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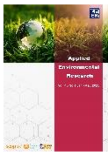

Research Article

Assessment of Metal Contamination and Potential Health Risk of Roadside Vegetables along the Sayre Highway, Province of Bukidnon, Philippines

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Abstract

This study assessed heavy metal contamination in roadside vegetables (*Ipomoea batatas* and *Moringa oleifera*) across five urbanized localities in Bukidnon, Philippines, and evaluated potential human health risks. Metal concentrations (Cd, Cr, Cu, Co, Fe, Mn, and Zn) were analyzed via atomic absorption spectrophotometry and compared against FAO/WHO maximum permissible limits. The results revealed severe contamination, with Mn (575.27–862.17 mg kg^{-1}) and Fe (256.46–706.68 mg kg^{-1}) dominating natural soil mineralogy (Adtuyon series) and anthropogenic inputs. Toxic Cr (16.20–21.93 mg kg^{-1}) exceeded permissible limits by nine and a half times in Quezon. Health risk assessments revealed negligible noncarcinogenic risks (THQ<1) but significant carcinogenic risks (TCR: 4.02E^{-2} to 4.94E^{-2}; exceeding the USEPA's 1E^{-4} threshold), driven by Cd/Cr ingestion. Correlation analysis revealed synergistic (Zn-Fe: 0.453*) and antagonistic (Zn-Cr: -0.417*) interactions. Urgent mitigation strategies include buffer zones (≥30 m from roads), *Moringa*-based phytoremediation, and TCR integration into national food safety policies.

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Introduction

Bukidnon, Philippines, is renowned for its thriving economy, extensive transportation network, and robust agricultural industry. However, the concentration of human activities in these areas raises concerns regarding metal contamination in the environment. Vehicular emissions, industrial activities, and farming practices are significant sources of metal pollution in the vegetation along the roadsides of these localities. The problem is that the extent of metal contamination in the roadside vegetables of Bukidnon's urbanized localities remains largely unknown. *Ipomoea batatas* and *Moringa oleifera* were selected because of their high consumption rates in Bukidnon [1–2] and their hyperaccumulation potential for Cd/Co [3]. The potential risks associated with metal contamination, such as bioaccumulation and human exposure through the food chain, are also unclear. This lack of understanding makes it challenging to develop effective measures to mitigate the impacts of metal pollution on human health and the environment [4]. The significance of this study lies in its contribution to understanding metal contamination in the roadside vegetation of highly urbanized localities in Bukidnon, Philippines. The study results provide baseline data on metal concentrations in the study area, which can be used to develop effective strategies for managing metal pollution in the region. This is crucial for ensuring the safety of the food supply and protecting human health from the harmful effects of metals. Additionally, the study's focus on the five urbanized localities in Bukidnon is significant because it allows for a more targeted approach to monitoring metal pollution in the region. By identifying

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differences in metal concentrations among localities, this study can provide insights into the sources and extent of metal contamination in specific areas, which can guide local authorities in implementing appropriate mitigation measures.

Assessing the potential risks to human health associated with exposure to hazardous substances, such as metals, chemicals, or pathogens, in environmental media, such as air, water, soil, or food, is known as a potential human health risk assessment or PHRHA [5–6]. In the PHHRA, exposure pathways are identified, exposure levels are quantified, and the likelihood and severity of unfavorable health effects are assessed via toxicological information and exposure standards. PHHRA is a crucial tool for evaluating environmental and public health risks because it provides a foundation for risk management and decision-making strategies to safeguard human health from exposure to hazardous substances. The work of the U.S. contains one of the earliest mentions of the PHHRA. In the early 1990s, the Environmental Protection Agency (EPA) established a framework for assessing the risks to human health posed by hazardous ecological substances. Since then, PHHRA has been extensively used in environmental and public health studies to evaluate potential health risks associated with exposure to dangerous substances [7]. A quantitative method for evaluating the potential health risks linked to contact with a single chemical or contaminant found in a particular food or environmental medium is called the target hazard quotient (THQ) [8–9]. It is calculated by dividing the chemical or contaminant's estimated daily intake by the reference dose (RfD) value [10]. The RfD estimates the maximum amount of a chemical that can be ingested daily for the rest of one's life without harming one's health [11]. The THQ is employed in risk assessment studies to ascertain the possible health risks associated with contact with a particular chemical or contaminant for a specific food or environmental medium [12]. To evaluate the potential health risks associated with exposure to contaminants such as heavy metals, pesticides, and persistent organic pollutants, the THQ is frequently used in environmental and public health studies [13-14].

