClO₄ (2: 1) and analysed by flame atomic absorption spectrophotometry; the method returned recoveries of 94.7–102.3%, relative standard deviations of 1.7–2.9% and determination coefficients above 0.999. Concentrations in vegetables (dry weight) ranged from 3.92 to 15.98 mg/kg for Cu, 0.50 to 2.96 mg/kg for Cr and 7.27 to 21.90 mg/kg for Pb; matched soils ranged from 9.78 to 24.93, 20.23 to 88.00 and 10.84 to 31.59 mg/kg, respectively. Every field soil complied with FAO/WHO agricultural soil guidelines for all three metals, yet every vegetable composite exceeded the 0.3 mg/kg maximum allowable limit for Pb. Pollution load indices exceeded unity in all 30 vegetables (1.10–2.55) and remained below unity in all 30 soils (0.20–0.46), while potential ecological risk indices indicated uniformly low ecological risk. Hazard indices exceeded unity and cumulative cancer risks exceeded 10^{−4} in every sample, with Pb contributing 78–90% of the non-carcinogenic hazard. A fresh-weight sensitivity analysis reduced these magnitudes roughly nine-fold but did not alter the exceedance conclusions. Soil compliance therefore coexists with crop non-compliance, and regulatory screening in Bangladesh must be based on direct analysis of the edible crop rather than on soil.

Keywords

Bioaccumulation Factor, Dietary Exposure, Lead, Pollution Load Index, Soil-crop Transfer, Human Health Risk

*Correspondence: Md. Sajjad Hossain (sajjadhossain@sau.edu.bd)

Received: 25 September 2026; **Accepted:** 10 October 2026; **Published:** 29 October 2026



Copyright: © The Author(s), 2026. Published by Science Publishing Group. This is an **Open Access** article, distributed under the terms of the Creative Commons Attribution 4.0 License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution and reproduction in any medium, provided the original work is properly cited.

1. Introduction

Heavy metal contamination of agricultural soils and food crops has become a global concern driven by intensive cultivation, rapid urbanization, industrialization and mining [1, 2]. Where environmental planning is weak, industrial and municipal effluents are discharged into surface waters that are subsequently used for irrigation, and contamination spreads to fields that have no local pollution source of their own [3-5]. Additional inputs arise from the routine use of fertilizers and metal-bearing agrochemicals, from effluent released by industry, mining and power generation, and from atmospheric deposition [6, 7]. Because these elements are neither biodegradable nor readily removed, they persist in soils for decades and are progressively transferred to the edible parts of crops, reducing yield and compromising food safety simultaneously [8, 9].

The terms "trace element" and "heavy metal" overlap but are not interchangeable. Trace elements are simply those present in living tissue at low concentration and include both essential nutrients and non-essential toxicants, whereas "heavy metal" denotes the subset of metals and metalloids of relatively high density whose environmental behaviour is of toxicological concern. Copper is an essential micronutrient required in small amounts by plants and animals and is homeostatically regulated in plant tissue [10]; lead has no known biological function and is toxic at low chronic exposure. For consistency, "heavy metal" is used throughout to denote Cu, Cr and Pb collectively.

Vegetables are the commodity group through which this transfer most directly reaches consumers. They are eaten frequently, often with minimal processing, and are valued for vitamins, minerals and bioactive compounds that reduce cardiovascular and age-related disease risk [11, 12]. The same properties that make them a dietary staple make contamination consequential: metals may be taken up through roots from polluted soil or deposited directly on foliar surfaces during production, transport and marketing [13, 14]. Recent Bangladeshi surveys have repeatedly reported vegetables from industrial and peri-urban belts exceeding FAO/WHO maximum allowable limits for Pb, Cd, Cr and Ni [15-19], and a recent nationwide systematic review concluded that dietary exposure to toxic metals has become a governance-level food safety concern in the country [20].

An assumption embedded in much of the regulatory response to these findings is that soil contamination is a workable proxy for crop contamination, and therefore that soil monitoring can serve as an efficient screening tool. Several recent studies cast doubt on this. Bushra et al. [21] reported brinjal fruit exceeding regulatory Pb limits in a major production belt while the corresponding topsoils remained within guideline values, and Kumar et al. [22] observed the same pattern around a lead-acid battery recycling facility. The mismatch

has a straightforward arithmetic basis, since food and soil criteria for Pb differ by more than two orders of magnitude and were set for different protective purposes, but its practical implication for monitoring policy has received little attention.

Cumilla is an important agricultural and industrial hub of eastern Bangladesh where these pressures converge. The district combines intensive year-round vegetable production with the Cumilla Export Processing Zone, a dense network of brick kilns, battery and metal-recycling workshops, and two heavily trafficked national highways. Effluent discharge from the export processing zone into adjoining canals has been reported to affect farmland and fisheries in Sadar Dakshin upazila, while highway-side and peri-urban fields elsewhere receive atmospheric and road-runoff metal loads. Crops grown in comparable industrial regions of Bangladesh have exceeded permissible limits for several toxic metals [16, 23-25], and vegetables from the adjoining Noakhali region have returned hazard indices above unity for adult consumers [26]. Despite this, no systematic multi-upazila soil-vegetable survey has been reported for Cumilla, and the pollution indices and dietary risk estimates that would allow regulators to prioritize intervention in the district remain unquantified.

This study was therefore undertaken to (i) determine Cu, Cr and Pb concentrations in five widely grown vegetables and their matched field soils across six upazilas of Cumilla district selected to span an industrial-to-rural gradient; (ii) assess contamination, bioaccumulation, pollution load and potential ecological risk in both matrices; and (iii) evaluate the non-carcinogenic and carcinogenic health risks to adult consumers. The underlying hypothesis tested is that crop contamination tracks soil contamination closely enough for soil concentration to serve as a reliable screening proxy for food safety.

2. Materials and Methods

2.1. Study Area

Cumilla district lies in Chattogram Division of eastern Bangladesh between approximately 23°01' and 23°51' N and 90°39' and 91°22' E, covering about 3,146 km². It is bordered by Brahmanbaria and Narayanganj to the north, Noakhali and Feni to the south, Tripura State of India to the east, and Munshiganj and Chandpur to the west. The district lies mainly within the Middle Meghna River Floodplain (AEZ-16) and the Old Meghna Estuarine Floodplain (AEZ-19), with the Lalmai-Mainamati hills forming a small area of Northern and Eastern Hills (AEZ-29) in the centre. Fertile floodplain silt loams, a warm humid climate and reliable irrigation make the area highly suitable for year-round vegetable production, and vegetables and spices are now more profitable for many Cumilla farmers than paddy. The district simultaneously hosts the Cumilla Export Processing Zone, a dense concentration of

brick kilns, several battery and metal-recycling workshops, and the Dhaka-Chattogram and Cumilla-Noakhali national highway corridors.

2.2. Sampling Design and Sample Collection

The study was a cross-sectional survey conducted between December 2025 and January 2026, coinciding with the peak *rabi* vegetable harvest. Six upazilas were selected to represent a gradient of anthropogenic pressure: industrial and export-processing-zone-affected (Cumilla Sadar Dakshin), urban and

traffic-affected (Cumilla Adarsha Sadar), intensive vegetable production (Burichang), vegetable-based agriculture (Chandina), riverine and highway-influenced (Daudkandi), and rural agricultural reference (Barura) (Figure 1). Within each upazila, five farmers' fields growing potato (*Solanum tuberosum* L.), tomato (*Solanum lycopersicum* L.), chili pepper (*Capsicum annuum* L.), cauliflower (*Brassica oleracea* var. *botrytis* L.) and cabbage (*Brassica oleracea* var. *capitata* L.) respectively were sampled, giving 30 matched vegetable-soil field pairs and 60 composite samples in total.

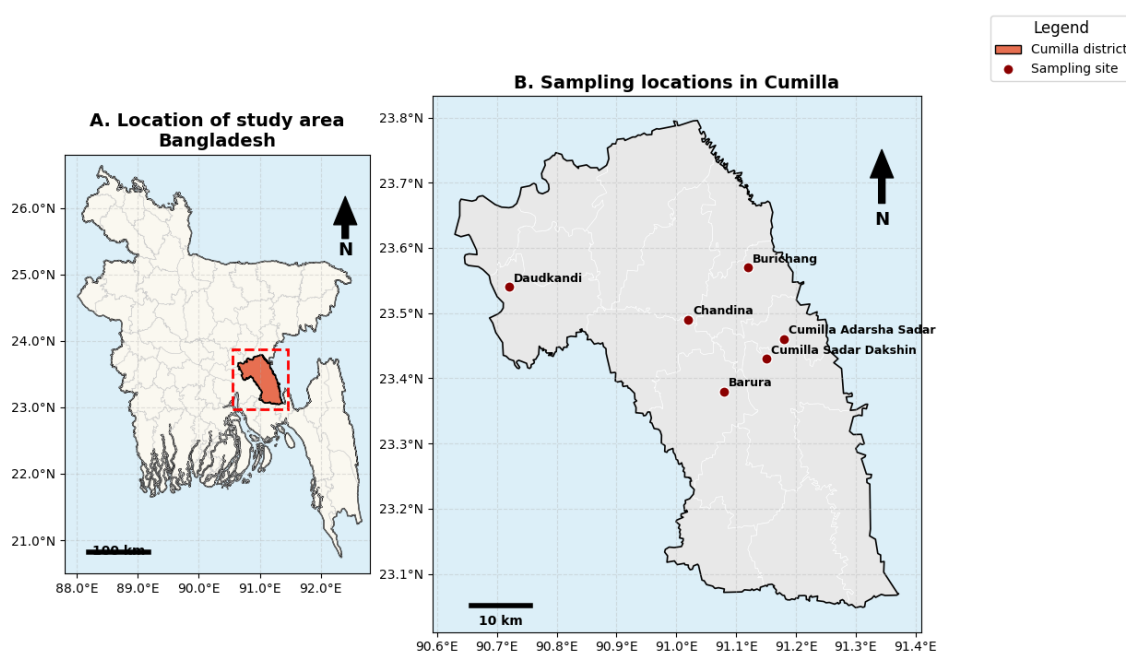


Figure 1. Location of the 30 vegetable field sampling sites across six upazilas of Cumilla district, Bangladesh.

Vegetables were collected at the harvesting stage. Three subsamples were taken from separate points within each field and combined into a single representative composite. Samples were rinsed with distilled water immediately after harvest, sealed in ziplock polythene bags and transported to the Food Safety Laboratory, Department of Agricultural Chemistry, Sher-e-Bangla Agricultural University, Dhaka. At the same three points in each field, surface soil (0-15 cm) subsamples were collected and combined to give approximately 1.5 kg of composite soil per field.

2.3. Sample Preparation and Digestion

Vegetable samples were oven-dried at 60-70 °C for three days to constant weight, ground and stored in sealed polythene bags. Soil samples were hand-cleaned to remove stones, gravel, roots and plant debris, air-dried for three days at 30-40 °C and passed through a 2 mm sieve. All vegetable and soil concentrations reported in this paper are therefore expressed on a dry-weight basis; the implications of this for comparison

with regulatory limits are addressed in Section 4.4.

One gram of dried, ground vegetable material and one gram of finely ground soil were placed into separate glass digestion tubes and pre-digested overnight with 20 mL of a di-acid mixture (2: 1 HNO₃: HClO₄). Digests were then heated at 180-220 °C for two hours until digestion was complete, cooled for 30 minutes, diluted to 100 mL with deionized water, vortexed for 10 seconds and filtered through Whatman No. 42 filter paper. Filtrates were stored at 4-7 °C in labelled polythene bottles. The acid ratio and overnight pre-digestion step follow Samma et al. [27]. The overnight nitric acid pre-digestion is essential because perchloric acid presents a serious explosion hazard when heated in direct contact with undigested organic matter; all digestions were carried out in a dedicated perchloric acid fume hood with a water wash-down facility, and tubes were never allowed to evaporate to dryness. Heavy metal standards (> 95% purity) for Cu, Cr and Pb were obtained from Scharlau Chemicals (Spain) through Bangladesh Scientific and Chemical Company Pvt. Ltd., Dhaka. Analytical- and EMSURE-grade nitric acid, perchloric acid and hydrogen peroxide were

obtained from Kuri & Company (Pvt.) Ltd., Dhaka.

2.4. Instrumentation and Quantification

Total Cu, Cr and Pb in the digests were determined with an Analytik Jena novAA 400P flame atomic absorption spectrophotometer (Analytik Jena AG, Jena, Germany) using element-specific hollow cathode lamps and an air-acetylene

flame. Instrumental operating conditions are given in Table 1. Calibration curves were constructed by plotting absorbance against the concentration of standard solutions over the range 0.0-1.0 mg/L, each standard measured in triplicate, and a fresh curve was generated for every analytical run. Solution concentrations were obtained from the fitted curve as

Table 1. Instrumental operating conditions and method validation parameters for the determination of Cu, Cr and Pb by flame atomic absorption spectrophotometry.

