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Authors: Samma, Sadia, Khan, Md. Sirajul Islam, Chowdhury, Md. Tazul Islam, Islam, Mohammed Ariful, Fick, Jerker, et al.

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Evaluating Soil-Vegetable Contamination with Heavy Metals in Bogura, Bangladesh: A Risk Assessment Approach

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Sadia Samma[1], Md. Sirajul Islam Khan[1], Md. Tazul Islam Chowdhury[1], Mohammed Ariful Islam[1], Jerker Fick[2] and Abdul Kaium[1,2]

[1]Department of Agricultural Chemistry, Sher-e-Bangla Agricultural University, Dhaka, Bangladesh.
[2]Department of Chemistry, Umeå Universitet, Umeå, Sweden.

ABSTRACT: This study quantified hazardous heavy metals (Cu, Cr, and Pb) in soil and vegetables (potato, tomato, pepper, cauliflower, and cabbage) across six upazilas (Kahaloo, Bogura Sadar, Shajahanpur, Shibganj, Nandigram, and Dupchanchia) in Bogura district, Bangladesh, assessing their health and environmental impacts. The detection method was validated for its accuracy and precision with QC samples. Results indicated that Cu levels in all samples were within safe limits set by BFSA and FAO/WHO, whereas Cr and Pb in vegetables exceeded permissible levels, though soil concentrations remained within limits. Pb contamination was particularly severe in vegetables (CF > 6), and all vegetables showed significant contamination degrees (CD), highlighting extensive heavy metal pollution. The Pollution Load Index (PLI) identified Kahaloo and Bogura Sadar as the most polluted, whereas Nandigram and Dupchanchia were the least. Bioaccumulation factors (BF) for all metals were < 1, suggesting minimal transfer to edible parts. However, the ecological risk index (ERi) and potential ecological risk index (PERI) suggested low ecological risks, but health risk assessments indicated that vegetable consumption poses significant carcinogenic and non-carcinogenic risks (CHR > 10^{-4}, HI > 1) across all upazilas. The findings underscore the urgent need for measures to mitigate heavy metal pollution in these areas to safeguard environmental and public health.

KEYWORDS: Vegetables, soil, Bogura, heavy metals, environmental pollution, risk assessment

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CORRESPONDING AUTHOR: Abdul Kaium, Departement of Chemistry, KBC-huset (KB), Umeå Universitet, Linnaeus väg 10, Umeå 901 87, Sweden. Email: abdul.kaium@umu.se

Introduction

Heavy metal contamination of agricultural soils and subsequent accumulation in food crops poses a critical threat to both human health and ecological integrity. Due to rapid industrialization and intensive agricultural practices, heavy metals enter the food chain through contaminated soil and irrigation water.[1,2] The problem of excessive quantities of heavy metals in the environment is caused by human activities such as industrial discharge, agriculture practices that use pesticides and fertilizers, wastewater irrigation, and atmospheric deposition.[3,4] Unlike organic pollutants, heavy metals are non-degradable and can persist in the environment for long periods, making their presence in the environment a perpetual problem.[5,6] These pollutants not only degrade soil quality but also pose a risk to soil ecology.[5,7,8] The ecological impact of heavy metals significantly affects multiple trophic levels, impairing physiological functions, growth, fertility, and survival rates in plants and animals even at sub-lethal concentrations. Acute toxicity at higher levels results in extensive morbidity and mortality. Additionally, heavy metals disrupt ecosystem functions, alter species composition, diminish biodiversity, and impair ecosystem services.[4,9] The bioaccumulation and biomagnification of heavy metals in food webs further exacerbate their ecological impacts, leading to toxic effects even in organisms not directly exposed to contaminated environments.[10] Assessing the ecological risk of heavy metals entails evaluating their concentrations in the environment, bioaccumulation potential, and toxicity to organisms. The widely adopted Potential Ecological Risk Index (PERI), proposed by Hakanson[11], assesses heavy metal risks in sediments by integrating metal toxicity and environmental concentrations.[11] It integrates the toxicity of different metals with their environmental concentrations, aiding in the identification of high-risk areas and prioritizing remediation efforts.

Given the critical role of vegetables in the human diet as a primary source of vitamins, minerals, and fibers, ensuring their safety is paramount for public health. The World Health Organization (WHO) and the Food and Agriculture Organization (FAO) have set maximum permissible limits for heavy metals in soils and vegetables to safeguard consumer health.[12] Despite these guidelines, many regions, including parts of Bangladesh, continue to face challenges in maintaining safe levels of heavy metal concentrations in agricultural products.[13,14] The agricultural soils and irrigation systems in different regions of the country are known to contain elevated levels of toxic metals.[15] One such area of concern is the Bogura district, where intensive vegetable cultivation relies heavily on potentially contaminated sources.[16-18] The accumulation of hazardous heavy metals such as copper (Cu), chromium (Cr), and lead (Pb) in the soil-vegetable system can lead to serious health risks upon consumption of contaminated produce.[19,20] They can trigger a range of detrimental health effects, including

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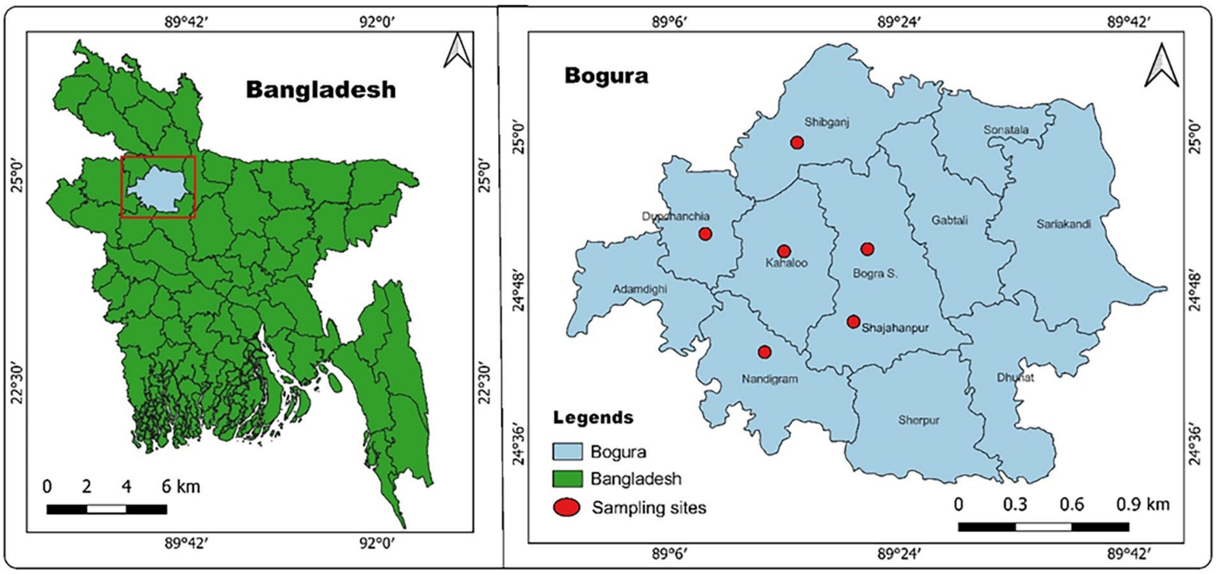