The process of assessing a substance's potential to cause cancer by exposure to radiation, chemicals, or other environmental factors is known as carcinogenic risk assessment [15]. Identifying the risk, describing the exposure, and calculating the likelihood of developing cancer are all steps in the risk assessment process. Risk characterization, exposure assessment, dose–response assessment, and hazard identification are the four main steps in the carcinogenic risk assessment process [14, 16]. Identifying hazards involves determining whether a substance or agent is capable of causing cancer. Assessing the dose–response relationship involves determining how much exposure corresponds to how likely you are to develop cancer. Measuring or estimating the level of exposure in a population is part of the exposure assessment process [16–17]. To determine the overall risk of developing cancer, the results of the previous steps are combined during the risk characterization process.

This study aims to assess the metal concentrations in roadside vegetables from five highly urbanized localities in the Province of Bukidnon, Philippines. Specifically, this study aims to 1) determine the concentrations of metals (e.g., cadmium (Cd), chromium (Cr), copper (Cu), cobalt (Co), iron (Fe), manganese (Mn), and zinc (Zn)) in vegetable samples from sweet potato tops (*Ipomoea batatas*) and Malungay (*Moringa oleifera*) collected from roadside areas and 2) evaluate the potential risks associated with metal contamination in the roadside vegetables of the study area.

Materials and methods

1) Sampling sites, sample collection and analysis

Plant leaf samples of sweet potato tops (*Ipomoea batatas*) and Malungay (*Moringa oleifera*) were collected from each selected sampling site across five localities in the Province of Bukidnon along the Sayre Highway, as shown in Figure 1. The samples were thoroughly washed with distilled water to remove any attached soil particles. They were then cut into smaller pieces, placed in a clean large crucible, and oven-dried at 65 °C for 12 hours until brittle and crisp [18]. The plants were collected in accordance with the FAO GACP guidelines [19]. The dried leaf samples were ground into a fine powder via a clean Osterizer and sieved through a 0.2 mm sieve [20]. The collection was conducted during the dry season from April to May 2023. The samples were analyzed at the Soil and Plant Analysis Laboratory (SPAL), Central Mindanao University (CMU), Maramag, Bukidnon, Philippines. Metal analysis was performed via Agilent 200 Series AAS calibrated with NIST-certified standards. The operational parameters (wavelength, slit width, lamp current) were optimized according to the manufacturer's guidelines for each specific metal. The digestion protocols included HCl (Cu, Co, Fe, Mn, Zn) [21] and H_2SO_4-H_2O_2 (Cd, Cr) [22].

2) Potential human health risk assessment

The potential human health risk of vegetable consumption was estimated by calculating the estimated daily intake (EDI) of metals, health hazard index (HHI), and target cancer risk (TCR) [23]. The EDI (Eq.1) was used to calculate the level of exposure to a particular metal in vegetables via the ingestion/oral route [24].

$$EDI = \frac{E_f \times E_D \times F_{IR} \times C_m \times C_f}{B_w \times T_A} \times 10^{-3} \qquad \text{(Eq.1)}$$