Parameter	Cu	Cr	Pb
Instrumental conditions			
Wavelength (nm)	324.8	357.9	217.0
Spectral slit width (nm)	1.2	0.2	1.2
Lamp type	HCL	HCL	HCL
Lamp current (mA)	2	4	2
Flame	Air-acetylene	Air-acetylene	Air-acetylene
Air/acetylene flow (L/min)	50	100	65
Burner head (mm)	100	100	100
Burner height (mm)	6	8	6
Read time (s)	3	3	3
Validation parameters			
Calibration equation	$y = 0.1650x + 0.0014$	$y = 0.0700x + 0.0008$	$y = 0.0411x + 0.0005$
Determination coefficient (R^2)	0.9999	0.9999	0.9999
Method sensitivity (mg/L)	0.0381	0.0835	0.0708
Limit of detection (mg/L)	0.0354	0.0676	0.0375
Limit of quantification (mg/L)	0.1298	0.2529	0.1431
Equivalent method LOQ (mg/kg) ^a	≈ 3.5	≈ 6.8	≈ 3.8
Spike level (mg/L)	0.2	0.6	0.4
Mean recovery (%)	102.3	100.8	94.7
Precision, RSD (%)	2.9	2.3	1.7

HCL, hollow cathode lamp; RSD, relative standard deviation. Calibration range 0.0-1.0 mg/L, each standard measured in triplicate; a fresh calibration curve was generated for every analytical run. ^aInstrumental limits converted to a sample basis using the 1.0 g / 100 mL digestion factor.

$$x = (y - b) / m \quad (1)$$

where x is the solution concentration of the metal, y the measured absorbance, and m and b the slope and intercept of the calibration line. Concentrations in the original sample were then calculated as

$$\text{Metal (mg/kg)} = (C \times V \times D) / W \quad (2)$$

where C is the curve-derived solution concentration (mg/L), V the total digest volume (mL), D the dilution factor and W the sample mass (g).

2.5. Method Validation and Quality Control

The method was validated for linearity, determination coefficient, limit of detection (LOD), limit of quantification

(LOQ), sensitivity, accuracy and precision using Analytik Jena Aspect LS software. Accuracy was assessed as percent recovery from spiked quality-control samples and precision as the relative standard deviation of triplicate determinations at the 95% confidence level, following Borošová et al. [28] and Al-Weher [29]. Each composite sample was measured in analytical triplicate and results are reported as mean $\pm$ standard deviation. Reagent blanks were run with every batch.

2.6. Pollution and Ecological Risk Indices

The single-metal contamination factor (CF_i) is the ratio of the metal concentration in a given medium to the corresponding regulatory reference value [30]:

$$CF_i = C_{\text{exp}} / C_{\text{re}}^f \quad (3)$$

where C_{exp} is the measured concentration in the vegetable or soil and C_{re}^f the regulatory reference. Vegetable reference values of 40, 2.3 and 0.3 mg/kg and soil reference values of 100, 100 and 50 mg/kg were applied for Cu, Cr and Pb respectively. Bangladesh has not promulgated national soil quality standards for heavy metals in agricultural land; the soil references used here are the FAO/WHO maximum permissible concentrations for agricultural soils as compiled by Ogundele et al. [31], and the vegetable references are the FAO/WHO maximum allowable limits for edible plant tissue. Because the two sets of reference values are established on different criteria and differ by more than two orders of magnitude for Pb, contamination factors calculated for the two matrices are not directly comparable with one another, a point returned to in Section 4.1. Contamination factors were classified as $CF < 1$ (low), $1 \leq CF < 3$ (moderate), $3 \leq CF < 6$ (significant) and $CF \geq 6$ (severe).

The ecological risk factor for a single metal weights the contamination factor by the biological toxic-response factor T_r [30]:

$$ER_i = T_r \times CF_i \quad (4)$$

with $T_r = 5$ for Cu and Pb and 2 for Cr. Classes are $ER_i < 40$ (low), $40 \leq ER_i < 80$ (moderate), $80 \leq ER_i < 160$ (significant), $160 \leq ER_i < 320$ (high) and $ER_i \geq 320$ (severe). The contamination degree is the sum of the contamination factors at a site [32]:

$$CD = \sum CF_i \quad (5)$$

classified as $CD < 8$ (low), $8 \leq CD < 16$ (moderate), $16 \leq CD < 32$ (significant) and $CD \geq 32$ (severe) [33]. The pollution load index is the geometric mean of the contamination factors of all metals measured [34]:

$$PLI = (CF_1 \times CF_2 \times \dots \times CF_n)^{1/n} \quad (6)$$

with $PLI > 1$ indicating overall pollution and $PLI < 1$ indicating none. The bioaccumulation factor is the ratio of the metal concentration in the edible plant part to that in the matched field soil [35]:

$$BF = C_{\text{plant}} / C_{\text{soil}} \quad (7)$$

Values above 1 classify the crop as an accumulator and values below 1 as an excluder, following the plant metal-response strategies defined by Baker [36]. It should be stressed that BF describes transfer relative to the soil concentration only; a BF below 1 does not imply that the crop is safe to eat, because safety is judged against the food regulatory limit rather than against the soil. The potential ecological risk index is the sum of the single-metal ecological risk factors [37]:

$$PERI = \sum ER_i \quad (8)$$

classified as $PERI < 150$ (low), $150 \leq PERI < 300$ (moderate), $300 \leq PERI < 600$ (high) and $PERI \geq 600$ (severe).

2.7. Human Health Risk Assessment

Non-carcinogenic and carcinogenic risks to adult consumers were estimated using the framework of the United States Environmental Protection Agency (USEPA) [38]. The estimated daily intake of each metal was calculated as

$$EDI = (C \times IR \times EF \times ED) / (BW \times AT) \quad (9)$$

where C is the metal concentration in the vegetable (mg/kg), IR the vegetable ingestion rate ($0.1673 \text{ kg person}^{-1} \text{ day}^{-1}$) [16], EF the exposure frequency ($365 \text{ days year}^{-1}$), ED the exposure duration (70 years), BW the body weight (60 kg) and AT the averaging time ($25,550 \text{ days}$) [16, 39]. The hazard quotient for a single metal and the cumulative hazard index for multiple metals were calculated as

$$HQ_i = EDI / RfD_i, HI = \sum HQ_i \quad (10)$$

Oral reference doses of 0.04, 0.003 and $0.0035 \text{ mg kg}^{-1} \text{ day}^{-1}$ were applied for Cu, Cr and Pb respectively [40]. The provenance of these values differs and is stated explicitly. The Cr value is the USEPA IRIS chronic oral reference dose for Cr(VI), for which the agency itself records "low" confidence. The IRIS database contains no verified oral reference dose for copper; the value of $0.04 \text{ mg kg}^{-1} \text{ day}^{-1}$ is the figure the agency derives from its drinking water action level and applies in its Regional Screening Levels, and a recent comprehensive review of the toxicological literature concluded that this value remains the best-supported oral reference dose for copper, protective of both acute and chronic effects in adults and chil-

dren [41]. An HQ or HI above unity does not mean that adverse effects will certainly occur; it indicates that estimated exposure exceeds the reference dose and that a potential risk exists warranting further investigation and, where practicable, exposure reduction [42].

Incremental lifetime cancer risk for a single metal and cumulative carcinogenic health risk for multiple metals were calculated as

$$\text{ILCR}_i = \text{EDI} \times \text{CSF}_i, \text{CHR} = \sum \text{ILCR}_i \quad (11)$$

using cancer slope factors of 0.5 and 0.0085 ($\text{mg kg}^{-1} \text{day}^{-1}$)⁻¹ for Cr and Pb respectively. Risk was classified as no significant carcinogenic risk ($< 10^{-6}$), acceptable risk (10^{-6} - 10^{-4}) or unacceptable risk ($> 10^{-4}$).

2.8. Statistical Analysis

Descriptive statistics were computed in Microsoft Excel 2016. Pollution indices, bioaccumulation factors and health risk estimates were derived from the composite means. Inferential analyses were performed on the 30 composite means for each matrix. Because the design is a fully crossed six-upazila $\times$ five-crop layout with one field composite per cell, differences between sampling areas and between crops were tested by two-way analysis of variance without replication, in which the upazila $\times$ crop interaction mean square serves as the error term. One-way analysis of variance across upazilas, treating the five crops as replicates, was run in parallel so that the two error structures could be compared. The soil-to-crop relationship was examined by Pearson product-moment correlation, by Spearman rank correlation as a distribution-free check, and by ordinary least-squares regression of vegetable concentration on matched soil concentration. The contrast between the anthropogenically influenced upazilas (Cumilla Sadar Dakshin and Cumilla Adarsha Sadar) and the rural reference upazila (Barura) was tested by Welch's unequal-variance *t*-test with Cohen's *d* as the effect size, and monotonic change along the ordered exposure gradient by Spearman correlation against an ordinal exposure rank. All tests were two-tailed and evaluated at $\alpha = 0.05$, and were carried out in Python 3.12 using the SciPy statistics library.

2.9. Ethical Considerations

The study did not involve human participants, human tissue, or animals. Vegetable and soil samples were collected from farmers' fields after verbal permission from the landowners, who were informed about the purpose of sampling. The health-risk component applied published exposure factors to analytical measurements and collected no personal or clinical data. Institutional ethical approval and individual informed consent were therefore not required.

3. Results

3.1. Method Performance

Calibration was linear across the working range for all three metals, with fitted curves $y = 0.1650x + 0.0014$ for Cu, $y = 0.0700x + 0.0008$ for Cr and $y = 0.0411x + 0.0005$ for Pb, each with a determination coefficient of 0.9999 (Supplementary Figure 1). Method sensitivity ranged from 0.0381 to 0.0835 mg/L, instrumental limits of detection from 0.0354 to 0.0676 mg/L and limits of quantification from 0.1298 to 0.2529 mg/L (Table 1). Recoveries from spiked quality-control samples were 94.7-102.3% and relative standard deviations 1.7-2.9%, indicating acceptable accuracy and precision.

These validation figures are instrumental limits expressed in mg/L of digest solution. Applying the 1.0 g / 100 mL digestion factor, they correspond to method limits of approximately 3.5, 6.8 and 3.8 mg/kg for Cu, Cr and Pb respectively. Of the 540 individual readings, 267 were fully quantifiable, 183 fell between the LOD and the LOQ and 90 fell below the instrumental LOD; the latter group consisted almost entirely of Cr readings in vegetable digests, where absolute concentrations are lowest. Vegetable Cr results, and to a lesser extent vegetable Cu results, should therefore be read as semi-quantitative, and every quantity derived from them is flagged accordingly in the tables and figures that follow. No vegetable Pb reading and no soil reading of any metal fell below the LOQ, so the Pb-driven findings that dominate the conclusions of this study rest entirely on fully quantifiable data.

3.2. Copper, Chromium and Lead in Vegetables and Field Soils

Copper. Concentrations in vegetables ranged from 3.92 to 15.98 mg/kg and in matched field soils from 9.78 to 24.93 mg/kg (Table 2, Figure 2). The highest crop value was recorded in chili pepper from Cumilla Sadar Dakshin and the lowest in cauliflower from Barura; the highest soil value occurred in cabbage field soil at Cumilla Sadar Dakshin and the lowest in tomato field soil at Daudkandi. Mean crop accumulation followed the order chili pepper > tomato > cabbage > potato > cauliflower, and mean soil accumulation cabbage > pepper > cauliflower > tomato > potato field soil. Across all 30 composites, mean vegetable Cu was 9.57 mg/kg against a soil mean of 14.99 mg/kg. No sample of either matrix approached its guideline value: the highest vegetable value reached 40% of the 40 mg/kg crop limit and the highest soil value 25% of the 100 mg/kg soil limit. A consistent enrichment was nevertheless observed along the exposure gradient, mean vegetable Cu declining from 12.18 mg/kg in Cumilla Sadar Dakshin to 8.24 mg/kg in rural Barura and mean soil Cu from 19.59 to 12.84 mg/kg over the same sequence.

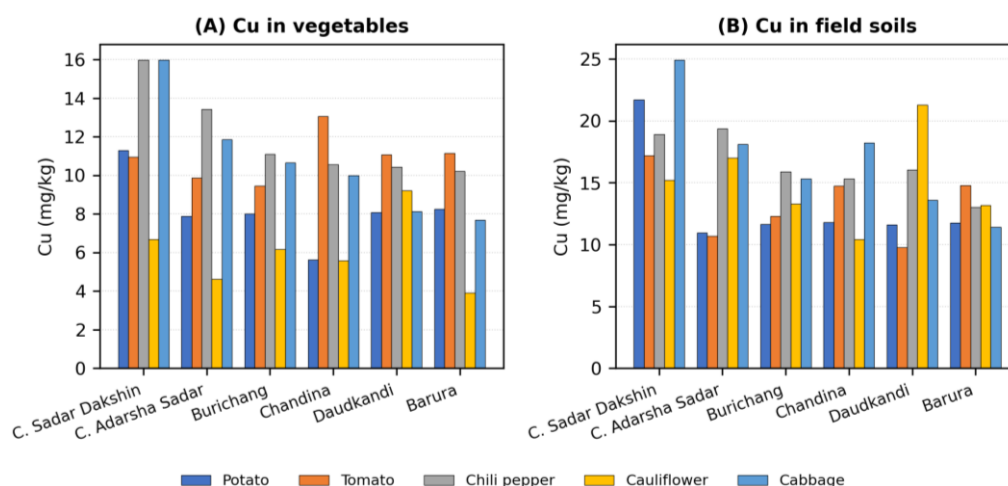


Figure 2. Copper concentrations in vegetables (A) and their matched field soils (B) in six upazilas of Cumilla district. Concentrations are on a dry-weight basis.