Figure 1. Sampling sites in the study area.

organ damage, nervous system disruption, and an increased risk of cancer.[21,22] Therefore, the carcinogenic and non-carcinogenic risks associated with the ingestion of heavy metals through contaminated vegetables necessitate an urgent assessment of their levels and potential health impacts.[23]

The Bogura district in Bangladesh is known for its fertile land and agricultural productivity,[24] and it is also the most industrialized city in the northern part of Bangladesh. However, rapid industrialization and urbanization have raised concerns about soil and vegetable contamination with heavy metals.[18,25] Previous studies in different regions of Bangladesh have highlighted the heavy metal pollution on the soil and its adverse effects on human health.[26-29] Despite growing awareness, studies specifically targeting the soil-vegetable heavy metal contamination levels in the different upazilas of Bogura district remain limited. Therefore, this assessment will assist to determine the metal contamination level, potential health and ecological risks posed to consumers, and ecosystem. This assessment will also assist in identifying regions that require focused mitigation strategies.

Materials and Methods

Chemicals and reagents

Analytical-grade reagents, including heavy metal standards for Pb, Cu, and Cr (1000 mg/L), were purchased from Scharlau Chemicals (Spain) via Bangladesh Scientific and Chemical Company Pvt. Ltd. (Dhaka, Bangladesh). Nitric acid, perchloric acid, distilled water, and hydrogen peroxide (analytical and EMSURE grade) were obtained from Kuri & Company (Pvt.) Limited (Dhaka, Bangladesh).

Study area

This study was conducted in the Bogura district, a rapidly growing and industrialized district in northern Bangladesh. Located in the Rajshahi Division, Bogura lies between 24° 50′ 59.99″ North latitude and 89° 21′ 59.99″ East longitude and covers an area of 71.56 km^2. Vegetable and soil samples were collected from fields within six Upazilas of the district: Kahaloo, Bogura Sadar, Shajahanpur, Shibganj, Nandigram, and Dupchanchia (Figure 1).

Collection of vegetable samples

Potato, tomato, chili pepper, cabbage, and cauliflower samples were randomly collected at the harvesting stage from farmers' fields in six Upazilas (Kahaloo, Bogura Sadar, Shajahanpur, Shibganj, Nandigram, and Dupchanchia) within the Bogura district (Table 1). To ensure representativeness, three collections per vegetable were made at each site, mixed to form composite samples for analysis. Immediately after harvest, the vegetables were rinsed with distilled water, placed in ziplock bags, and transported to the Food Safety Laboratory at Sher-e-Bangla Agricultural University, Dhaka, Bangladesh.

Collection of soil sample

Sampling sites were selected in five vegetable fields (potato, tomato, chili pepper, cauliflower, and cabbage) across six Upazilas (Kahaloo, Bogura Sadar, Shajahanpur, Shibganj, Nandigram, and Dupchanchia) within the Bogura district. At the same locations where vegetable samples were collected, three surface soil samples (0-15 cm depth) were taken from each vegetable field at each site, combined to form a composite of 1.5 kg per site. Consequently, a total of 30 composite soil samples from the six upazilas were gathered. These samples were then thoroughly mixed in clean ziplock bags to create a uniform and representative sample for subsequent sample preparation and analysis.

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Table 1. Name of the vegetable samples collected for the study.

SL. NO.	LOCAL NAME	ENGLISH NAME	TYPE	SCIENTIFIC NAME	FAMILY
1	Alu	Potato	Root vegetable	*Solanum tuberosum*	Solanaceae
2	Tomato	Tomato	Fruit vegetable	*Solanum lycopersicum*	Solanaceae
3	Morich	Chili pepper	Fruit vegetable	*Capsicum annuum*	Solanaceae
4	Badhakopi	Cabbage	Leaf vegetable	*Brassica oleracea*	Brassicaceae
5	Fulkopi	Cauliflower	Flower vegetable	*Brassica oleracea*	Brassicaceae

Sample preparation

Vegetable samples were dried in a laboratory oven at 60°C to 70°C for 3 days to achieve a consistent dry weight. The dried vegetables were then ground using a grinder and stored in zip-lock poly bags. Soil samples were manually cleaned to remove rocks, gravel, roots, leaves, and other debris. Prior to laboratory analysis, the soil samples were air-dried for 3 days at 30°C to 40°C and subsequently passed through a 2 mm sieve. Both the 30 sieved soil samples and the 30 ground vegetable samples were stored in closed plastic containers until acid digestion.

Digestion of vegetables and soil samples

One gram of dry-ground vegetable samples and 1 g of finely ground soil were placed into separate glass digestion tubes and pre-digested with 20 ml of a di-acid mixture (2:1, HNO_3:$HClO_4$). The following day, the digest preparations were heated for 2 hours at 180°C to 220°C, ensuring complete digestion of the plant and soil matter. After digestion, all samples were allowed to cool for 30 minutes, then diluted to 100 ml with deionized water, mixed using a vortex mixer for 10 seconds, and filtered through Whatman No. 42 filter papers. The samples were stored in clearly labeled plastic bottles in a refrigerator at 4°C to 7°C. An atomic absorption spectrophotometer was used to detect and quantify heavy metals in the digested vegetable and soil samples.

Instrumental analysis

Analytik Jena's NovAA 400P atomic absorption spectrophotometer was used to determine the total content of copper, chromium, and lead in the vegetable and soil digests (Analytik Jena NovAA 400P, 2012, country of origin: Germany). The hollow cathode lamps in AAS were used for estimations in a wide range of situations, depending on the element that was being analyzed. The concentration of heavy metals was reported in parts per million (mg/kg). Table 2 shows the detailed instrumental conditions for determining copper, chromium, lead, and cadmium.

Quality control of the instrumental analysis

The quality control of the instrumental analysis was confirmed by evaluating the method's linearity, determination coefficient, accuracy, and precision. Linearity and determination coefficients were determined by generating calibration curves with standard solutions ranging in concentration from 0.0 to 1.0 mg/L. All analyses were conducted in triplicate. The Analytical Jena Aspect LS software was used for Quantification and quality control of the analytical method. Spiked QC samples were used to determine the percent recovery and relative standard deviation at a 95% confidence level.

Table 2. Instrumental conditions of AAS for determination of Cu, Cr, and Pb.