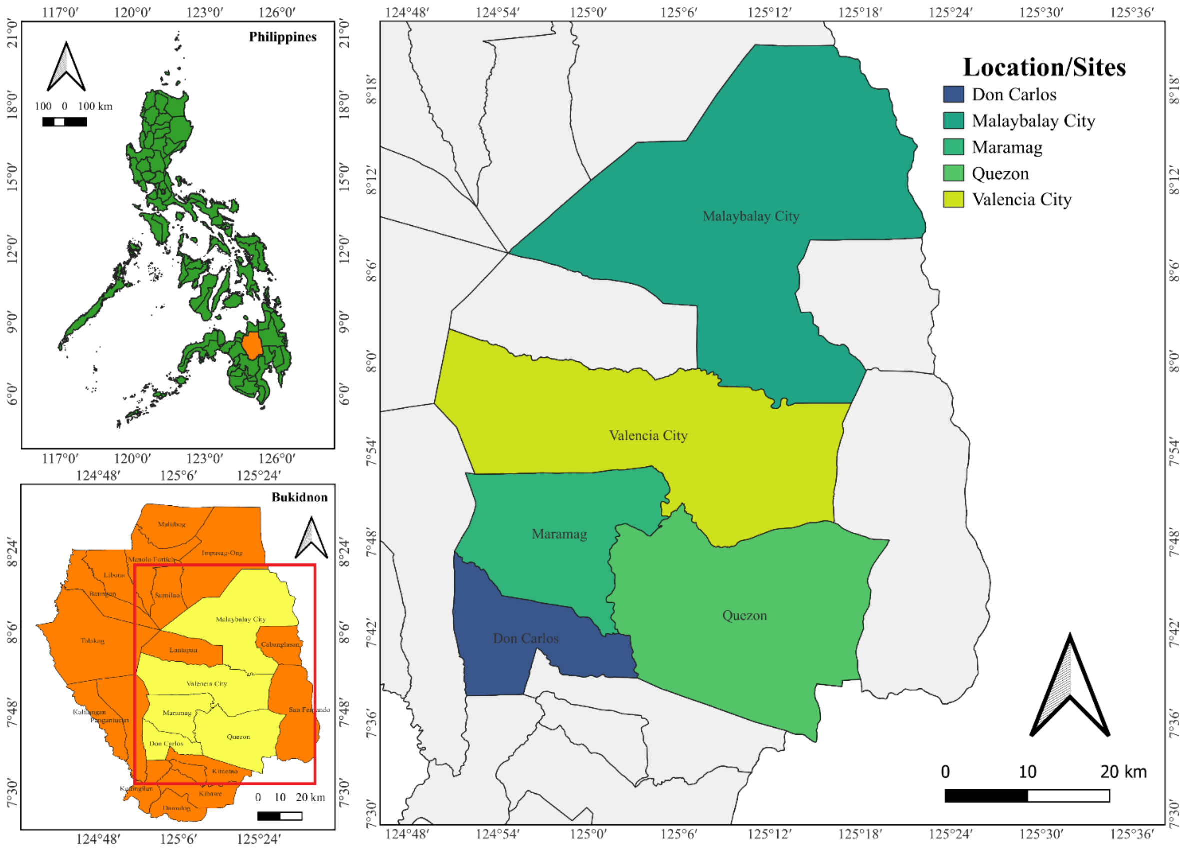


Figure 1 Location map of the study sites of the five localities in Bukidnon, Philippines.

where Ef is the exposure frequency (365 days per year); ED is the exposure duration (in years); Cm is the metal concentration (mg kg^{-1}); F_{IR} is the daily average vegetable consumption (g $person^{-1}$ day^{-1}); and Cf is the conversion factor for fresh vegetable weight to dry weight (0.085) [25–26]. Bw is the reference body weight for an adult (kg), and TA is the average exposure time (days). The exposure duration was 70 years [27–28]. This was based on the average life expectancy of the Philippine population. The Philippine population FIRs for Malungay and Sweet Potato leaves are 15.00 and 16.88 g $person^{-1}$ day^{-1}, respectively [28–29].