Table 2. Concentrations (mg/kg, dry weight) of Cu, Cr and Pb and bioaccumulation factors in five vegetables and their matched field soils across six upazilas of Cumilla district ($n = 6$ upazila composites per crop-matrix combination).

Crop	Matrix	Cu		Cr		Pb	
		Mean $\pm$ SD	Range	Mean $\pm$ SD	Range	Mean $\pm$ SD	Range
Potato	Vegetable	8.19 ± 1.80	5.63-11.29	$1.63 \pm 0.46^\dagger$	1.09-2.27 †	11.78 ± 2.37	8.69-14.85
	Field soil	13.25 ± 4.15	10.97-21.70	41.05 ± 11.88	29.43-63.91	20.54 ± 3.59	16.19-24.89
Tomato	Vegetable	10.93 ± 1.26	9.45-13.07	$1.56 \pm 0.31^\dagger$	1.11-1.91 †	15.34 ± 4.14	11.42-21.90
	Field soil	13.26 ± 2.82	9.78-17.19	30.00 ± 6.22	20.23-36.70	24.14 ± 4.34	19.70-31.59
Chili pepper	Vegetable	11.96 ± 2.30	10.22-15.98	$0.80 \pm 0.21^\dagger$	0.50-1.03 †	12.37 ± 3.77	7.27-18.46
	Field soil	16.44 ± 2.36	13.04-19.36	43.16 ± 12.89	31.08-64.29	19.93 ± 6.20	14.37-30.59
Cauliflower	Vegetable	6.03 ± 1.85	3.92-9.21	$1.85 \pm 0.60^\dagger$	1.25-2.96 †	13.69 ± 2.93	9.13-17.11
	Field soil	15.06 ± 3.76	10.44-21.29	65.80 ± 18.29	37.57-88.00	19.22 ± 5.68	10.84-28.29
Cabbage	Vegetable	10.72 ± 3.01	7.68-15.98	$1.35 \pm 0.43^\dagger$	0.74-1.82 †	14.31 ± 2.29	10.26-16.93
	Field soil	16.94 ± 4.71	11.43-24.93	48.46 ± 9.82	40.31-67.67	21.46 ± 3.31	17.35-26.81
<i>Bioaccumulation factor (vegetable: matched field soil)</i>							
Potato	BF	0.63	0.48-0.72	0.040 †	0.033-0.055 †	0.58	0.48-0.83
Tomato	BF	0.85	0.64-1.13	0.052 †	0.050-0.055 †	0.63	0.54-0.76
Chili pepper	BF	0.73	0.65-0.84	0.019 †	0.015-0.024 †	0.63	0.49-0.86
Cauliflower	BF	0.41	0.27-0.53	0.028 †	0.022-0.034 †	0.73	0.58-0.84
Cabbage	BF	0.63	0.55-0.70	0.028 †	0.017-0.037 †	0.67	0.59-0.76
<i>Maximum allowable limit (FAO/WHO)</i>							
Vegetables	n/a	40		2.3		0.3	
Field soils	n/a	100		100		50	

Values are the mean, standard deviation and range of the six upazila composite means; each composite was measured in

analytical triplicate. BF, bioaccumulation factor, calculated across the six matched crop-soil pairs for that crop. † Semi-

quantitative. All vegetable Cr determinations fell below the method limit of quantification and many below the limit of detection (Section 3.1); these values and every quantity derived from them should be treated as indicative. All vegetable Pb values and all soil values of every metal were fully quantifiable.

Chromium. Concentrations in vegetables ranged from 0.50 to 2.96 mg/kg and in matched soils from 20.23 to 88.00 mg/kg (Table 2, Figure 3). The highest crop value was recorded in cauliflower from Cumilla Sadar Dakshin and the lowest in chili pepper from Barura; cauliflower field soil at Cumilla Sadar Dakshin carried the highest soil value and tomato field soil

at Barura the lowest. Mean crop accumulation followed the order cauliflower > potato > tomato > cabbage > chili pepper, and mean soil accumulation cauliflower > cabbage > pepper > potato > tomato field soil. Chromium showed by far the widest soil-to-crop contrast of the three metals, with a soil mean of 45.7 mg/kg against a vegetable mean of 1.44 mg/kg, a ratio exceeding 30: 1. All 30 field soils remained below the 100 mg/kg FAO/WHO soil guideline, and 29 of the 30 vegetable composites remained below the 2.3 mg/kg vegetable limit; only cauliflower from Cumilla Sadar Dakshin (2.96 mg/kg) exceeded it.

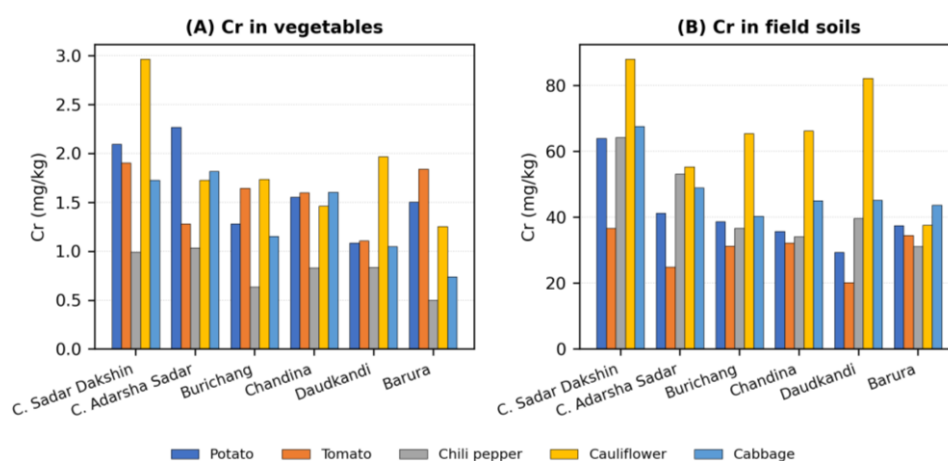


Figure 3. Chromium concentrations in vegetables (A) and their matched field soils (B) in six upazilas of Cumilla district. Vegetable values are semi-quantitative (Section 3.1).

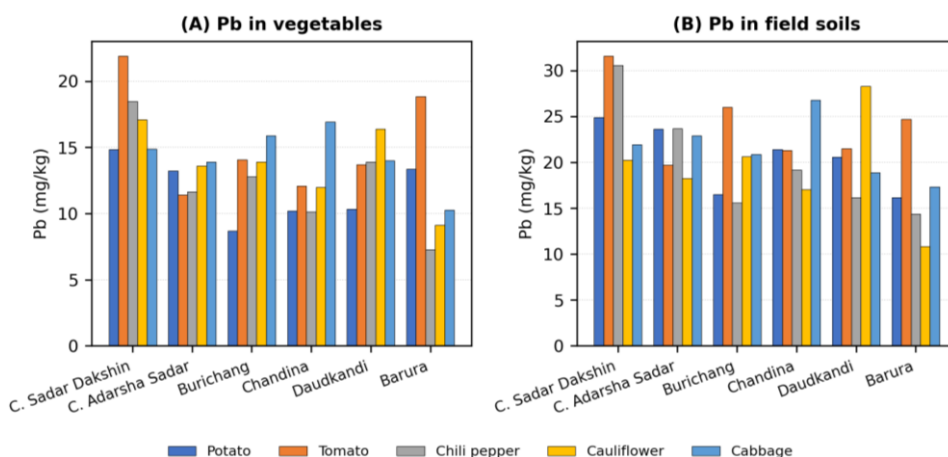


Figure 4. Lead concentrations in vegetables (A) and their matched field soils (B) in six upazilas of Cumilla district. Every vegetable composite exceeded the 0.3 mg/kg maximum allowable limit while every field soil remained below the 50 mg/kg soil guideline.

Lead. Concentrations in vegetables ranged from 7.27 to 21.90 mg/kg and in matched soils from 10.84 to 31.59 mg/kg (Table 2, Figure 4). Tomato from Cumilla Sadar Dakshin carried the highest crop value and chili pepper from Barura the lowest; the corresponding soil extremes were tomato field soil at Cumilla Sadar Dakshin and cauliflower field soil at Barura.

Mean crop accumulation followed the order tomato > cabbage > cauliflower > chili pepper > potato, and mean soil accumulation tomato > cabbage > potato > pepper > cauliflower field soil. Every one of the 30 vegetable composites exceeded the 0.3 mg/kg maximum allowable limit, while every one of the 30 field soils remained below the 50 mg/kg soil guideline.

The exceedance was not marginal: vegetable Pb averaged 13.5 mg/kg on a dry-weight basis, and even the least contaminated sample carried 24 times the food limit. Both crop and soil Pb

declined from the export-processing-zone-affected and traffic-affected upazilas towards rural Barura.

3.3. Contamination Factor, Contamination Degree and Pollution Load Index

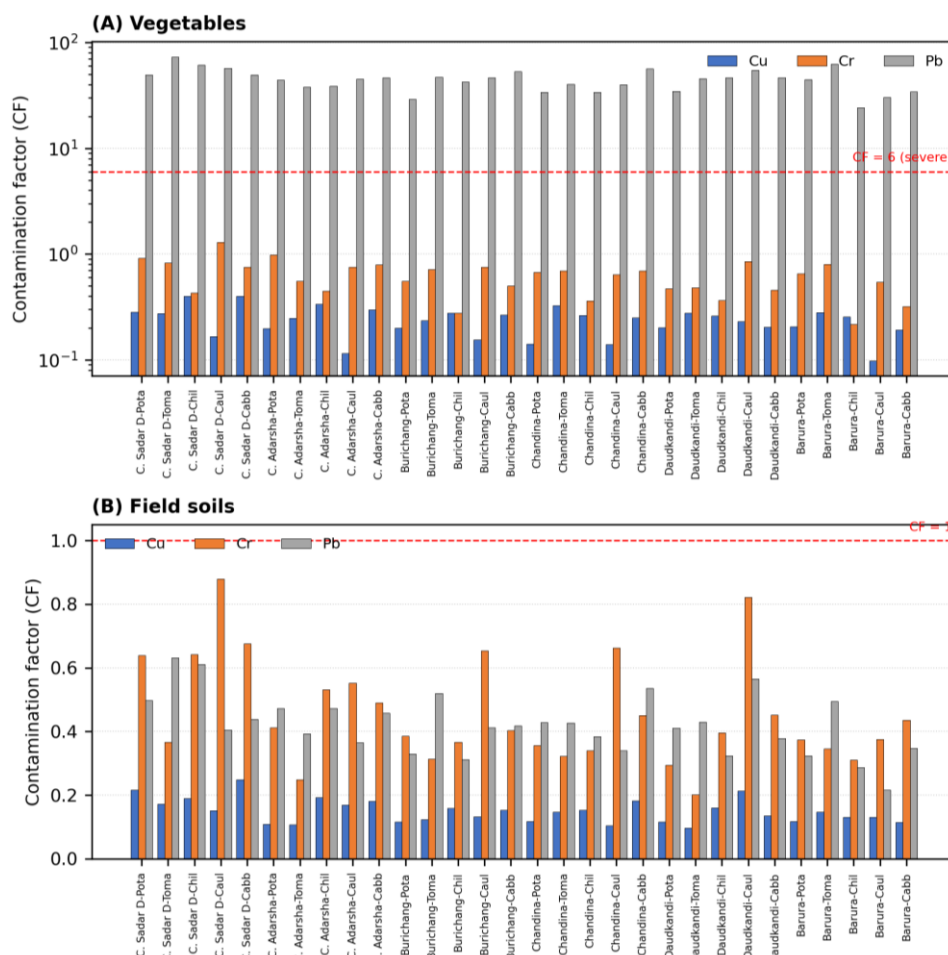


Figure 5. Contamination factors for Cu, Cr and Pb in vegetables (A) and their field soils (B) in six upazilas of Cumilla district. Note the logarithmic scale in panel A.

In vegetables, only Pb produced contamination factors in the severe class, ranging from 24.23 to 73.01 and exceeding the $CF \geq 6$ threshold in every sample (Figure 5A). Contamination factors for Cu ranged from 0.10 to 0.40 and for Cr from 0.22 to 1.29, indicating low to moderate contamination; only cauliflower from Cumilla Sadar Dakshin returned a Cr contamination factor above unity. In field soils, contamination factors were below unity for all three metals (Cu 0.10-0.25, Cr 0.20-0.88 and Pb 0.22-0.63), placing every soil in the low contamination class (Figure 5B). The highest vegetable Pb contamination factors occurred in Cumilla Sadar Dakshin and the lowest in Barura.

Twenty-seven of the 30 vegetable composites fell into the severe contamination degree class ($CD \geq 32$), the remaining three (potato from Burichang at 29.71, and chili pepper at 24.70 and cauliflower at 31.07 from Barura) falling into the

significant class (Supplementary Figure 2). All 30 field soils returned contamination degrees between 0.72 and 1.60, more than an order of magnitude below the $CD < 8$ low-contamination threshold. Tomato from Cumilla Sadar Dakshin recorded the highest value at 74.12. Because the contamination degree is a simple sum of contamination factors and the Pb contamination factor is one to two orders of magnitude larger than those of Cu and Cr, the vegetable contamination degree is effectively a restatement of the Pb burden; Cu and Cr together contributed less than 3% of the total in every sample.