ELEMENT	CU	CR	PB
Wavelength (nm)	324.8	357.9	217.0
Slit (nm)	1.2	0.2	1.2
Lamp	HCL	HCL	HCL
Lamp current (mA)	2	4	2
Flame	Air-Ac	Air-Ac	Air-Ac
Air/Ac flow (L/min)	50	100	65
Burner head (mm)	100	100	100
Burner height (mm)	6	8	6
Read time (s)	3	3	3

Assessment of pollution indices

Copper (Cu), lead (Pb), and chromium (Cr) were quantified in vegetable and soil samples from vegetable fields. The Pollution Index processes, evaluates, and communicates raw environmental data to decision-makers, managers, professionals, and the public. Single-metal pollution at specific sites was indicated by the contamination factor (CF), whereas multi-metal pollution was diagnosed by the contamination degree (CD), pollution load index (PLI), bioaccumulation factor (BF) and potential ecological risk index (PERI).[11]

Contamination factor (CF). The single metal contamination factor (CFi) is the ratio of the single metal concentration in a biotic or abiotic medium to the regulatory standard set by national or international organizations like the Bangladesh Food Safety Authority (BSFA), the World Health Organization (WHO),

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and the United States Environmental Protection Agency (EPA) (USEPA). Using equation (1), the single metal contamination factor (CF) was computed.

$$CF_i = C_{vegetable\ or\ soil} / C_{BFSA\ or\ WHHO/FAO} \quad (1)$$

Where $C_{\text{vegetable or soil}}$ is the metal concentration in the vegetable or soil sample. $C_{\text{BFSA or EHO/FAO}}$ is the value of the regulatory limit for heavy metals set by the BFSA or FAO/WHO. The CF values were divided into four broad categories: CF < 1 (low contamination), 1 < CF < 3 (moderate contamination), 3 < CF < 6 (significant contamination), and CF > 6 (severe contamination).[11]

Contamination degree (CD). The CD is the sum of the CFs of the heavy metals that have been measured at specific sites. It measures the overall contamination level at the study location. The following equation (2) was used to determine the contamination degree (CD) at different sites.

$$\text{CD} = \sum CF \quad (2)$$

The CD values were divided into four broad categories: CF < 8 (low degree contamination), 8 < CF < 16 (moderate degree contamination), 16 < CF < 32 (significant degree contamination), and CF > 32 (severe degree contamination).[30] The Cd is intended to provide a measurement of the degree of overall contamination in certain samples at a certain sampling site.

Pollution load index (PLI). The PLI is used to measure the total heavy metal concentrations in vegetables and soils, which were computed using the geometrical mean of all metal concentrations. Using equation (3), the PLI was computed.[31]

$$PLI = \left(CF_1 \times CF_2 \times CF_3 \times \ldots\ldots\ldots \times CF_n\right)^{1/n} \quad (3)$$

The contamination factor is represented by CF, and the total number of parameters is represented by *n*. This PLI gives a quick and easy way to analyze the level of heavy metal pollution. If PLI is greater than 1, there is pollution; however, if PLI is less than 1, there is no metal pollution.[31]

Bioaccumulation factor for plants (BF). The BF is the ratio of metal concentrations in plants (the total of each plant's concentration of heavy metals) to soil concentrations. The bioaccumulation factor (BF) was calculated using the following equation (4):

$$BF = \left(C_1 / C_2\right) \quad (4)$$

The mean concentrations of metal in vegetables and soil are represented by C1 and C2, respectively. If the bioaccumulation factor (BF) is greater than 1, then the vegetables are shown to be heavy metal accumulators, whereas a bioaccumulation factor less than 1 indicates that the vegetable is an excluder of heavy metal accumulation.

Ecological risk factor (ERi). The ecological risk factor (ERi) is introduced to evaluate the contamination of soils by a single toxic compound. The following equation (5) was used to determine the ecological risk factor (EF) for single-metal pollution at different sites.

$$ER_i = TR \times CF_i \quad (5)$$

TR is the biological toxic response factor for each element. For Cu and Pb, it is 5, and for Cr, it is 2.[11] The ecological risk factor (ERi) is classified using the following categories: ERi < 40 (low ecological risk factor); 40 ⩽ ERi < 80 (moderate ecological risk factor); 80 ⩽ ERi < 160 (significant ecological risk factor); 160 ⩽ ERi < 320 (high ecological risk factor); and ERi ⩾ 320 (severe ecological risk factor). The formula indicates the degree of heavy metal toxicity and environmental sensitivity to heavy metal contamination.

Potential Ecological Risk Index (PERI). The Potential Ecological Risk Index (PERI), developed by Swedish scientist Hakanson[11], has been widely utilized to evaluate the risk posed by multiple heavy metals in soils.[11] This method has made a significant impact internationally. PERI not only assesses soil contamination by various toxic compounds but also calculates the ecological risk for multiple heavy metals through the aggregation of individual potential risk factors. Guo et al[5] outlined the specific equations used to calculate PERI, enhancing the application of Hakanson's original framework.[5]

$$\text{PERI} = \sum_{i=1}^{m} ER_i \quad (6)$$

The PERI is classified using the following categories: PERI < 150 (low potential ecological risk index); 150 ⩽ PERI < 300 (moderate potential ecological risk index); 300 ⩽ PERI < 600 (high potential ecological risk index); and PERI ⩾ 600 (severe potential ecological risk index).[5,30] It indicates the potential ecological risk posed by the total contamination and represents the biological community's sensitivity to the poisonous element.

Assessment of health risk

The assessment of human health risks due to heavy metal contamination in food and the environment has highlighted adverse health outcomes. This study focused on evaluating both cancer-related and non-cancer health risks to adults in Bangladesh from consuming vegetables tainted with heavy metals. The findings aim to inform strategies for protecting consumer health. Notably, the United States Environmental Protection Agency (USEPA) has provided equations to assess the non-carcinogenic and carcinogenic health risks associated with exposure to heavy metals in food.[32]

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Table 3. Quality control parameters of instrumental analysis.