3) Target hazard quotient (THQ)

The target hazard quotient (THQ) as shown in Eq.2 estimates the risk associated with pollutant exposure. The potential health risks of metal consumption through vegetables were evaluated. The equation below was used to estimate the THQ values of the population as a result of consuming contaminated vegetables, as described by Chen et al. [8] and Ezemonye et al. [9].

$$THQ = EDI / RfD \qquad (Eq.2)$$

where RfD is the oral reference dose (mg kg^{-1} day^{-1}). The RfD is an estimate with uncertainty spanning an order of magnitude of daily oral exposure to the human population that is likely to be without an appreciable risk of deleterious effects during a lifetime [28].

Considering the uncertainty factor, this number was based on the no-observed-adverse-effect level (NOAEL). If the estimated daily intake of contaminated vegetables in a population exceeds the RfD, then the occurrence of associated health risks increases.

A THQ <1 is considered safe or has noncarcinogenic consequences.

When THQ >1, the probability of danger increases.

The equation determines the HHI by adding the individual metal target hazard quotient values.

$$HHI = \sum_{i}^{n} THQ_i \qquad (Eq.3)$$

4) Carcinogenic risk assessment (CR)

Carcinogenic risk assessment estimates the cumulative probability of developing cancer throughout a lifetime by exposure to a unit dose of a probable carcinogen [33]. The possibility of cancer risk in sample vegetables through the intake of carcinogenic heavy metals was estimated via the cancer risk (CR) shown in Eq.4 [34]. The TCR from heavy metal intake, which can have a carcinogenic effect depending on the exposure level, was subsequently calculated via Eq.5.

$$CR = EDI \times CSF \qquad (Eq.4)$$

$$TCR = \sum_{i=1}^{n} CR_i \qquad (Eq.5)$$

where CSF is the cancer slope factor, which is defined as the risk generated by an average lifetime amount of

1 mg kg^{-1} day^{-1} of carcinogen chemical and is contaminant specific. Cancer risk was expressed as incremental lifetime cancer risk, i.e., the probability of developing cancer over 70 years due to 24-hour exposure to a potential carcinogen. In contrast, if the TCR exceeds the maximum threshold values of 1.00×10^{-4} and 1.00×10^{-4}, there is a high risk of carcinogen exposure. EDI = LADD for the TCR calculations. Body weight (Bw): 60 kg, average exposure time (TA): 25,550 days (70 years × 365 days) [28].

Table 1 summarized the values of RfD and CSF used in this study.

Table 1 Oral reference dose (RfD) and cancer slope factor for heavy metals in the unit of mg kg^{-1} day^{-1}

Metal(oids)	RfD	Source	CSF
Cadmium	0.001	USEPA [24]	6.30
Chromium	1.50	USEPA [24]	4.10
Cobalt	0.020	USEPA [24]	**
Copper	0.040	ECI [27]	**
Iron	0.007	USEPA [24]	**
Manganese	0.140	USEPA [28]	**
Zinc	0.300	USEPA [29]	**

Remark: ** CSF value not available/not applicable

5) Statistical analysis

The statistical analysis in this study was performed via Pearson correlation to evaluate metal interactions via SPSS version 28. A significance level of $p < 0.05$ was considered.