Every vegetable composite returned a pollution load index above unity, ranging from 1.10 to 2.55, indicating overall pollution (Figure 6A). Tomato from Cumilla Sadar Dakshin recorded the highest value (2.55), followed by cabbage from the same upazila (2.46) and tomato from Barura (2.41); chili pep-

per from Barura returned the lowest (1.10). All field soils returned values below unity, from 0.20 to 0.46, indicating no overall pollution (Figure 6B). Aggregated by upazila, mean soil pollution load index declined from 0.394 in Cumilla Sadar

Dakshin through 0.306, 0.294, 0.289 and 0.281 in Cumilla Adarsha Sadar, Daudkandi, Chandina and Burichang to 0.248 in Barura.

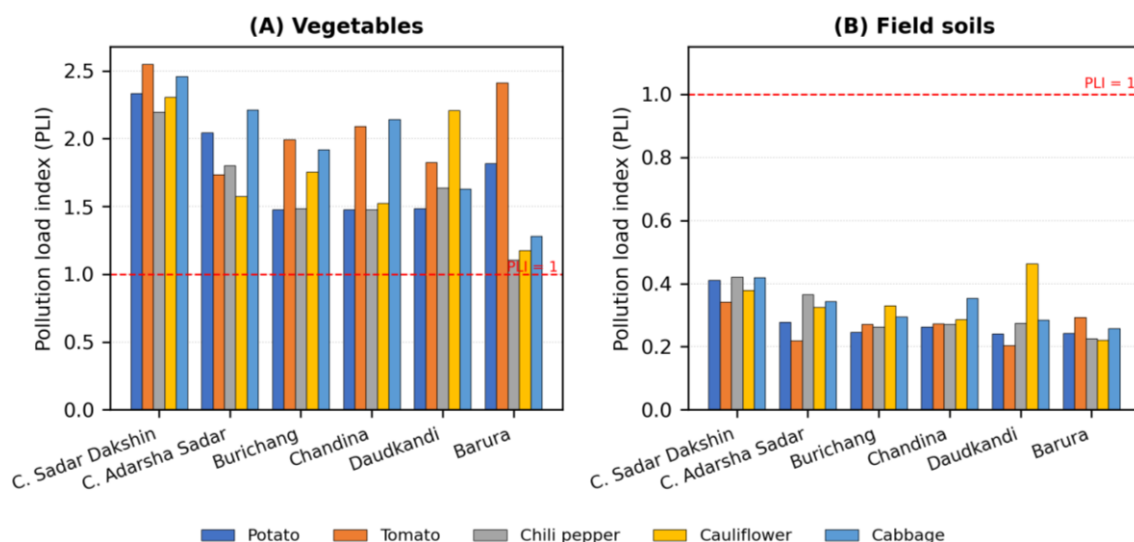


Figure 6. Pollution load index for vegetables (A) and their field soils (B) in six upazilas of Cumilla district. Values above unity indicate overall pollution.

3.4. Bioaccumulation.

Metal concentrations in the edible parts were lower than in the matched soils in almost every crop-soil pair (Table 2, Figure 7). Mean bioaccumulation factors for Cu were highest in tomato (0.85) and lowest in cauliflower (0.41); for Cr highest in tomato (0.05) and lowest in chili pepper (0.02); and for Pb highest in cauliflower (0.73) and lowest in potato (0.58). Across all 30 pairs, values ranged from 0.27 to 1.13 for Cu,

0.015 to 0.055 for Cr and 0.48 to 0.86 for Pb. All values fell below unity with a single exception: tomato grown at Daudkandi returned a Cu bioaccumulation factor of 1.13 on an unusually low-Cu soil (9.78 mg/kg), classifying that crop as an accumulator. Chromium bioaccumulation factors were one to two orders of magnitude lower than those of Cu and Pb in every crop. Because many vegetable Cr readings fell between the instrumental LOD and LOQ, these particular ratios should be treated as indicative rather than exact.

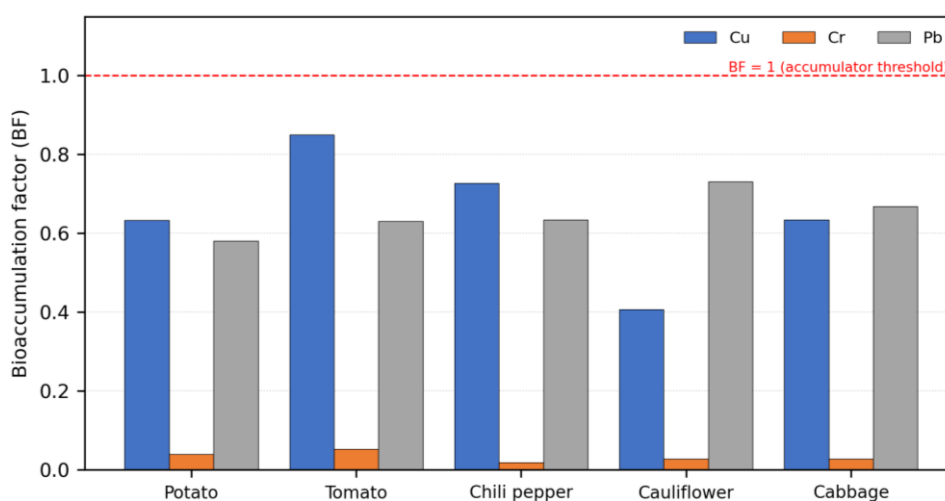


Figure 7. Bioaccumulation factors for Cu, Cr and Pb in five vegetables of Cumilla district. Chromium values are semi-quantitative (Section 3.1).

3.5. Ecological Risk.

All 30 field soils posed low ecological risk for every metal, with single-metal ecological risk factors far below the threshold of 40 (Supplementary Figure 3). Values ranged from 0.49 to 1.25 for Cu (mean 0.75), 0.40 to 1.76 for Cr (mean 0.91) and 1.08 to 3.16 for Pb (mean 2.11). Lead therefore posed the highest ecological risk factor, followed by chromium and copper. Potential ecological risk indices for individual field soils

ranged from 2.50 to 5.54, the highest being cauliflower field soil at Daudkandi (5.54) and chili pepper field soil at Cumilla Sadar Dakshin (5.29) (Figure 8). Summed across the five matched field soils in each upazila, cumulative values ranged from 15.24 in Barura to 24.23 in Cumilla Sadar Dakshin, following the order Cumilla Sadar Dakshin > Cumilla Adarsha Sadar > Daudkandi > Chandina > Burichang > Barura. All values fell far below the low-risk ceiling of 150.

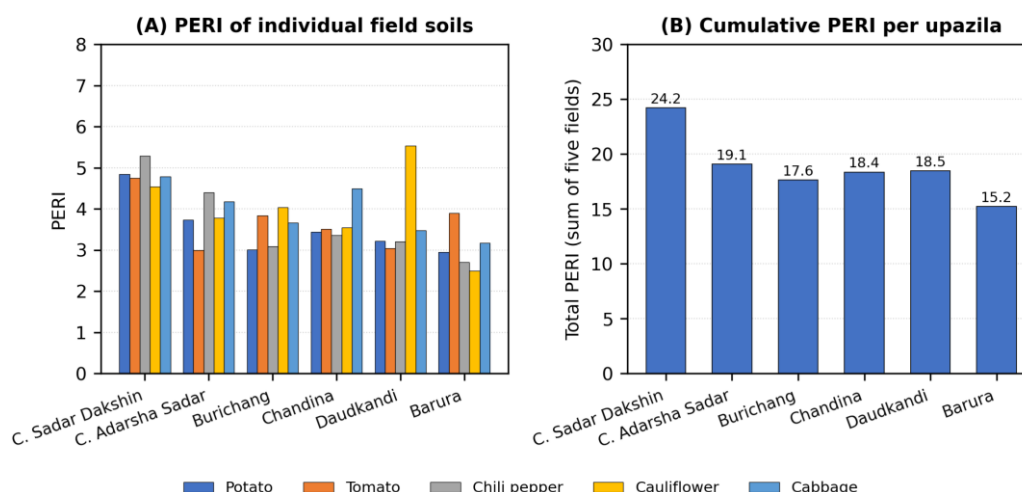


Figure 8. Potential ecological risk index for multiple heavy metals in vegetable field soils of six upazilas of Cumilla district. All values fall far below the low-risk threshold of 150.

3.6. Human Health Risk.

Estimated daily intakes ranged from 0.011 to 0.045 mg kg⁻¹ BW day⁻¹ for Cu, 0.0014 to 0.0083 for Cr and 0.020 to 0.061 for Pb. Copper hazard quotients exceeded unity in only two of the 30 samples, chili pepper (1.11) and cabbage (1.11) from Cumilla Sadar Dakshin, with all other values falling between 0.27 and 0.94 (Table 3). Chromium hazard quotients exceeded

unity in 22 of the 30 samples, ranging from 0.46 to 2.76, with cauliflower consistently highest; the eight samples remaining within the safe limit were chili pepper from all six upazilas and cabbage from Daudkandi and Barura. Lead hazard quotients ranged from 5.79 to 17.45 in every sample, that is 6 to 17 times the safe level, reflecting the combination of high crop concentrations and a very low reference dose. Lead alone accounted for 78-90% of the hazard index of every sample.

Table 3. Non-carcinogenic health risk to adult consumers: hazard quotients (HQ) for individual metals and cumulative hazard index (HI) for vegetables produced in six upazilas of Cumilla district.

Sampling area	Metric	Potato	Tomato	Chili pepper	Cauliflower	Cabbage	Σ
Cumilla Sadar Dakshin	HQ Cu	0.79	0.76	1.11	0.47	1.11	4.24
	HQ Cr†	1.95	1.77	0.92	2.76	1.60	9.00
	HQ Pb	11.83	17.45	14.71	13.63	11.86	69.48
	HI	14.57	19.98	16.74	16.86	14.57	82.72
Cumilla Adarsha Sadar	HQ Cu	0.55	0.69	0.94	0.32	0.83	3.33
	HQ Cr†	2.11	1.19	0.96	1.60	1.69	7.55
	HQ Pb	10.53	9.10	9.29	10.82	11.08	50.82

Sampling area	Metric	Potato	Tomato	Chili pepper	Cauliflower	Cabbage	Σ
Burichang	HI	13.19	10.98	11.19	12.74	13.60	61.70
	HQ Cu	0.56	0.66	0.77	0.43	0.74	3.16
	HQ Cr†	1.19	1.53	0.59	1.61	1.07	5.99
	HQ Pb	6.92	11.20	10.19	11.08	12.65	52.04
Chandina	HI	8.67	13.39	11.55	13.12	14.46	61.20
	HQ Cu	0.39	0.91	0.74	0.39	0.70	3.13
	HQ Cr†	1.44	1.49	0.77	1.36	1.49	6.55
	HQ Pb	8.13	9.62	8.07	9.54	13.49	48.85
Daudkandi	HI	9.96	12.02	9.58	11.29	15.68	58.53
	HQ Cu	0.56	0.77	0.73	0.64	0.57	3.27
	HQ Cr†	1.01	1.03	0.78	1.83	0.97	5.62
	HQ Pb	8.24	10.92	11.08	13.06	11.16	54.46
Barura	HI	9.81	12.72	12.59	15.53	12.70	63.35
	HQ Cu	0.57	0.78	0.71	0.27	0.54	2.87
	HQ Cr†	1.40	1.71	0.46	1.16	0.69	5.42
	HQ Pb	10.65	15.02	5.79	7.27	8.18	46.91
	HI	12.62	17.51	6.96	8.70	9.41	55.20

HQ > 1 indicates that estimated intake exceeds the oral reference dose and that a potential non-carcinogenic risk exists warranting further investigation; it does not mean that harm will certainly occur. HI is the sum of the three metal-specific hazard quotients for a given crop; Σ is the sum across the five vegetables. Reference doses: Cu 0.04, Cr 0.003, Pb 0.0035 mg kg⁻¹ day⁻¹ [40]. Estimates are based on dry-weight concentrations; see Table 7 and Section 4.4 for the fresh-weight equivalents. †Semi-quantitative (Section 3.1).

Cumulative hazard indices exceeded unity in all 30 samples. Per-vegetable values ranged from 6.97 for chili pepper in Barura to 19.99 for tomato in Cumilla Sadar Dakshin, and summed across the five vegetables the total hazard index by upazila ranged from 55.20 in Barura to 82.72 in Cumilla Sadar Dakshin, following the order Cumilla Sadar Dakshin > Daudkandi > Cumilla Adarsha Sadar > Burichang > Chandina > Barura. The range across the district is narrow: the most exposed upazila carried only 1.5 times the burden of the least

exposed.

Incremental lifetime cancer risk for Cr exceeded the 10⁻⁴ unacceptable threshold in all 30 samples, with values from 6.97 × 10⁻⁴ to 4.13 × 10⁻³, and for Pb in all 30 samples, from 1.72 × 10⁻⁴ to 5.19 × 10⁻⁴ (Table 4). Chromium contributed approximately 80-90% of the cumulative cancer risk in most samples despite Pb dominating the non-carcinogenic risk, a reversal arising from the sixty-fold difference in cancer slope factors. Cumulative carcinogenic health risk exceeded 10⁻⁴ in every sample, with per-vegetable values from 8.69 × 10⁻⁴ (chili pepper, Barura) to 4.54 × 10⁻³ (cauliflower, Cumilla Sadar Dakshin). Summed across the five vegetables, values ranged from 9.53 × 10⁻³ in Barura to 1.56 × 10⁻² in Cumilla Sadar Dakshin, following the order Cumilla Sadar Dakshin > Cumilla Adarsha Sadar > Chandina > Burichang > Daudkandi > Barura. These chromium-derived figures are conservative upper bounds for the reasons set out in Section 4.5.