METAL ELEMENT	CU	CR	PB
Linearity	$Y = 0.1144x + 0.0008$	$Y = 0.523x - 0.0007$	$Y = 0.0671x + 0.0005$
Determination coefficient	0.9987	0.998	0.9993
Method sensitivity (mg/L)	0.0381	0.0835	0.07084
Spiked sample (mg/L)	0.2	0.6	0.4
Mean accuracy (%)	102.3	100.8	94.7
RSD (%)	2.9	2.3	1.7

Non-carcinogenic health risk. The health risk to consumers is measured by comparing the estimated daily intake (EDI) with the oral reference dose (RfD), which is set by regulatory bodies like the FAO and WHO. The following is an assessment of the EDI values for different heavy metals, as provided by the USEPA.

$$EDI = \frac{C \, x \, IR \, x \, EF \, x \, ED}{BW \, x \, AT} \quad (7)$$

Where C is the heavy metal concentration in the vegetable (mg/kg), IR is the ingestion rate of the vegetable (0.1673 kg/person/day), EF is the exposure frequency (365 days/year), ED is the exposure duration (70 years), BW is the bodyweight of the exposed individual (60 kg), and AT is the time over which the dose is averaged (365 days/year × the number of exposure years, average 70 years).[28,29]

The non-carcinogenic hazard for a single metal in a vegetable was characterized by the hazard quotient (HQ) computed using equation (8), and the non-carcinogenic hazard for multiple metals was calculated using equation (9).

$$HQ_i = EDI \; / \; RfD_i \quad (8)$$

$$\mathrm{HI} = \sum_{i=1}^{n} HQ_i \quad (9)$$

Where RfDi represents the standard oral reference dose for metal i, the reference dose (mg/kg/day) indicates the maximum risk posed to humans by a lifetime of daily exposure. The RfDi values for Pb, Cr, and Cu are 0.0035, 0.003, and 0.04 mg/kg/day, respectively.[33] The sum of HQ (Hazard Quotient) values for multiple heavy metals is the Hazard Index (HI). If the HQ and HI values are greater than one, exposed individuals are likely to suffer negative health impacts. Conversely, if both the HQ and HI values are less than one, the heavy metal exposure is considered safe for human health.[34]

Carcinogenic health risk. The Incremental Lifetime Cancer Risk (ILCRi) is calculated to assess the potential cancer risk resulting from the consumption of carcinogenic single heavy metals via foods, as estimated below (equation (10)).[32]

$$ILCRi = EDI \times CSF \quad (10)$$

EDI is for estimated daily intake of heavy metals (mg/kg BW/day), and CSF stands for cancer slope factor (mg/kg/day). The cancer slope factor CSF for heavy metals Cr and Pb is 0.5 and 0.0085 kg/day/mg, respectively.

The CHR is used to calculate the total cancer risk associated with the intake of different heavy metals from a certain food type.

$$CHR = \sum_{i=1}^{n} ILCRi \quad (11)$$

The CHR is the sum of the carcinogenic health risks of individual heavy metals. Thus, the cancer risk could be expressed as no significant carcinogenic health risk (ILCRi or CHR $< 10^{-6}$); acceptable carcinogenic health risk ($10^{-6} <$ ILCRi or CHR $< 10^{-4}$); or unacceptable carcinogenic health risk (ILCRi or CHR $> 10^{-4}$).[32]

Results and Discussion

Quality control of the instrumental analytical method

The Analytica Jena Aspect LS software was utilized for the quality control of our analytical method. This involved evaluating the linearity and determination coefficient of the method through calibration curves for various heavy metals. The determination coefficients were outstanding, ranging between 0.998 and 0.9993, which confirms the linearity of the instrumental quantification. The instrumental method sensitivity ranged from 0.0381 to 0.0835 mg/L, indicating the method's adequacy for the quantitative determination of heavy metals in plant and soil samples, as detailed in Table 3. Quality control samples demonstrated robust instrumental performance with an accuracy recovery rate between 94.7% and 102.3% and exceptional precision, as evidenced by a percentage relative standard deviation (%RSD) of less than 2.9% (Table 3).

Heavy metal content in the vegetable field of Bogura district

Copper (Cu) content in vegetable fields. Copper concentrations in vegetables and soils from several upazilas in Bogura district

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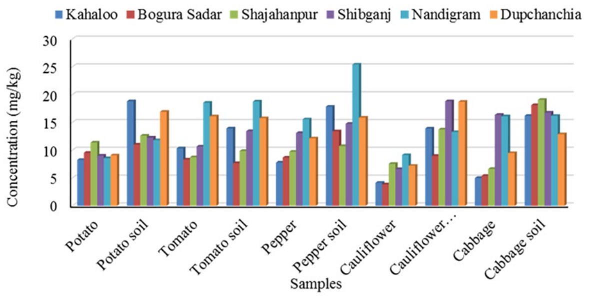

Figure 2. Copper (Cu) accumulation in vegetables and their field soils in different upazilas of Bogura district.

show significant variation (Figure 2). Cu levels in vegetables such as potato, tomato, pepper, cauliflower, and cabbage ranged between 3.86 and 18.55 mg/kg (Table 4). In soil samples from the same fields, Cu levels ranged from 7.68 to 25.41 mg/kg. Tomatoes exhibited the highest Cu bioaccumulation (18.55 mg/kg), while cauliflower had the lowest (3.86 mg/kg). The highest soil Cu contamination was found in pepper fields (25.41 mg/kg) and the lowest in tomato fields (7.68 mg/kg). The differential bioaccumulation of Cu in vegetables could be attributed to several factors, including soil pH, organic matter content, and the specific uptake mechanisms of each vegetable species.[35] Tomatoes, having a higher bioaccumulation factor, might possess more efficient mechanisms for Cu uptake or storage than other vegetables like cauliflowers, which exhibit lower accumulation rates.

The order of mean Cu bioaccumulation in vegetables was tomato > pepper > cabbage > potato > cauliflower. For soil, the order was cabbage field > pepper field > cauliflower field > potato field > tomato field (Figure 2 and Table 4). All Cu concentrations for vegetables were within the BFSA safe limits for human consumption.[36] The findings align with previous studies indicating that heavy metal contamination in agricultural soils can vary significantly based on crop type and soil management practices.[37] Further, the variation in soil Cu concentrations suggests localized differences in soil management practices, Cu application in fertilizers, or historical agricultural activities that may influence heavy metal distribution.[38] This study's findings are in line with previous research indicating that while vegetables can accumulate heavy metals from contaminated soils, the levels in this case are below toxic thresholds for humans, supporting the continued safe consumption of these vegetables.[39] Moreover, consistent monitoring and management of soil Cu levels are essential to ensure that they remain within safe limits, as indicated by both international guidelines and local regulations.