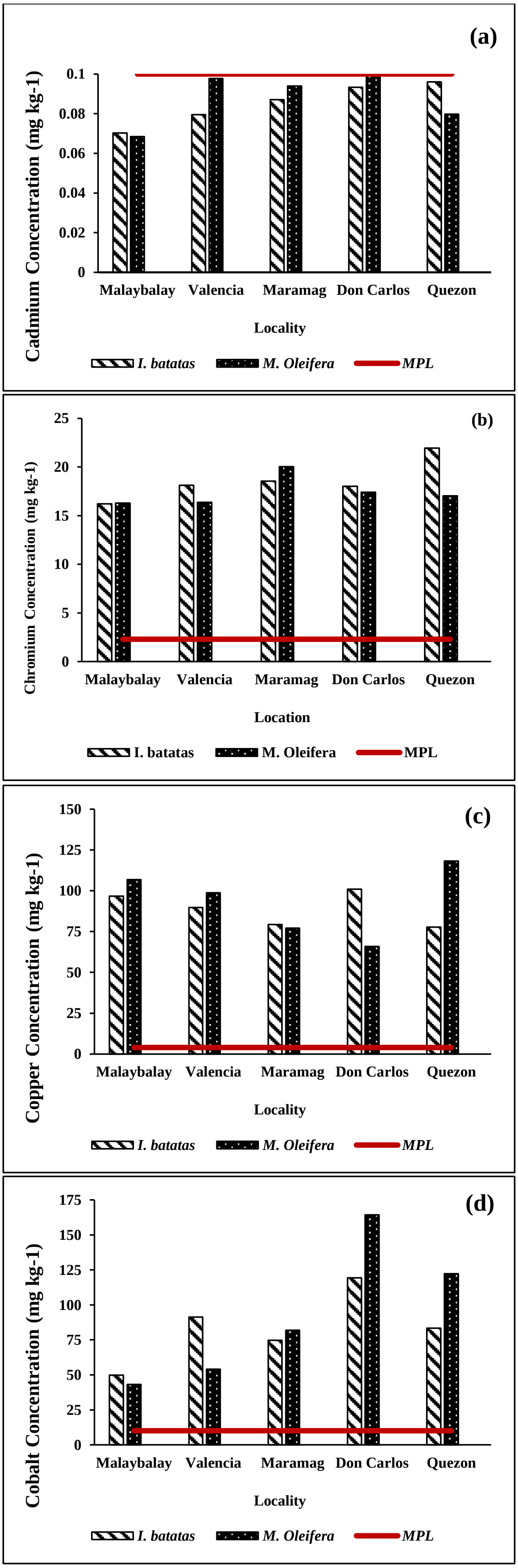
Results and discussion

1) Metal concentrations in vegetables (*I. batatas* and *M. oleifera*)

The concentrations of metals in *I. batatas* (sweet potato tops) and *M. oleifera* (moringa) from Bukidnon, Philippines, provide critical insights into agricultural contamination and its implications for human health. While metals such as Co, Mn, Fe, and Zn are essential micronutrients, their excessive accumulation disrupts plant physiology and poses severe health risks. The mean metal concentrations in *I. batatas* and *M. oleifera* across five localities along the Sayre highway in the Province of Bukidnon, Philippines, are presented in Figure 2, with comparisons to FAO/WHO maximum permissible limits (MPLs). For Cd, Cr, Cu, Co, Fe, Mn, and Zn, the MPLs are 0.1, 2.3, 4.0, 10, 425.50, 500, and 50 mg kg^{-1} [35–37], respectively. The *I. batata* samples presented concentrations of Cd (0.070-0.096), Cr (16.20-21.93), Cu (77.70-100.96), Co (49.90-119.26), Fe (256.46-706.68), Mn (575.27-855.71), and Zn (9.94-55.16) mg kg^{-1}. The concentrations of Cd (0.069-0.101), Cr (16.29-20.03), Cu (65.92-118.21), Co (43.17-164.30), Fe (309.78-700.76), Mn (686.85-862.17), and Zn (17.79-45.94) mg kg^{-1} in *M. oleifera* are shown in Figure 2. The metal distribution trends (Table 2) revealed that Mn and Fe were the dominant contaminants across localities, constituting 68-76% of the total metal loads (Figure 2), with Mn concentrations exceeding the FAO/WHO limit (500 mg kg^{-1}) in Quezon (*I. batatas*) and Fe levels surpassing the upper threshold (425.50 mg kg^{-1}) in Don Carlos (*I. batatas*). The top two metals across all the sites are likely due to natural soil mineralogy and anthropogenic inputs such as fertilizers, and the dominant soil type, the Adtuyon soil series, is predominant in the province, with soils classified as such containing mica and iron oxides [38–39]. While Mn is vital for enzyme activation [40], its excessive accumulation risks neurotoxicity, and elevated Fe may induce oxidative stress or hemochromatosis in humans [41]. These findings align with studies in Marinduque, where Fe in sweet potato tops reached 625.35 mg kg^{-1} [36], emphasizing the need to balance agricultural productivity with contamination control.