Table 4. Carcinogenic health risk to adult consumers: incremental lifetime cancer risk (ILCR) for individual metals and cumulative carcinogenic health risk (CHR) for vegetables produced in six upazilas of Cumilla district.

Sampling area	Metric	Potato	Tomato	Chili pepper	Cauliflower	Cabbage	Σ
Cumilla Sadar Dakshin	ILCR Cr†	2.92E-03	2.66E-03	1.38E-03	4.13E-03	2.41E-03	1.35E-02
	ILCR Pb	3.52E-04	5.19E-04	4.37E-04	4.06E-04	3.53E-04	2.07E-03

Sampling area	Metric	Potato	Tomato	Chili pepper	Cauliflower	Cabbage	Σ
Cumilla Adarsha Sadar	CHR	3.27E-03	3.18E-03	1.82E-03	4.54E-03	2.76E-03	1.56E-02
	ILCR Cr†	3.16E-03	1.79E-03	1.44E-03	2.41E-03	2.53E-03	1.13E-02
	ILCR Pb	3.13E-04	2.71E-04	2.76E-04	3.22E-04	3.30E-04	1.51E-03
Burichang	CHR	3.47E-03	2.06E-03	1.72E-03	2.73E-03	2.86E-03	1.28E-02
	ILCR Cr†	1.79E-03	2.29E-03	8.86E-04	2.42E-03	1.61E-03	9.00E-03
	ILCR Pb	2.06E-04	3.33E-04	3.03E-04	3.30E-04	3.76E-04	1.55E-03
Chandina	CHR	2.00E-03	2.62E-03	1.19E-03	2.75E-03	1.99E-03	1.05E-02
	ILCR Cr†	2.17E-03	2.23E-03	1.16E-03	2.04E-03	2.23E-03	9.83E-03
	ILCR Pb	2.42E-04	2.86E-04	2.40E-04	2.84E-04	4.01E-04	1.45E-03
Daudkandi	CHR	2.41E-03	2.52E-03	1.40E-03	2.32E-03	2.63E-03	1.13E-02
	ILCR Cr†	1.51E-03	1.55E-03	1.17E-03	2.74E-03	1.46E-03	8.43E-03
	ILCR Pb	2.45E-04	3.25E-04	3.29E-04	3.89E-04	3.32E-04	1.62E-03
Barura	CHR	1.76E-03	1.88E-03	1.50E-03	3.13E-03	1.79E-03	1.00E-02
	ILCR Cr†	2.10E-03	2.56E-03	6.97E-04	1.75E-03	1.03E-03	8.14E-03
	ILCR Pb	3.17E-04	4.47E-04	1.72E-04	2.16E-04	2.43E-04	1.40E-03
	CHR	2.42E-03	3.01E-03	8.69E-04	1.97E-03	1.27E-03	9.53E-03

ILCR or CHR < 10^{-6} , no significant carcinogenic risk; 10^{-6} – 10^{-4} , acceptable; > 10^{-4} , unacceptable. CHR is the sum of the two metal-specific risks for a given crop; Σ is the sum across the five vegetables. Cancer slope factors: Cr 0.5, Pb 0.0085 ($\text{mg kg}^{-1} \text{ day}^{-1}$)⁻¹. Estimates are based on dry-weight concentrations; see Table 7 and Section 4.4. †Conservative upper bound: the Cr(VI) cancer slope factor was applied to total Cr without speciation, and the underlying concentrations are semi-quantitative (Sections 3.1 and 4.5).

3.7. Spatial and Crop-related Variation

Two-way analysis of variance without replication identified

crop identity as the stronger determinant for chromium and copper (Table 5). Crop effects were highly significant for vegetable Cu ($F(4,20) = 10.40$, $p = 0.0001$), vegetable Cr ($F(4,20) = 8.21$, $p = 0.0004$) and soil Cr ($F(4,20) = 12.36$, $p < 0.0001$), but not significant for vegetable Pb ($p = 0.198$), soil Cu ($p = 0.157$) or soil Pb ($p = 0.320$). Sampling area produced significant differences for vegetable Cu ($p = 0.049$), vegetable Cr ($p = 0.015$), vegetable Pb ($p = 0.046$), soil Cu ($p = 0.037$) and soil Cr ($p = 0.003$), and fell just short of significance for soil Pb ($p = 0.064$). When the same data were analysed by one-way analysis of variance across upazilas, treating the five crops as replicates, no metal reached significance in either matrix ($p = 0.052$ to 0.405).

Table 5. Two-way and one-way analysis of variance for Cu, Cr and Pb concentrations in vegetables and their field soils across six upazilas and five crops.

Matrix	Metal	Two-way ANOVA: upazila			Two-way ANOVA: crop			One-way ANOVA: upazila			CV (%)
		F	p	Sig.	F	p	Sig.	F	p	Sig.	
Vegetable	Cu	2.73	0.0489	*	10.40	0.0001	***	1.06	0.4049	ns	19.2
Vegetable	Cr	3.74	0.0150	*	8.21	0.0004	***	1.70	0.1736	ns	23.6
Vegetable	Pb	2.77	0.0463	*	1.66	0.1979	ns	2.50	0.0589	ns	20.3
Field soil	Cu	2.96	0.0368	*	1.86	0.1571	ns	2.59	0.0519	ns	20.7
Field soil	Cr	5.33	0.0029	**	12.36	<0.0001	***	1.84	0.1429	ns	20.0

Matrix	Metal	Two-way ANOVA: upazila			Two-way ANOVA: crop			One-way ANOVA: upazila			CV (%)
		F	p	Sig.	F	p	Sig.	F	p	Sig.	
Field soil	Pb	2.51	0.0643	ns	1.26	0.3201	ns	2.41	0.0665	ns	19.8

Two-way ANOVA without replication: upazila df = 5, crop df = 4, error df = 20. One-way ANOVA across upazilas: df = 5, 24. CV, coefficient of variation of the two-way error term. Significance: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; ns, not significant.

All three metals showed positive and statistically significant soil-to-crop associations across the 30 matched pairs (Table 6, Figure 9). Lead gave the strongest relationship ($r = +0.748$, $p < 0.0001$; $\rho = +0.676$, $p < 0.0001$), with soil Pb explaining 56% of the variance in vegetable Pb. Copper followed ($r = +0.576$, $p = 0.0009$; $R^2 = 0.331$) and chromium was weakest but still significant ($r = +0.531$, $p = 0.0025$; $R^2 =$

0.282). The agreement between parametric and rank-based coefficients indicates that these relationships are not artefacts of a small number of influential points. Regression slopes differed markedly between metals: vegetable concentration rose by 0.51 mg/kg per 1 mg/kg increase in soil Pb and by 0.45 mg/kg for Cu, but by only 0.017 mg/kg for Cr. Intercepts were substantially positive for Pb (+2.75 mg/kg) and Cu (+2.76 mg/kg).

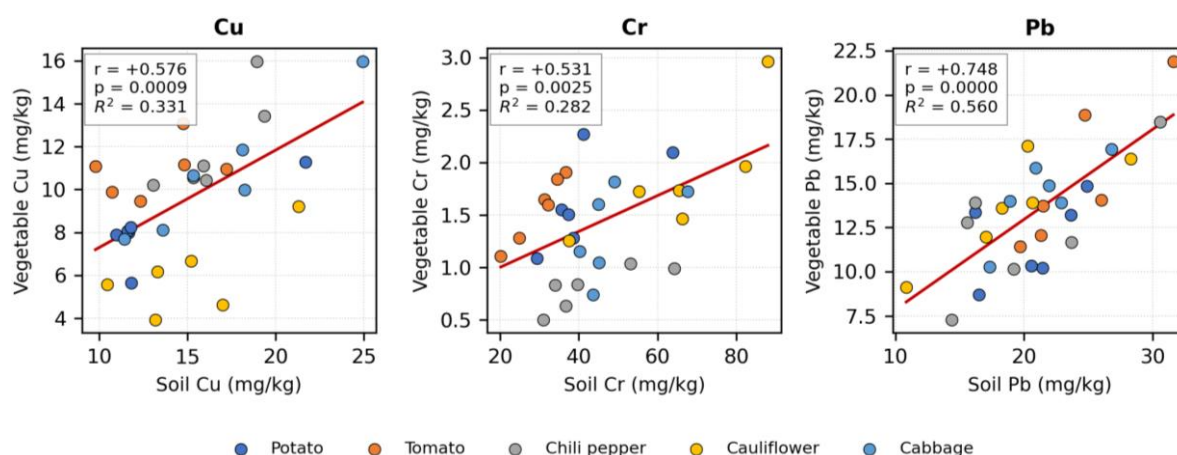


Figure 9. Relationship between matched field soil and vegetable concentrations of Cu, Cr and Pb across 30 crop-soil pairs, with fitted ordinary least-squares regression lines.

Table 6. Soil-vegetable correlation and regression, industrial-versus-rural contrast, and monotonic trend across the exposure gradient for Cu, Cr and Pb.

Metal	Pearson		Spearman		OLS regression			Welch <i>t</i>		Trend ρ	
	<i>r</i>	<i>p</i>	ρ	<i>p</i>	Slope	Intercept	<i>R</i> ²	Soil	Veg.	Soil	Veg.
Cu	+0.576	0.0009***	+0.552	0.0015**	0.454	+2.76	0.331	3.03*	1.51 ns	+0.448*	+0.319 ns
Cr	+0.531	0.0025**	+0.393	0.0318*	0.017	+0.66	0.282	2.92*	1.99 ns	+0.409*	+0.369*
Pb	+0.748	<0.0001***	+0.676	<0.0001***	0.510	+2.75	0.560	2.64*	1.46 ns	+0.468**	+0.470**

Correlation and regression are across all 30 matched crop-soil pairs; the regression is of vegetable concentration on matched soil concentration. Contrast *t*, Welch unequal-variance *t*-test comparing the two anthropogenically influenced upazilas (Cumilla Sadar Dakshin and Cumilla Adarsha Sadar, $n = 10$) against the rural reference upazila (Barura, $n = 5$). Trend ρ , Spearman correlation against an ordinal exposure rank from 1 (Barura) to 6 (Cumilla Sadar Dakshin), $n = 30$. Significance: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; ns, not significant.

Contrasting the two anthropogenically influenced upazilas against the rural reference, soil differences were significant for all three metals: Cu was 35.6% higher (17.41 versus 12.84 mg/kg; $t = 3.03$, $p = 0.011$, $d = 1.41$), Cr 47.7% higher (54.42 versus 36.85 mg/kg; $t = 2.92$, $p = 0.014$, $d = 1.35$) and Pb 42.2% higher (23.74 versus 16.69 mg/kg; $t = 2.64$, $p = 0.033$, $d = 1.48$), all effect sizes exceeding the conventional threshold for a large effect. In vegetables none of the three contrasts reached significance despite differences of 28-53% in the same direction (Cu $p = 0.159$, Cr $p = 0.079$, Pb $p = 0.193$), although effect sizes remained large ($d = 0.79$ -1.07). The Spearman trend test across the full ordered gradient was significant for vegetable Cr ($\rho = +0.369$, $p = 0.045$), vegetable Pb ($\rho = +0.470$, $p = 0.009$) and all three metals in soil ($p = 0.009$ -0.025), but not for vegetable Cu ($p = 0.086$).

4. Discussion

4.1. Soil Compliance Coexisting with Crop Exceedance

The central result of this survey is a systematic divergence between the two matrices. Every one of the 30 field soils complied with FAO/WHO agricultural soil guidelines for all three metals, and every one of the 30 vegetable composites exceeded the maximum allowable limit for Pb. A soil-based regulatory screen would have classified every field in the district as clean; a food-based screen classified every crop as non-compliant. This directly contradicts the hypothesis under test, namely that soil concentration can serve as a reliable proxy for crop contamination, and it is the finding with the clearest policy consequence.

The divergence is arithmetically straightforward once the reference values are inspected. A soil carrying 20 mg/kg Pb sits at 40% of the 50 mg/kg soil guideline and is classified as low contamination, yet a crop grown in it carrying 10 mg/kg Pb sits at more than 30 times the 0.3 mg/kg food limit and is classified as severe. The two criteria differ by more than two orders of magnitude and were established for different protective purposes: soil function and ecosystem protection in one case, consumer protection in the other. The divergence is therefore not an artefact to be explained away but a structural feature of the regulatory architecture, and it is not unique to Cumilla. Bushra et al. [21] reported the same soil-compliant, crop-exceeding pattern for brinjal in a major Bangladeshi production belt, Kumar et al. [22] observed it around a lead-acid battery recycling facility, and Lima et al. [24] documented crop Pb declining with distance from a point source while the corresponding soils remained within guideline values throughout the transect. Liu et al. [43], in a multi-medium analysis of soil-vegetable systems, likewise concluded that risk characterization based on soil concentration alone systematically misclassifies dietary exposure. What the present

data add is that the pattern holds across an entire district, in five botanically diverse crops, and in the rural reference upazila as much as in the industrial one.