Chromium (Cr) content in vegetable fields. Chromium (Cr) concentrations varied significantly in both vegetables and soils across various upazilas in the Bogura district (Figure 3). Cr levels in vegetables such as potatoes, tomatoes, peppers, cauliflowers, and cabbages ranged from below detectable limits up to 5.44 mg/kg, with tomatoes showing the highest bioaccumulation at 5.44 mg/kg. Soil samples displayed Cr concentrations ranging from 11.95 mg/kg in pepper fields to 110.70 mg/kg in cauliflower fields, indicating notable variability in Cr retention. The average Cr bioaccumulation in vegetables followed the order of cauliflower > tomato > potato > cabbage > pepper, while in soils, it was cauliflower > cabbage > pepper > potato > tomato. This distribution suggests that Cr concentrations in vegetables often exceeded FSSAI's safe limits, underscoring a need for increased awareness and improvement in farming practices to mitigate soil contamination. The results align with global observations where Cr contamination in agricultural produce is influenced by local agricultural practices. For instance, studies conducted in Nigeria and India have reported similar variations in Cr levels, emphasizing the importance of localized soil management and monitoring practices.[37,40]

Lead (Pb) content in vegetable fields. Lead (Pb) concentrations in vegetables and soils from several Upazila vegetable fields in the Bogura district varied significantly (Figure 4). Pb levels in vegetables such as potato, tomato, pepper, cauliflower, and cabbage ranged from 5.97 to 25.77, 3.12 to 21.69, 4.61 to 20.58, 4.76 to 22.84, and 6.93 to 23.28 mg/kg, respectively (Table 4). In soil samples from these fields, Pb levels ranged from 10.42 to 31.38 mg/kg for potato soil, 10.56 to 33.03 mg/kg for tomato soil, 13.49 to 35.57 mg/kg for pepper soil, 16.42 to 26.09 mg/kg for cauliflower soil, and 13.43 to 35.64 mg/kg for cabbage soil (Table 4). The highest Pb bioaccumulation in vegetables was found in potatoes (25.77 mg/kg), while the lowest was in tomatoes (3.12 mg/kg). Such differences could be influenced by specific plant physiology, root system characteristics, and translocation abilities.[41] The highest Pb concentration in soils was found in cabbage field soil (35.64 mg/kg), and the lowest in potato field soil (10.42 mg/kg) (Table 4). This spatial variability in Pb soil content could also be due to differences in soil properties such as pH, organic matter, and moisture content, which affect the mobility and bioavailability of lead in the soil.[42] China and India have reported elevated Pb levels in vegetables due to industrial pollution and the use of contaminated water for irrigation.[43,44]

The mean Pb bioaccumulation in vegetables followed the order: potato > cauliflower > cabbage > pepper > tomato. For soils, the order was: cabbage field soil > tomato field soil > pepper field soil > cauliflower field soil > potato field soil (Table 4 and Figure 4). Notably, the Pb bioaccumulation in vegetables exceeds the maximum allowable limit set by the Bangladesh Food Safety Authority (BFSA). This underscores the need for farmers to adopt practices that minimize Pb contamination in agricultural soils.

Environmental pollution by heavy metals

Contamination factor (CF). The single metal contamination factor (CFi) is the ratio of the single metal concentration in a biotic or abiotic medium to the regulatory standard set by

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Table 4. Summary of concentrations (mg/kg) of heavy metals and bioaccumulation factor (BF), maximum allowable limit (MAL) in vegetables and surface soil from the vegetable fields in several upazilas of Bogura district.

METAL	CONCENTRATION (MG/KG)	POTATO	POTATO SOIL	TOMATO	TOMATO SOIL	PEPPER	PEPPER SOIL	CAULIFLOWER	CAULIFLOWER SOIL	CABBAGE	CABBAGE SOIL
Cu	Mean	9.31	13.91	12.12	13.24	11.17	16.34	6.42	14.58	9.83	16.54
	Min	8.26	11.02	8.34	7.68	7.79	10.75	3.86	8.99	5.01	12.88
	Max	11.38	18.81	18.55	18.77	15.56	25.41	9.13	18.81	16.36	19.06
	BF (mean)	0.67		0.92		0.68		0.44		0.59	
	MAL*, **, ***	30	36	30	36	30	36	30	36	30	36
Cr	Mean	1.6	41.3	1.6	29.9	0.7	43.5	1.8	70.2	1.3	44.8
	Min	BDL	20.4	BDL	16.8	BDL	12.0	BDL	26.2	BDL	21.3
	Max	3.8	90.9	5.4	72.3	2.8	88.9	3.8	110.7	3.1	64.3
	BF (mean)	0.04		0.05		0.02		0.03		0.03	
	MAL*, **, ***	1.0	100	1.0	100	1.0	100	1.0	100	1.0	100
Pb	Mean	12.41	21.47	13.88	22.51	11.81	21.09	13.73	21.39	13.27	22.41
	Min	5.97	10.42	3.12	10.56	4.61	13.49	4.76	16.42	6.93	13.43
	Max	25.77	31.38	21.69	33.03	20.58	35.57	22.84	26.09	23.28	35.64
	BF (mean)	0.58		0.62		0.56		0.64		0.59	
	MAL*, **, ***	0.10	85	0.10	85	0.10	85	0.30	85	0.30	85

BDL is below the detectable limit, MAL is the Maximum Allowable Limit set by the *Bangladesh Food Safety Authority (Food Safety (Contaminants, Toxins and Harmful Residues) Regulations, 2017), **Food Safety and Standards Authority of India (Food Safety and Standards (Contaminants, Toxins and Residues) Regulation, 2011), and ***Target values are specified to indicate desirable maximum levels of elements in unpolluted soils. Source: Denneman and Robberse 1990; Ministry of Housing, Netherlands 1994 (D. Ogundele et al., 2015).

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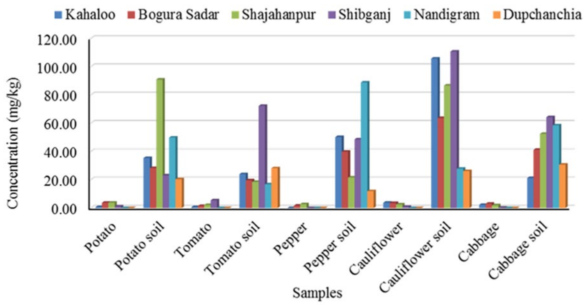

Figure 3. Chromium (Cr) accumulation in vegetables and their field soil in different upazilas of Bogura district.

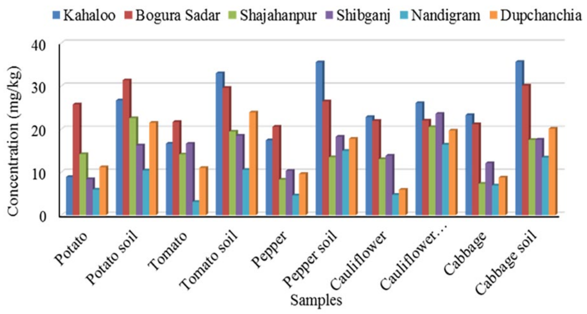

Figure 4. Lead (Pb) accumulation in vegetables and their field soil in different upazilas of Bogura district.