Severe contamination from Cr and Co consistently exceeded permissible limits. Cr peaked at 21.93±3.90 mg kg^{-1} in Quezon (*I. batatas*), which is nine times higher than the limit of 2.30 mg kg^{-1}. The highest Co concentration was observed in Don Carlos (M. oleifera: 164.30 ±37.33 mg kg^{-1}). These toxic metals, although less abundant than Mn and Fe, require urgent remediation because of their disproportionate health impacts. Copper (Cu) and Zn play dual roles as essential nutrients and contaminants. The Cu level in *M. oleifera* (Quezon: 118.21 ± 70.19 mg kg^{-1}) exceeded limits, disrupting photosynthesis [42], whereas the Zn level in Malaybalay (*I. batatas*: 55.16 ± 13.70 mg kg^{-1}) exceeded limits. Although Zn supports immune function [43], chronic overexposure causes anemia, underscoring the need for regulated use. The Cd concentrations in *M. oleifera* from Don Carlos were lower than the FAO/WHO limit (0.100 mg kg^{-1}), mirroring urban Cd levels in Quezon City, Philippines [44]. The phytotoxicity of Cd disrupts photosynthesis and nutrient uptake [45] and has the lowest distribution, reflecting its limited environmental prevalence despite high toxicity. Elevated Co/Cu in Don Carlos was linked to mining slag [38], whereas Cr in Quezon was linked to vehicular emissions [46]. The metal trends at each location are presented in Table 2, such as elevated Co and Cu in Don Carlos and Zn in Malaybalay, highlighting the influence of mining and farming practices.

Compared with nonleafy vegetables, the leafy vegetable *I. batatas* and *M. oleifera* accumulate greater amounts of metals [36, 47]. The distribution trend of metals in the roadside vegetables in Figure 2 shows that Mn and Fe had the highest concentrations of metals in the two vegetables across all localities along the Sayre Highway. Integrating these insights, targeted strategies such as phytoextraction using *M. oleifera* for Cd and Co and monitoring *I. batatas* for Fe and Mn are vital for mitigating risks while preserving nutritional benefits.