The regression results reinforce the point quantitatively. Although soil Pb was the strongest single predictor of crop Pb of any metal examined, it explained only 56% of the variance, leaving 44% attributable to factors not captured by soil concentration. This is consistent with the long-recognized observation that root uptake is governed less by total soil metal than by the soluble and exchangeable fraction, which varies with soil pH, texture, organic matter, fertilizer regime and crop physiological stage [44, 45]. Soil analysis is therefore a real but incomplete predictor of crop contamination and cannot substitute for direct analysis of the edible portion. The absence of national soil quality criteria for heavy metals in Bangladeshi agricultural land, noted by Kibria et al. [46] more than a decade ago and still unresolved, compounds the problem: in the absence of domestic standards, screening currently defaults to international soil guidelines that were never designed to protect the food chain.

4.2. Metal-selective Soil-to-crop Transfer

Bioaccumulation factors below unity in 29 of 30 crop-soil pairs indicate that all five crops behave as excluders in the sense of Baker [36], translocating only a fraction of the soil metal burden to their consumable parts. Transfer was, however, strongly metal-selective. Chromium gave bioaccumulation factors one to two orders of magnitude lower than Cu and Pb in every crop, and a regression slope roughly thirty times shallower. The mechanistic explanation is well established: chromium in aerated, near-neutral floodplain soils exists predominantly as sparingly soluble Cr(III) oxides and hydroxides, which are poorly available for root uptake and are further restricted at the root endodermis, so translocation to shoots and fruits is minimal [47, 48]. Cui et al. [49] reached a comparable conclusion for leafy vegetables grown on mine-affected soils, where transfer to edible tissue differed by more than an order of magnitude between elements at similar soil concentrations. The present data are consistent with this: all 30 field soils carried substantial Cr, a mean of 45.7 mg/kg, while 29 of 30 crops remained below the vegetable limit.

This finding differs from that reported for Bogura district by Samma et al. [27], where vegetable Cr exceeded the WHO limit across the study area, and the difference is worth emphasizing rather than glossing over: it indicates that Cr in Cumilla vegetable fields is largely lithogenic and only weakly mobile, a source assignment consistent with the geogenic Cr and Ni signatures identified by Alam et al. [17] in Bangladeshi peri-urban topsoils. The single exceedance recorded in a *Brassica* crop grown in the export-processing-zone-affected upazila nevertheless indicates that the margin is not large for that crop group, in line with the greater metal accumulation reported for leafy and flower vegetables relative to fruit and tuber crops

[45, 50]. Practices that can enrich soil Cr, including the use of tannery-derived or industrially contaminated organic amendments, therefore warrant attention in Cumilla Sadar Dakshin.

Copper and lead, by contrast, gave bioaccumulation factors in the 0.4-0.9 range. For copper this reflects its status as an essential micronutrient that is actively taken up and homeostatically regulated in plant tissue [10, 51], which also explains why crop values remained comfortably below the guideline even where soil supply was elevated. This is consistent with Bigdeli and Seilsepour [14], who found no Cu contamination at sites where Pb and Cd exceeded permissible levels, and with Bangladeshi surveys in which Cu was the least problematic metal examined [17, 52, 53]. The modest enrichment of Cu along the exposure gradient observed here, from 12.18 mg/kg in the crop and 19.59 mg/kg in the soil at Cumilla Sadar Dakshin to 8.24 and 12.84 mg/kg respectively at Barura, matches the urbanization gradient in cropland metal enrichment described by Rezapour et al. [2] and probably reflects the combined contribution of Cu-based fungicides in intensive vegetable production and industrial and vehicular inputs near the export processing zone.

Lead requires a different explanation. Two features of the data point beyond root uptake. First, the highest crop values occurred in tomato and cabbage, crops with large exposed surfaces harvested close to the ground, rather than in the tuber crop, and Pb transfer to cauliflower and cabbage exceeded that to potato. Second, the regression intercept for Pb was substantially positive at +2.75 mg/kg, implying a crop burden that persists as soil concentration approaches zero. Both observations are consistent with foliar deposition, in which Pb reaching edible surfaces as roadside and kiln-derived particulate matter bypasses the soil-root barrier entirely [13, 54]. Independent support for this pathway in the Bangladeshi context comes from Aktaruzzaman et al. [55], who found Pb and Cd to be the dominant accumulators in leafy vegetables grown along the Dhaka-Aricha highway, from Alamgir et al. [56], who attributed elevated metal loads in Chittagong roadside soils to vehicular sources, and from Khan et al. [53], whose source apportionment identified traffic emissions and agrochemical inputs as jointly explaining most of the variance in edible-tissue Pb across Bangladeshi cropland. Sharma and Prasad [50] reported the same highway-proximity effect for Pb and Cd in Indian vegetable crops. The interpretation must nevertheless be qualified, because the regression intercepts lie outside the range of soil concentrations actually sampled; a study including genuinely low-Pb reference soils would be required to test it properly. The absence of a significant crop effect on Pb in either matrix supports the same reading: Pb does not discriminate strongly between crops, as would be expected of a diffuse deposition-driven source affecting all fields rather than a crop-specific uptake pathway.

4.3. Divergence of Ecological and Dietary Risk

Ecological risk was uniformly low. All 30 soils returned

single-metal ecological risk factors below 3.2 against a low-risk ceiling of 40, and all six upazilas returned potential ecological risk indices below 25 against a ceiling of 150. This places the vegetable fields of Cumilla in the same low-risk category that Kabir et al. [39] reported for most rice field soils near the Buriganga River, and well below the values Islam et al. [32] recorded for urban land-use soils elsewhere in Bangladesh. Lead nevertheless posed the highest ecological risk factor of the three metals despite chromium being present at roughly twice the concentration, because Pb combines the higher toxic-response factor of 5 with a stricter soil reference value. As Ramos-Miras et al. [57] emphasize, it is this weighting rather than absolute concentration that governs the ecological risk index. This ordering differs from that reported for Bogura by Samma et al. [27], where copper ranked highest, which follows directly from the different relative abundances of the three metals in the two districts.

The 59% increase in cumulative potential ecological risk index from rural Barura to export-processing-zone-affected Cumilla Sadar Dakshin traces a clear anthropogenic gradient, and although the absolute values are far from any regulatory concern they provide a useful baseline against which future change can be measured. It must be stressed, however, that a low ecological risk index describes risk to the soil system and says nothing about dietary risk to consumers. In this study the two diverge sharply: soils that are ecologically unremarkable supported crops that failed every dietary risk criterion applied. Kabir et al. [39] reported the same divergence for the soil-rice system near the Buriganga, where ecological risk was low while the metal pollution index of the field soils and the associated dietary exposure remained of concern.

4.4. Expression Basis and Its Effect on Regulatory Comparison and Risk Estimates

The concentrations reported above are expressed on a dry-weight basis, since vegetable samples were oven-dried to constant weight before digestion. The FAO/WHO maximum allowable limits and the ingestion rate used in the exposure model, by contrast, refer to vegetables as consumed, that is on a fresh-weight basis. Direct comparison of dry-weight concentrations with fresh-weight criteria therefore overstates both the exceedance factor and the estimated dietary intake, and this must be made explicit rather than left implicit. The distinction is frequently left unstated in the regional literature, which complicates cross-study comparison: national surveys reporting Pb in Bangladeshi fruits and vegetables on a fresh-weight basis [15, 58] are not directly comparable with dry-weight surveys without knowledge of moisture content. Because moisture content was not determined for the samples analysed here, a sensitivity analysis was conducted using standard published dry-matter fractions for the five crops (Table 7).

Table 7. Sensitivity of regulatory comparison and health risk estimates to the expression basis: dry-weight results as measured, and fresh-weight equivalents obtained using published dry-matter fractions.

Crop	Dry matter (%)	Pb (mg/kg)		CF for Pb		Hazard index		Cancer risk (CHR)	
		dw	fw	dw	fw	dw	fw	dw	fw
Potato	20.7	11.78	2.44	39.3	8.1	11.5	2.37	2.56E-03	5.28E-04
Tomato	5.5	15.34	0.84	51.1	2.8	14.4	0.79	2.55E-03	1.40E-04
Chili pepper	12.0	12.37	1.48	41.2	5.0	11.4	1.37	1.42E-03	1.69E-04
Cauliflower	7.9	13.69	1.08	45.6	3.6	13.0	1.03	2.91E-03	2.29E-04
Cabbage	7.8	14.31	1.12	47.7	3.7	13.4	1.05	2.22E-03	1.73E-04

Values are means across the six upazilas. dw, dry weight; fw, fresh weight; CF, contamination factor against the 0.3 mg/kg FAO/WHO maximum allowable limit for Pb in vegetables. Fresh-weight concentrations were obtained by multiplying dry-weight concentrations by the dry-matter fraction shown; moisture content was not determined for the samples analysed here, so the fresh-weight column is an assumption-based sensitivity analysis rather than a measured result. Corresponding fresh-weight means for Cu were 1.70, 0.60, 1.44, 0.48 and 0.84 mg/kg and for Cr 0.34, 0.09, 0.10, 0.15 and 0.11 mg/kg for potato, tomato, chili pepper, cauliflower and cabbage respectively, all far below their maximum allowable limits of 40 and 2.3 mg/kg.

On a fresh-weight basis, mean Pb concentrations fall to 0.84–2.44 mg/kg, still 2.8 to 8.1 times the 0.3 mg/kg maximum allowable limit in all five crops. Copper falls to 0.48–1.70 mg/kg, far below the 40 mg/kg limit, and chromium to 0.086–0.34 mg/kg, so the single Cr exceedance recorded in cauliflower on a dry-weight basis disappears on a fresh-weight basis. Recalculated hazard indices fall from 6.97–19.99 to 0.79–2.37, remaining above unity in four of the five crops, and cumulative cancer risk falls from 8.69×10^{-4} – 4.54×10^{-3} to 1.40×10^{-4} – 5.28×10^{-4} , remaining above the 10^{-4} unacceptable threshold in all five. The fresh-weight hazard indices are of the same order as those reported for Bangladeshi foodstuffs by Kormoker et al. [59] and for vegetables of the adjoining Noakhali region by Hossen et al. [26], which supports the internal consistency of the converted estimates.

Two conclusions follow. First, the magnitude of every risk estimate reported in Sections 3.3 and 3.6 is inflated by roughly nine-fold relative to a fresh-weight calculation, and the dry-weight figures should be read as such. Second, and more importantly, every qualitative conclusion of the study survives the conversion: Pb exceeds the food limit in all crops, hazard indices exceed unity in most, cumulative cancer risk exceeds the acceptable threshold in all, and Cu remains unproblematic throughout. Only the Cr exceedance is basis-dependent. Reporting moisture content and expressing results on both bases

should be regarded as a minimum requirement for future surveys of this kind, and the absence of measured moisture data is a limitation of the present work.

4.5. Uncertainty in the Chromium Cancer Risk

Chromium and lead are both classified as carcinogenic to humans by the International Agency for Research on Cancer, and chronic low-level exposure to either is associated with a range of malignancies as well as with renal, haematological and neurological injury [60, 61]. The cancer slope factor of $0.5 \text{ (mg kg}^{-1} \text{ day}^{-1})^{-1}$ applied here to chromium is, however, derived specifically for hexavalent chromium, whereas this study measured total chromium without speciation. Chromium in the aerated, near-neutral floodplain soils sampled here is predominantly trivalent, which is very much less toxic and is not classified as an oral carcinogen. Applying the Cr(VI) slope factor to total Cr therefore overestimates the true carcinogenic risk, potentially by a large margin, a caveat Infante et al. [47] raised explicitly when assessing Cr and Ni in rice grown on serpentine soils. This bears most heavily on precisely the metal that dominates the result: because Cr contributes 80–90% of the cumulative cancer risk, the cumulative figures inherit its uncertainty in full. If the bulk of the measured chromium is Cr(III), as the soil chemistry of the study area suggests, the true cancer risk could be lower than the tabulated figures by an order of magnitude or more.

Two further sources of uncertainty in the non-carcinogenic estimates should be acknowledged. The oral reference dose for Cr used here is the USEPA IRIS value for Cr(VI), for which the agency records low confidence, and the copper value of $0.04 \text{ mg kg}^{-1} \text{ day}^{-1}$ is not a verified IRIS reference dose but a screening value that a recent comprehensive review nevertheless found to remain the best-supported figure for oral exposure [41]. Speciation of Cr in both soil and crop is accordingly the single most valuable methodological addition a follow-up study could make. The Pb-derived risk is not subject to any of these uncertainties: it rests on fully quantifiable

measurements and a well-established reference dose, and it exceeded the acceptable threshold on its own in all 30 samples on both dry- and fresh-weight bases.

4.6. Spatial Pattern and Implications for Mitigation

The statistical analysis reveals an instructive asymmetry between the two matrices. Soil data show clearly that anthropogenic pressure has enriched the industrial and urban upazilas, with all three metals significantly elevated relative to the rural reference and large effect sizes throughout, reproducing at district scale the urban-to-rural enrichment gradient documented by Rezapour et al. [2] and the distance-decay pattern reported by Lima et al. [24] around an industrial point source. Vegetable data trend in the same direction and, across the full six-point gradient, do so significantly for Cr and Pb; but the two-group contrast is underpowered at five fields per upazila and cannot demonstrate that crops from Barura are meaningfully safer than crops from Cumilla Sadar Dakshin. Given that every vegetable sample from every upazila, Barura included, exceeded the Pb food limit by at least 24-fold on a dry-weight basis and 2.8-fold on a fresh-weight basis, the practical reading is that the spatial gradient is real in the soil but largely immaterial to consumer safety. Contamination of the edible crop is a district-wide condition, not a localized industrial one, a conclusion consistent with the regional findings of Hossen et al. [26] for the adjoining Noakhali region, of Salam et al. [18] for highway-adjacent cultivation, and of Kormoker et al. [59] and Roky et al. [20] for Bangladeshi foodstuffs nationally.