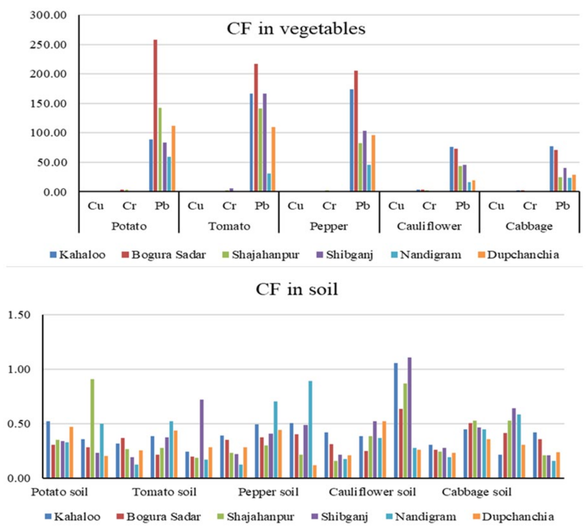

Figure 5. Contamination factor (CF) of heavy metals in vegetables (A) and their field soils (B) in different Upazilas of Bogura district.

national or international organizations like the Bangladesh Food Safety Authority (BSFA), Food Safety and Standards Authority of India (FSSAI), the World Health Organization (WHO), and the Food and Agricultural Organization of the UN (FAO). In terms of vegetable contamination, only Pb severely contaminated the vegetables ($CF > 6$) produced in different upazilas of the Bogura district, while the $CF < 1$ and $1 < CF < 3$ values for Cu and Cr indicated low to moderate contamination in vegetables produced in the Bogura district (Figure 5). In the case of vegetable field soil samples, contamination factor ($CF < 1$) values for Cu, Cr, and Pb revealed low

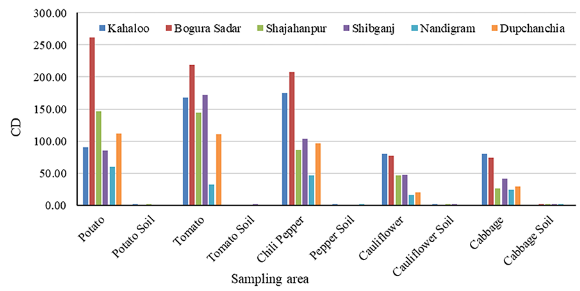

Figure 6. Contamination degree (CD) of heavy metals in vegetables and their field soils in different Upazilas of Bogura district.

contamination in all vegetable field soil collected from different upazilas of the Bogura district (Figure 5). The soil samples from vegetable fields showed low contamination for all three metals ($CF < 1$). This suggests that the soil itself is not heavily contaminated, and the high levels of Pb in vegetables might be attributed to other factors such as atmospheric deposition, irrigation water, or the use of contaminated fertilizers and pesticides.[3] The severe contamination of Pb in vegetables ($CF > 6$) observed in our study aligns with findings by Sinha et al,[45] who documented significant Pb accumulation in vegetables grown in urban and peri-urban areas due to traffic emissions and industrial activities.[45] This underscores the importance of considering external contamination sources when evaluating heavy metal levels in crops.

Contamination degree (CD). The Contamination Degree (CD) is the sum of the Contamination Factors (CF) of heavy metals measured at specific sites, assessing the overall contamination level in specific samples from a particular sampling location. CD values varied significantly between the soils of vegetable fields and the vegetable samples collected from the study area. All vegetable samples (potato, tomato, pepper, cauliflower, and cabbage) collected from various locations within the Bogura district exhibited a severe degree of contamination, whereas the soils from the vegetable fields had a low degree of contamination (Figure 6). The highest contamination levels were found in vegetables from Bogura Sadar and Kahaloo, while the lowest levels were in vegetables from Nandigram and Dupchanchia (Figure 6). These CD results indicate that although the soils of vegetable fields in different Upazilas of Bogura district had a low degree of contamination, the vegetables produced in these fields had a severe degree of contamination. This discrepancy between soil and vegetable contamination levels is consistent with findings in other studies. The previous studies reported that vegetables grown in urban and peri-urban areas frequently exhibit higher contamination levels than the soils they are grown in, attributing this to pollution sources beyond soil contamination.[1,20] Similarly, Muchuweti et al[2] highlighted that vegetables can accumulate heavy metals from atmospheric deposition, especially in areas with high vehicular emissions and industrial activities. This is particularly relevant for regions like Bogura Sadar and Kahaloo, where higher contamination levels

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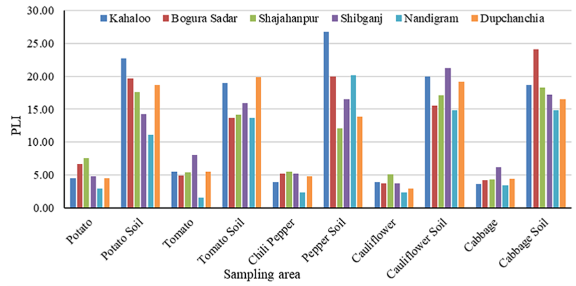

Figure 7. Pollution load index (PLI) of heavy metals in vegetables and their field soil of different upazilas of Bogura district.

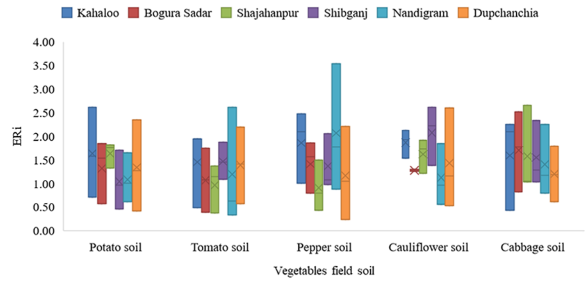

Figure 8. Ecological risk factors by Cu, Cr, and Pb in vegetable field soil of different upazilas of Bogura district.

were observed, possibly due to their proximity to urban and industrial areas.

Pollution load index (PLI). The Pollution Load Index (PLI) measures the total heavy metal concentrations in vegetables and soils by calculating the geometric mean of all metal concentrations. This index evaluates the samples' overall metal pollution scenario and is influenced by the contribution of three hazardous elements. PLI values varied significantly between the soils and vegetable samples collected from the study area. According to Figure 7, the pepper field soils in Kahaloo exhibited the highest PLI values. Conversely, the PLI was lower in all vegetables compared to their corresponding field soils. Therefore, the vegetable field soils of Kahaloo and Bogura Sadar had the highest pollution load indices, while the vegetables produced in Nandigram and Dupchanchia had the lowest pollution load indices. These results are consistent with findings from other studies on heavy metal pollution in agricultural soils and crops. Similar research by Saeed and Shaker[46] found that the PLI values in urban agricultural soils were significantly higher than those in rural areas, attributing the difference to urban pollution sources such as traffic emissions and industrial activities.[46] The higher PLI values in the soils of Kahaloo and Bogura Sadar suggest that these areas are subject to greater environmental pollution, possibly due to their proximity to urban centers and industrial activities. This is supported by the work of Wei and Yang,[47] who found that heavy metal contamination in urban soils is often higher due to increased human activities and industrial emissions. Conversely, the lower PLI values in vegetables from Nandigram and Dupchanchia indicate that these areas are less impacted by such pollution sources, resulting in cleaner agricultural produce.