The contrast between the two analysis-of-variance models is similarly instructive rather than contradictory. The one-way model pools crop-to-crop variation into the error term, and because crop identity is a genuine and, in several cases, large source of variation, this inflates the residual and masks the spatial signal that the two-way model recovers. Spatial differences between upazilas are therefore real but modest in relation to variation between crops, and any future survey seeking to resolve them will need either more fields per upazila or a design restricted to a single indicator crop.

Three practical implications follow. Regulatory monitoring in the district must be based on crop analysis rather than soil analysis, since every field soil sampled here would have passed a soil-based screen while every crop failed a food-based one. Because the contamination is district-wide rather than confined to the industrial upazila, mitigation measures such as setback distances from highways and brick kilns, control of contaminated organic amendments, and evidence-based consumer guidance on washing and peeling should be applied throughout the district rather than targeted at the export processing zone periphery. Where a substantial fraction of the Pb burden is surface-deposited, as the intercept and crop-pattern evidence suggest, domestic washing and peeling may be the most rapidly deployable intervention available [13], and quantifying its effect should be an early priority.

4.7. Limitations

Several limitations qualify the strength of the conclusions and should guide the design of subsequent work. Vegetable Cr determinations fell below the method limit of quantification and many below the limit of detection, so those results and every index derived from them are semi-quantitative; reducing the digest volume, increasing the sample mass or applying a pre-concentration step would place them above the LOQ. Chromium was not speciated, so the carcinogenic risk attributed to it is an upper bound of unknown tightness. Moisture content was not measured, so the fresh-weight sensitivity analysis in Section 4.4 rests on published rather than measured dry-matter fractions. Sampling was confined to a single *rabi* harvest and should not be extrapolated to the pre-monsoon or monsoon crop without verification, since soil solution and crop tissue concentrations vary with irrigation regime, rainfall and atmospheric deposition rate [44]. The design provides one field composite per crop per upazila, which is adequate to detect the large crop and soil effects reported but leaves the between-upazila contrasts in vegetables underpowered. Only three metals and five crops were studied; cadmium, arsenic and nickel are all of documented concern in Bangladeshi vegetables [15, 16, 19] and were not measured, and leafy crops other than cabbage, which are known to accumulate metals more readily [45, 49], were not included. No genuinely undisturbed background soils were sampled, so the geogenic baseline cannot be established and enrichment factors or a geoaccumulation index could not be calculated against a local background. Irrigation water, agrochemical inputs and atmospheric deposition were not sampled, so the relative contribution of each pathway to the observed Pb burden is inferred rather than measured, and the foliar-deposition mechanism remains a hypothesis consistent with the data rather than a demonstrated finding. Finally, the health risk estimates apply a single fixed ingestion rate, body weight and exposure duration to all adults, assess only the five crops studied and therefore exclude contributions from cereals, fish and other dietary components [59], and exclude children, who have higher intake per unit body weight.

5. Conclusions

This survey of 30 matched crop-soil pairs across six upazilas of Cumilla district found copper concentrations comfortably within guideline values in both matrices, chromium below guideline values in all soils and in 29 of 30 crops, and lead above the maximum allowable limit in every single vegetable composite while every matched field soil remained compliant. Pollution load indices exceeded unity in all vegetables and remained below unity in all soils; potential ecological risk indices indicated uniformly low ecological risk; and hazard indices and cumulative cancer risks exceeded their respective safe thresholds in every sample, with lead contributing 78-90% of the non-carcinogenic hazard and chromium dominating the

carcinogenic estimate. A fresh-weight sensitivity analysis reduced the magnitude of these estimates roughly nine-fold without altering any exceedance conclusion except the single chromium case.

The hypothesis that soil contamination can serve as a screening proxy for crop contamination is rejected. Soil concentration explained at most 56% of the variance in crop concentration, and the categorical mismatch between soil compliance and crop exceedance held across every crop and every upazila, including the rural reference. Regulatory monitoring of vegetables in Bangladesh must therefore be based on direct analysis of the edible portion. Because the contamination is district-wide rather than confined to the industrial upazila, mitigation measures such as setback distances from highways and brick kilns, control of contaminated organic amendments, and evidence-based consumer guidance on washing and peeling should be applied throughout the district rather than targeted at the export processing zone periphery. Chromium speciation, measured moisture content, replicated multi-season sampling and source apportionment using stable Pb isotopes are the priorities for follow-up work, and district-level datasets of this kind are a prerequisite for the national soil quality standards for agricultural land that Bangladesh has yet to promulgate.

Abbreviations

AEZ	Agro-ecological Zone
AT	Averaging Time
BF	Bioaccumulation Factor
BW	Body Weight
CD	Contamination Degree
CF	Contamination Factor
CHR	Cumulative Carcinogenic Health Risk
CSF	Cancer Slope Factor
CV	Coefficient of Variation
ED	Exposure Duration
EDI	Estimated Daily Intake
EF	Exposure Frequency
ER	Ecological Risk Factor
FAO	Food and Agriculture Organization
HCL	Hollow Cathode Lamp
HI	Hazard Index
HQ	Hazard Quotient
ILCR	Incremental Lifetime Cancer Risk
IR	Ingestion Rate
IRIS	Integrated Risk Information System
LOD	Limit of Detection
LOQ	Limit of Quantification
OLS	Ordinary Least Squares
PERI	Potential Ecological Risk Index
PLI	Pollution Load Index
RfD	Oral Reference Dose
RSD	Relative Standard Deviation
USEPA	United States Environmental Protection Agency
WHO	World Health Organization

Supplementary Material

The supplementary material can be accessed at <https://doi.org/10.11648/j.ijaas.20261205.15>

Acknowledgments

The authors gratefully acknowledge the farmers of Cumilla Sadar Dakshin, Cumilla Adarsha Sadar, Burichang, Chandina, Daudkandi and Barura upazilas, who allowed access to their fields and gave their time during sample collection.

Author Contributions

Khandaker Nadia Anjum: Conceptualization, Formal Analysis, Investigation, Methodology, Writing – original draft

Subrato Roy: Investigation, Writing – review & editing

Most Zakiya Islam: Writing – review & editing

Md. Sajjad Hossain: Writing – review & editing

Data Availability Statement

The data is available from the corresponding author upon reasonable request. The datasets include the field sampling register, calibration data, all 540 individual instrument readings with quality-control flags, composite results with derived indices, health risk calculations and full statistical output.

Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] Krishna, A. K., Mohan, K. R., Murthy, N. N., Periasamy, V., Bipinkumar, G., Manohar, K., Rao, S. S. Assessment of heavy metal contamination in soils around chromite mining areas, Nuggehally, Karnataka, India. *Environmental Earth Sciences*. 2013, 70(2), 699-708. <https://doi.org/10.1007/s12665-012-2153-6>
- [2] Rezapour, S., Siavash Moghaddam, S., Nouri, A., Khosravi Aqdam, K. Urbanization influences the distribution, enrichment, and ecological health risk of heavy metals in croplands. *Scientific Reports*. 2022, 12(1), 3868. <https://doi.org/10.1038/s41598-022-07789-x>
- [3] Lokeshwari, H., Chandrappa, G. T. Impact of heavy metal contamination of Bellandur Lake on soil and cultivated vegetation. *Current Science*. 2006, 91(5), 622-627.
- [4] Singh, J., Upadhyay, S. K., Pathak, R. K., Gupta, V. Accumulation of heavy metals in soil and paddy crop (*Oryza sativa*), irrigated with water of Ramgarh Lake, Gorakhpur, UP, India. *Toxicological & Environmental Chemistry*. 2011, 93(3), 462-473. <https://doi.org/10.1080/02772248.2010.546559>

- [5] Chanda, A., Akhand, A., Das, A., Hazra, S. Cr, Pb and Hg contamination on agricultural soil and paddy grain after irrigation using metropolitan sewage effluent. *Journal of Applied and Environmental Biological Sciences*. 2011, 1(10), 464-469.
- [6] Guevara-Riba, A., Sahuquillo, A., Rubio, R., Rauret, G. Assessment of metal mobility in dredged harbour sediments from Barcelona, Spain. *Science of the Total Environment*. 2004, 321(1-3), 241-255. <https://doi.org/10.1016/j.scitotenv.2003.08.021>
- [7] Taghipour, H., Mosafari, M. Heavy metals in the vegetables collected from production sites. *Health Promotion Perspectives*. 2013, 3(2), 185-193. <https://doi.org/10.5681/hpp.2013.022>
- [8] Fytianos, K., Katsianis, G., Triantafyllou, P., Zachariadis, G. Accumulation of heavy metals in vegetables grown in an industrial area in relation to soil. *Bulletin of Environmental Contamination and Toxicology*. 2001, 67(3), 423-430. <https://doi.org/10.1007/s00128-001-0141-8>
- [9] Solidum, J., Dykimching, E., Agaceta, C., Cayco, A. Assessment and identification of heavy metals in different types of cooked rice available in the Philippine market. In *Proceedings of the 2nd International Conference on Environmental and Agriculture Engineering*, IPCBEE, Singapore, 2012; Volume 37, pp. 35-39.
- [10] Shahriar, S., Haque, M. M., Naidu, R., Rahman, M. M. Concentrations of toxic elements and health risk assessment in arum grown in arsenic-contaminated areas of Bangladesh. *Food Control*. 2021, 129, 108240. <https://doi.org/10.1016/j.foodcont.2021.108240>
- [11] Iso, H. Relationship between vegetables and fruits (antioxidant vitamins, minerals, and fiber) intake and risk of cardiovascular disease. In *Reference Module in Biomedical Sciences*. Amsterdam: Elsevier; 2018. <https://doi.org/10.1016/B978-0-12-801238-3.99601-6>
- [12] Zhao, L., Zhao, X., Xu, Y., Liu, X., Zhang, J., He, Z. Simultaneous determination of 49 amino acids, B vitamins, flavonoids, and phenolic acids in commonly consumed vegetables by ultra-performance liquid chromatography-tandem mass spectrometry. *Food Chemistry*. 2021, 344, 128712. <https://doi.org/10.1016/j.foodchem.2020.128712>
- [13] Al-Jassir, M. S., Shaker, A., Khaliq, M. A. Deposition of heavy metals on green leafy vegetables sold on roadsides of Riyadh City, Saudi Arabia. *Bulletin of Environmental Contamination and Toxicology*. 2005, 75(5), 1020-1027. <https://doi.org/10.1007/s00128-005-0851-4>
- [14] Bigdeli, M., Seilsepour, M. Investigation of metals accumulation in some vegetables irrigated with waste water in Shahre Rey-Iran and toxicological implications. *American-Eurasian Journal of Agricultural & Environmental Sciences*. 2008, 4(1), 86-92.
- [15] Shaheen, N., Irfan, N. M., Khan, I. N., Islam, S., Islam, M. S., Ahmed, M. K. Presence of heavy metals in fruits and vegetables: health risk implications in Bangladesh. *Chemosphere*. 2016, 152, 431-438. <https://doi.org/10.1016/j.chemosphere.2016.02.060>
- [16] Laboni, F. A., Ahmed, M. W., Kaium, A., Alam, M. K., Parven, A., Jubayer, M. F., Rahman, M. A., Meftaul, I. M., Khan, M. S. I. Heavy metals in widely consumed vegetables grown in industrial areas of Bangladesh: a potential human health hazard. *Biological Trace Element Research*. 2023, 201(2), 995-1005. <https://doi.org/10.1007/s12011-022-03179-6>
- [17] Alam, M. N. E., Hosen, M. M., Ullah, A. K. M. A., Maksud, M. A., Khan, S. R., Lutfi, L. N., Choudhury, T. R. Pollution characteristics, source identification, and health risk of heavy metals in the soil-vegetable system in two districts of Bangladesh. *Biological Trace Element Research*. 2023, 201(10), 4985-5000. <https://doi.org/10.1007/s12011-023-03558-7>
- [18] Salam, M. A., Akhter, S., Nur-E-Alam, M., Islam, M. S., Dewanjee, S., Siddique, M. A. B., Chakraborty, T. K. Assessment of heavy metal contamination and health risk associated with cultivated vegetables along Dhaka-Mymensingh Highway, Bangladesh. *Biological Trace Element Research*. 2025, 203(2), 1162-1178. <https://doi.org/10.1007/s12011-024-04200-w>
- [19] Sadia, U., Islam, M. N., Hoque, M. A., Tanbi, T. A., Asha, S. M. A. A., Howlader, S., Sarker, N., Islam, M. S. Assessing trace metal based human health risks in the highly consumed vegetables collected from the industrialized zones of Bangladesh. *Environmental Geochemistry and Health*. 2026, 48(1). <https://doi.org/10.1007/s10653-025-02907-w>
- [20] Roky, M. S., Shiddique, S., Ud-Daula, A. Heavy metal contamination in the Bangladeshi food chain and associated human health risks: a systematic review with government implications. *Journal of Trace Elements and Minerals*. 2026, 17, 100309. <https://doi.org/10.1016/j.jtemin.2026.100309>
- [21] Bushra, A., Zakir, H. M., Sharmin, S., Quadir, Q. F., Rashid, M. H., Rahman, M. S., Mallick, S. Human health implications of trace metal contamination in topsoils and brinjal fruits harvested from a famous brinjal-producing area in Bangladesh. *Scientific Reports*. 2022, 12(1), 14278. <https://doi.org/10.1038/s41598-022-17930-5>
- [22] Kumar, S., Rahman, M. A., Islam, M. R., Hashem, M. A., Rahman, M. M. Lead and other elements-based pollution in soil, crops and water near a lead-acid battery recycling factory in Bangladesh. *Chemosphere*. 2022, 290, 133288. <https://doi.org/10.1016/j.chemosphere.2021.133288>
- [23] Hasan, A. B., Reza, A. H. M. S., Kabir, S., Siddique, M. A. B., Ahsan, M. A., Akbor, M. A. Accumulation and distribution of heavy metals in soil and food crops around the ship breaking area in southern Bangladesh and associated health risk assessment. *SN Applied Sciences*. 2020, 2(2), 155. <https://doi.org/10.1007/s42452-019-1933-y>
- [24] Lima, F. A., Bhattacharjee, S., Jahangir Sarker, M., Salam, M. A. Ecological risk assessment of potentially toxic elements (PTEs) in agricultural soil, vegetables and fruits with respect to distance gradient in proximity to lead-acid battery industry. *Environmental Nanotechnology, Monitoring and Management*. 2024, 21, 100932. <https://doi.org/10.1016/j.enmm.2024.100932>
- [25] Sahen, M. S., Naim, M. A. H. K., Hosen, M. S., Pranta, M. A., Hasan, M., Rahman, M. M., Rahman, S., Don, M. Multi-compartmental risk assessment of heavy metal contamination in soil, plants, and wastewater: a model from Industrial Gazipur, Bangladesh. *Environmental Monitoring and Assessment*. 2025, 197(4). <https://doi.org/10.1007/s10661-025-13818-9>