Bioaccumulation factor for plants (BF). Concentrations of copper, chromium, and lead in the vegetables were found to be lower than those in the field soil. The bioaccumulation factors (BF) for copper, chromium, and lead varied significantly among potatoes, tomatoes, peppers, and cabbages. Specifically, for copper, the highest BF (0.92) was observed in tomatoes, while the lowest BF (0.44) was in cauliflower (Table 4). For chromium, the highest BF (0.05) was recorded in tomatoes, and the lowest BF (0.02) in peppers (Table 4). Additionally, for lead, cauliflower exhibited the highest BF (0.64), and peppers the lowest BF (0.56) (Table 4).[48] The BF values for all vegetables (potatoes, tomatoes, peppers, cauliflower, and cabbages) were less than 1 for Cu, Cr, and Pb. This indicates that vegetable plants translocate only trace amounts of these metals (Cu, Cr, and Pb) to their edible parts compared to the concentrations in the soil. Our research suggests that hyperaccumulation is often metal-selective, and diffusion limits at the soil level reduce the potential of plants to accumulate certain metals, specifically Cu, Cr, and Pb.

Our research indicates that the hyperaccumulation of metals is selective to specific metals and that barriers at the soil level can restrict the ability of some plants to accumulate certain metals, with copper, chromium, and lead being likely candidates. This pattern of metal accumulation is consistent with findings from other studies. For instance, Sharma[49] observed similar bioaccumulation patterns in various vegetables, noting that the bioavailability and uptake of metals can be significantly influenced by soil properties and plant species.[50] Additionally, Cui et al[51] emphasized the role of root morphology and physiology in metal uptake, suggesting that variations in root architecture among different vegetable species could explain the observed differences in BF values. Moreover, McBride[52] highlighted that factors such as soil pH, organic matter content, and the presence of competing ions can impact metal uptake by plants.[52]

Ecological risk factor (ERi). The ecological risk factor (ER) is designed to assess soil contamination by a single toxic compound. The ERi values for soil samples collected from the study areas in the Bogura district are summarized in Figure 8. According to these values, the individual ERi values for Cu, Cr, and Pb in the soils of five vegetable fields (potato, tomato, pepper, cauliflower, and cabbage) across six study sites (Kahaloo, Bogura Sadar, Shajahanpur, Shibganj, Nandigram, and Dupchanchia) indicated low ecological risk, as all ERi values were less than 40. Among the metals, copper posed the highest ecological risk factor, followed by lead and chromium, in the vegetable field soils across the six upazilas in the Bogura district. The low ER values for Cu, Cr, and Pb in our study suggest that the soils in the vegetable fields of the Bogura district are relatively uncontaminated with these heavy metals, posing

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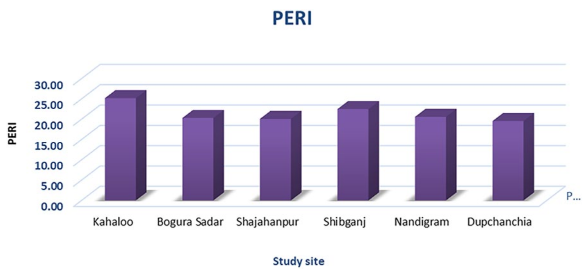

Figure 9. Potential ecological risk index by multi heavy metals in vegetable fields of different Upazilas of Bogura district.

minimal risk to the local ecosystem. Moreover, the observed trend of copper posing the highest ecological risk, followed by lead and chromium, has been noted in other studies as well. For example, Zhao et al[53] found that copper and lead often have higher ER values in contaminated soils due to their widespread use in agricultural practices and industrial activities.

Potential Ecological Risk Index (PERI). The potential ecological risk index (PERI) is widely used to evaluate soil quality and the degree of contamination by various toxic compounds. The PERI for soil samples collected from study areas in the Bogura district is summarized in Figure 9. According to the PERI values for Cu, Cr, and Pb in the soil samples, 6 study sites posed low ecological concerns, as their PERI values were all below 150. Ecological risk reflects the biological community's sensitivity to heavy metals due to excessive toxic metal contamination. The overall ecological risk assessment from this experiment indicates that the multiple toxic heavy metals present in vegetable fields in different upazilas of the Bogura district pose lower ecological risks. This index has been widely adopted and validated in numerous studies. Luo et al[54] and Wu et al[55] applied the PERI to agricultural soils in China and found that the ecological risks were predominantly low to moderate, similar to our findings in Bogura district. This supports our observation that vegetable fields in the Bogura district, despite being exposed to multiple toxic heavy metals, exhibit low PERI values, suggesting a limited ecological impact.

Health risks of heavy metals in vegetables of Bogura

This study assessed the cancerous and non-cancerous health risks to adults in Bangladesh from consuming vegetables contaminated with heavy metals in the Bogura district. It aimed to inform consumer health protection policies by utilizing the United States Environmental Protection Agency's (USEPA) guidelines for evaluating health risks associated with heavy metal pollution in food.

Non-carcinogenic health risk. The study assessed the non-carcinogenic hazard quotient (HQ) of individual heavy metals and the cumulative non-carcinogenic hazard index (HI) from multiple metals through the consumption of vegetables (potato, tomato, pepper, cauliflower, and cabbage) by adults in the study region, as detailed in Table 5. For copper (Cu), a hazard quotient exceeding safe levels ($HQ > 1$) was observed in tomatoes, peppers, and cabbages from Kahaloo, Dupchanchia, Nandigram, and Shibganj areas of the Bogura district. Other vegetables from these areas were within safe limits ($HQ < 1$) for Cu. For chromium (Cr), samples of potato, tomato, pepper, cauliflower, and cabbage from Shibganj, Shajahanpur, Bogura Sadar, and Kahaloo had hazard quotients above safe levels ($HQ > 1$), except for potatoes, tomatoes, and peppers from Kahaloo and peppers, cauliflowers, and cabbages from Shibganj Upazila. Lead (Pb) levels in vegetables from all study areas showed hazard quotients ($HQ > 1$) ranging from 2 to 20 times the safe limit for adults, indicating significantly higher risk compared to other metals due to the high Pb content and very low reference dose (RfD). The cumulative hazard index for multiple metals exceeded safe limits ($HI > 1$) for vegetable consumption in all study areas, indicating a significant non-cancer risk. The cumulative non-carcinogenic health risk was highest in Bogura Sadar, followed by Kahaloo, Shajahanpur, Shibganj, Dupchanchia, and Nandigram. The findings suggest that heavy metal contamination in vegetables poses a health hazard to consumers in various upazilas of the Bogura district. Therefore, measures are needed to reduce heavy metal pollution in these areas to protect consumer health.

These findings are consistent with other studies highlighting the health risks of heavy metal contamination in food crops. The previous studies reported that vegetables grown in contaminated soils in Bangladesh frequently exceed safe levels of heavy metals, posing significant health risks to consumers.[29,56] Similarly, a study by Kabir[57] found that heavy metal concentrations in rice grain from industrial areas in Bangladesh often surpass the permissible limits set by international standards, corroborating the elevated hazard quotients observed in this study.[28] Moreover, the observed high levels of Pb in the vegetables align with findings from a review by Islam,[58] which documented substantial Pb contamination in agricultural soils due to industrial emissions and the use of contaminated irrigation water in Bangladesh.[58]

Carcinogenic health risk. This experiment evaluated the cancer risk associated with consuming vegetables (potato, tomato, pepper, cauliflower, and cabbage) contaminated with chromium (Cr) and lead (Pb). The International Agency for Research on Cancer (IARC) classifies Cr and Pb as carcinogenic agents, with chronic exposure to low concentrations of these metals potentially causing various cancers.[22] Table 6 presents the calculated carcinogenic health risk (ILCRi) due to individual metals and the cumulative cancer risk for multiple metals (CHR) for Cr and Pb through vegetable consumption. The ILCRi for Pb exceeded the unacceptable cancer risk limit ($>10^{-4}$) in all vegetable samples from the six upazilas in the Bogura district. For Cr, the ILCRi exceeded the unacceptable cancer risk limit ($>10^{-4}$) in vegetables produced in Bogura Sadar and Shajahanpur Upazilas, posing an unacceptable cancer risk. Consequently, Pb is identified as

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Table 5. Non-carcinogenic health risk (HQi and HI) for the adult population through the consumption of vegetables produced in the study area.

HQI	POTATO			TOMATO			PEPPER			CAULIFLOWER			CABBAGE			HI
SAMPLING AREA	CU	CR	PB	CU	CR	PB	CU	CR	PB	CU	CR	PB	CU	CR	PB	
Kahaloo	0.58	0.67	7.10	1.31	0.69	13.27	0.54	0.00	13.89	0.29	3.49	18.20	0.35	2.10	18.55	81.02
Bogura Sadar	0.67	3.48	20.53	0.77	1.38	17.28	0.61	1.57	16.40	0.27	3.28	17.48	0.38	2.86	16.87	103.80
Shajahanpur	0.79	3.51	11.32	0.88	1.98	11.27	0.68	2.56	6.60	0.53	2.42	10.40	0.46	1.83	5.84	61.08
Shibganj	0.63	1.10	6.69	0.86	5.06	13.24	0.91	0.00	8.25	0.46	0.85	11.03	1.14	0.21	9.65	60.07
Nandigram	0.60	0.00	4.76	0.82	0.00	2.49	1.08	0.00	3.67	0.64	0.00	3.79	1.12	0.00	5.52	24.49
Dupchanchia	0.63	0.00	8.91	1.18	0.00	8.77	0.85	0.00	7.66	0.50	0.00	4.73	0.66	0.00	6.99	40.88

Table 6. Carcinogenic health risk (CHR) for the adult population through the consumption of vegetables produced in the study area.

ICLE	POTATO		TOMATO		PEPPER		CAULIFLOWER		CABBAGE		CHR
SAMPLING AREA	CR	PB	CR	PB	CR	PB	CR	PB	CR	PB	
Kahaloo	0.00	2.92	0.00	5.47	0.00	5.72	0.02	7.49	0.01	7.64	2.93E + 01
Bogura Sadar	0.02	8.45	0.01	7.12	0.01	6.75	0.02	7.20	0.02	6.94	3.65E + 01
Shajahanpur	0.02	4.66	0.01	4.64	0.02	2.72	0.01	4.28	0.01	2.40	1.88E + 01
Shibganj	0.01	2.76	0.03	5.45	0.00	3.40	0.01	4.54	0.00	3.97	2.02E + 01
Nandigram	0.00	1.96	0.00	1.02	0.00	1.51	0.00	1.56	0.00	2.27	8.33E + 00
Dupchanchia	0.00	3.67	0.00	3.61	0.00	3.15	0.00	1.95	0.00	2.88	1.53E + 01

the most abundant carcinogen in the research area, necessitating efforts to limit Pb exposure to protect the population from cancer risk. The cumulative carcinogenic health risk for multiple metals (CHR) in all analyzed vegetable samples from different upazilas in the Bogura district exceeded the unacceptable cancer risk level ($>10^{-4}$). Among all vegetable samples, those produced in Bogura Sadar have the highest cancer risk (3.65E + 01), while crops from Nandigram have the lowest risk (8.33E + 00). The CHR values for Cr and Pb in vegetables showed the following order: Bogura Sadar > Kahaloo > Shibganj > Shajahanpur > Dupchanchia > Nandigram (Table 6).

The elevated levels of Cr and Pb in the vegetables highlight significant public health concerns. Previous studies corroborate these findings. For instance, Li[59] reported a similar trend of high Pb levels in vegetables grown in urban areas of China, contributing to increased cancer risks among consumers.[59] The high levels of Pb and Cr in the vegetables align with findings from studies indicating widespread Pb and Cr contamination in agricultural soils due to industrial emissions and the use of contaminated agricultural inputs.[60,61] The study underscores the significant carcinogenic and non-carcinogenic risks posed by Cr and Pb in vegetables consumed in the Bogura district. The cumulative health risk levels necessitate urgent intervention to mitigate heavy metal contamination and protect public health. Public awareness campaigns can also play a crucial role in educating farmers and consumers about the potential health risks associated with heavy metal contamination.[62]

Conclusion

This study assessed heavy metal (Cu, Cr, Pb) contamination in soil and vegetables across six upazilas in Bogura, Bangladesh. While Cu levels were within safe limits, Cr and Pb in vegetables exceeded permissible limits, particularly Pb. Contamination was highest in Bogura Sadar and Kahaloo. Despite minimal transfer of metals to edible parts, health risk assessments indicated significant carcinogenic and non-carcinogenic risks from vegetable consumption. The findings underscore the urgent need for mitigation measures to reduce heavy metal pollution and protect public health in these areas.

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Author Contributions Statement

Sadia Samma: Conceptualization; Field experiment; Instrumental analysis; Data curation; Investigation; Methodology; Md. Sirajul Islam Khan: Methodology; Data curation, Review & editing, Resources; Supervision; Md. Tazul Islam Chowdhury: Instrumental analysis; Editing original draft; Mohammed Ariful Islam: Resources, Writing—review & editing; Jerker Fick: Writing—review & editing; Abdul Kaium: Conceptualization; Instrumental analysis; Data curation; Investigation; Methodology; Writing-original draft, Supervision.

ORCID iD

Abdul Kaium https://orcid.org/0000-0003-1952-8617

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