- [26] Hossen, K., Rahman, N., Ferdowsi, Z., Ferdous, T. Assessment of heavy metal levels and associated health risks linked to vegetables grown in Noakhali region of Bangladesh. *Environmental Health Insights*. 2026, 20.
<https://doi.org/10.1177/11786302261440637>
- [27] Samma, S., Khan, M. S. I., Chowdhury, M. T. I., Islam, M. A., Fick, J., Kaium, A. Evaluating soil-vegetable contamination with heavy metals in Bogura, Bangladesh: a risk assessment approach. *Environmental Health Insights*. 2024, 18.
<https://doi.org/10.1177/11786302241282601>
- [28] Borošová, D., Mocak, J., Beinrohr, E., Miškovič, P. Validation and quality assurance of arsenic determination in urine by GFAAS after toluene extraction. *Polish Journal of Environmental Studies*. 2002, 11(6), 617-623.
- [29] Al-Weher, S. Levels of heavy metals Cd, Cu and Zn in three fish species collected from the Northern Jordan Valley, Jordan. *Jordan Journal of Biological Sciences*. 2008, 1(1), 41-46.
- [30] Hakanson, L. An ecological risk index for aquatic pollution control: a sedimentological approach. *Water Research*. 1980, 14(8), 975-1001.
[https://doi.org/10.1016/0043-1354\(80\)90143-8](https://doi.org/10.1016/0043-1354(80)90143-8)
- [31] Ogundele, D., Adio, A., Oludele, O. Heavy metal concentrations in plants and soil along heavy traffic roads in north central Nigeria. *Journal of Environmental & Analytical Toxicology*. 2015, 5(6), 334. <https://doi.org/10.4172/2161-0525.1000334>
- [32] Islam, S., Ahmed, K., Masunaga, S. Potential ecological risk of hazardous elements in different land-use urban soils of Bangladesh. *Science of the Total Environment*. 2015, 512-513, 94-102. <https://doi.org/10.1016/j.scitotenv.2014.12.100>
- [33] Ogundele, L. T., Ayeku, P. O., Adebayo, A. S., Olufemi, A. P., Adejoro, I. A. Pollution indices and potential ecological risks of heavy metals in the soil: a case study of municipal wastes site in Ondo State, southwestern Nigeria. *Polytechnica*. 2020, 3(1-2), 78-86. <https://doi.org/10.1007/s41050-020-00022-6>
- [34] Varol, M. Assessment of heavy metal contamination in sediments of the Tigris River (Turkey) using pollution indices and multivariate statistical techniques. *Journal of Hazardous Materials*. 2011, 195, 355-364.
<https://doi.org/10.1016/j.jhazmat.2011.08.051>
- [35] Rashed, M. N. Monitoring of contaminated toxic and heavy metals from mine tailings through age accumulation, in soil and some wild plants at Southeast Egypt. *Journal of Hazardous Materials*. 2010, 178(1-3), 739-746.
<https://doi.org/10.1016/j.jhazmat.2010.01.147>
- [36] Baker, A. J. M. Accumulators and excluders: strategies in the response of plants to heavy metals. *Journal of Plant Nutrition*. 1981, 3(1-4), 643-654.
<https://doi.org/10.1080/01904168109362867>
- [37] Guo, W., Liu, X., Liu, Z., Li, G. Pollution and potential ecological risk evaluation of heavy metals in the sediments around Dongjiang Harbor, Tianjin. *Procedia Environmental Sciences*. 2010, 2(5), 729-736.
<https://doi.org/10.1016/j.proenv.2010.10.084>
- [38] U.S. Environmental Protection Agency. Risk Assessment Guidance for Superfund (RAGS) Volume III - Part A: Process for Conducting Probabilistic Risk Assessment. Washington, DC: Office of Emergency and Remedial Response, U.S. Environmental Protection Agency; 2001.
- [39] Kabir, S., Kaium, A., Chowdhury, M. T. I., Islam, M. A., Bhuiya, S. A., Ahmed, M. W., Khan, M. S. I. Environmental pollution, ecological and human health risk assessment of heavy metals in rice farming system near the Buriganga River in Dhaka, Bangladesh. *International Journal of Environmental Analytical Chemistry*. 2022, 1-20.
<https://doi.org/10.1080/03067319.2022.2075355>
- [40] U.S. Environmental Protection Agency. Regional Screening Levels (RSLs) - User's Guide. Available from: <https://www.epa.gov/risk/regional-screening-levels-rsls> (accessed [DD Month 2026]).
- [41] Taylor, A. A., Tsuji, J. S., Yeskey, D., Garry, M. R., Dorman, D. C. Recommended reference values for risk assessment of oral exposure to copper. *Risk Analysis*. 2023, 43(2), 211-218.
<https://doi.org/10.1111/risa.13906>
- [42] Li, Z., Ma, Z., van der Kuijp, T. J., Yuan, Z., Huang, L. A review of soil heavy metal pollution from mines in China: pollution and health risk assessment. *Science of the Total Environment*. 2014, 468-469, 843-853.
<https://doi.org/10.1016/j.scitotenv.2013.08.090>
- [43] Liu, X., Song, Q., Tang, Y., Li, W., Xu, J., Wu, J., Brookes, P. C. Human health risk assessment of heavy metals in soil-vegetable system: a multi-medium analysis. *Science of the Total Environment*. 2013, 463-464, 530-540.
<https://doi.org/10.1016/j.scitotenv.2013.06.064>
- [44] Sharma, R. K., Agrawal, M., Marshall, F. Heavy metal contamination in vegetables grown in wastewater irrigated areas of Varanasi, India. *Bulletin of Environmental Contamination and Toxicology*. 2006, 77(2), 312-318.
<https://doi.org/10.1007/s00128-006-1065-0>
- [45] Guttormsen, G., Singh, B. R., Jeng, A. S. Cadmium concentration in vegetable crops grown in a sandy soil as affected by Cd levels in fertilizer and soil pH. *Fertilizer Research*. 1995, 41(1), 27-32. <https://doi.org/10.1007/BF00749518>
- [46] Kibria, M. G., Islam, M., Alamgir, M. Influence of waste water irrigation on heavy metal accumulation in soil and plant. *International Journal of Applied and Natural Sciences*. 2012, 1(1), 43-54.
- [47] Infante, E. F., Dulfo, C. P., Dicen, G. P., Hseu, Z. Y., Navarrete, I. A. Bioaccumulation and human health risk assessment of chromium and nickel in paddy rice grown in serpentine soils. *Environmental Science and Pollution Research*. 2021, 28(14), 17146-17157. <https://doi.org/10.1007/s11356-020-12176-y>
- [48] Mithu, M. M. U., Shormela, S. A., Abdullah, A. T. M., Mubarak, M., Rahman, M. M., Khan, T. A., Moniruzzaman, M., Islam, M. S. Exploring heavy metal bioaccumulation in vegetables: unravelling environmental pollutants' impact on agricultural produce and human health. *Biological Trace Element Research*. 2026, 204(5), 3004-3021. <https://doi.org/10.1007/s12011-025-04871-z>

- [49] Cui, S., Wang, Z., Li, X., Wang, H., Wang, H., Chen, W. A comprehensive assessment of heavy metal (loid) contamination in leafy vegetables grown in two mining areas in Yunnan, China: a focus on bioaccumulation of cadmium in Malabar spinach. *Environmental Science and Pollution Research*. 2023, 30(6), 14959-14974. <https://doi.org/10.1007/s11356-022-23017-5>
- [50] Sharma, S., Prasad, F. M. Accumulation of lead and cadmium in soil and vegetable crops along major highways in Agra, India. *E-Journal of Chemistry*. 2010, 7(4), 1174-1183. <https://doi.org/10.1155/2010/678589>
- [51] Tani, F. H., Barrington, S. Zinc and copper uptake by plants under two transpiration rates. Part I. Wheat (*Triticum aestivum* L.). *Environmental Pollution*. 2005, 138(3), 538-547. <https://doi.org/10.1016/j.envpol.2004.06.005>
- [52] Ahmad, J. U., Goni, M. A. Heavy metal contamination in water, soil, and vegetables of the industrial areas in Dhaka, Bangladesh. *Environmental Monitoring and Assessment*. 2010, 166(1-4), 347-357. <https://doi.org/10.1007/s10661-009-1006-6>
- [53] Khan, R., Basir, M. S., Saha, N., Rahman, K. A., Islam, M. T., Biswas, G. G., Idris, A. M., Khan, M. H. R. Bioaccumulation of elements in the edible part of vegetables from the agricultural soil: source apportionment and potential risks. *Journal of Environmental Management*. 2025, 393, 127096. <https://doi.org/10.1016/j.jenvman.2025.127096>
- [54] Shammi, S. A., Salam, A., Khan, M. A. H. Assessment of heavy metal pollution in the agricultural soils, plants, and in the atmospheric particulate matter of a suburban industrial region in Dhaka, Bangladesh. *Environmental Monitoring and Assessment*. 2021, 193(2), 104. <https://doi.org/10.1007/s10661-021-08848-y>
- [55] Aktaruzzaman, M., Fakhruddin, A. N. M., Chowdhury, M. A., Fardous, Z., Alam, M. K. Accumulation of heavy metals in soil and their transfer to leafy vegetables in the region of Dhaka Aricha Highway, Savar, Bangladesh. *Pakistan Journal of Biological Sciences*. 2013, 16(7), 332-338. <https://doi.org/10.3923/pjbs.2013.332.338>
- [56] Alamgir, M., Islam, M., Hossain, N., Kibria, M. G., Rahman, M. M. Assessment of heavy metal contamination in urban soils of Chittagong city, Bangladesh. *International Journal of Plant & Soil Science*. 2015, 7(6), 362-372. <https://doi.org/10.9734/IJPSS/2015/18424>
- [57] Ramos-Miras, J. J., Gil, C., Rodríguez Martín, J. A., Bech, J., Boluda, R. Ecological risk assessment of mercury and chromium in greenhouse soils. *Environmental Geochemistry and Health*. 2020, 42(1), 313-326. <https://doi.org/10.1007/s10653-019-00354-y>
- [58] Kumar, S., Islam, R., Akash, P. B., Khan, M. H. R., Proshad, R., Karmoker, J., MacFarlane, G. R. Lead (Pb) contamination in agricultural products and human health risk assessment in Bangladesh. *Water, Air, and Soil Pollution*. 2022, 233(7), 257. <https://doi.org/10.1007/s11270-022-05711-9>
- [59] Kormoker, T., Proshad, R., Islam, M. S., Shamsuzzoha, M., Akter, A., Tusher, T. R. Concentrations, source apportionment and potential health risk of toxic metals in foodstuffs of Bangladesh. *Toxin Reviews*. 2021, 40(4), 1447-1460. <https://doi.org/10.1080/15569543.2020.1731551>
- [60] Järup, L. Hazards of heavy metal contamination. *British Medical Bulletin*. 2003, 68(1), 167-182. <https://doi.org/10.1093/bmb/ldg032>
- [61] Khan, S., Farooq, R., Shahbaz, S., Khan, M. A., Sadique, M. Health risk assessment of heavy metals for population via consumption of vegetables. *World Applied Sciences Journal*. 2009, 6(12), 1602-1606.