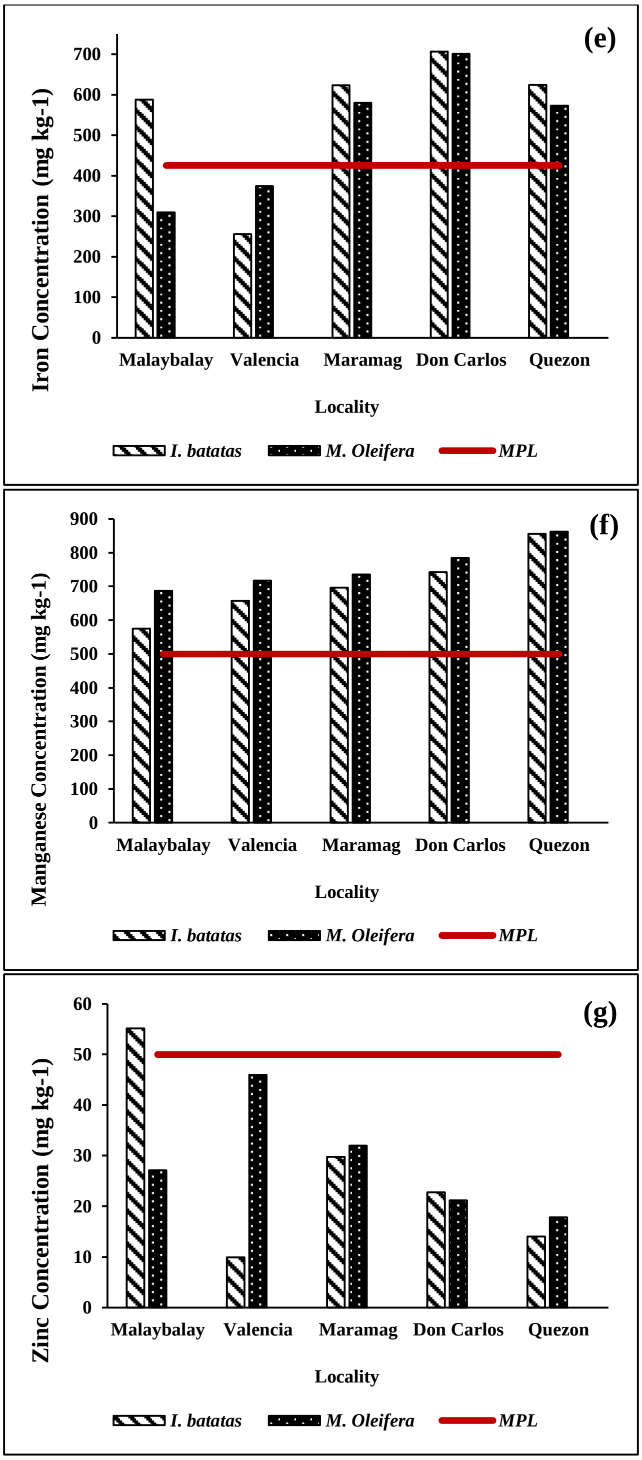


Figure 2 Metal concentrations (mg kg^{-1}) in vegetables: (a) Cd, (b) Cr, (c) Cu, (d) Co, (e) Fe, (f) Mn, and (g) Zn.

2) Estimated daily intake (EDI)

The EDI of metals through the consumption/oral intake of vegetables along the roadside. The FIRs used in the computation of the EDI for *I. batatas* and the leafy vegetable *M. oleifera* were 15 and 16.88, respectively [23]. The individual metal EDIs resulting from vegetable ingestion were in the order of Mn > Fe > Cu > Co > Zn > Cr > Cd, with EDI values ranging from 1.56E-02 to 2.32 E-02 for Mn, 6.94 E-03 to 1.91 E-02 for Fe, 2.10E-03 to 2.62E-03 for Cu, 1.35E-03 to 3.23E-03 for Co, 2.69E-04 to 1.49E-03 for Zn, 4.38E-04 to 5.94E-04 for Cr, and 1.90E-06 to 2.60E-06 for Cd.

Table 2 Distribution trend of metal concentrations in vegetables along the Sayre Highway, Bukidnon

Location/sites	Vegetables	
	I. batatas	***M. oleifera***
Malaybalay	Fe > Mn > Cu > Zn > Co > Cr > Cd	Mn > Fe > Cu > Co > Zn > Cr > Cd
Valencia	Mn > Fe > Co > Cu > Cr > Zn > Cd	Mn > Fe > Cu > Co > Zn > Cr > Cd
Maramag	Mn > Fe > Cu > Co > Zn > Cr > Cd	Mn > Fe > Co > Cu > Zn > Cr > Cd
Quezon	Mn > Fe > Co > Cu > Zn > Cr > Cd	Mn > Fe > Co > Cu > Zn > Cr > Cd
Don Carlos	Mn > Fe > Co > Cu > Cr > Zn > Cd	Mn > Fe > Co > Cu > Zn > Cr > Cd

Table 3 The EDI of metals in mg kg^{-1} day^{-1} through vegetables (*I. batatas and M. oleifera*) along the Sayre Highway, Bukidnon

Metal(oids)	Vegetables	Location/sites				
		Malaybalay	Valencia	Maramag	Don Carlos	Quezon
Cd	*I. batatas*	1.90E-06	2.15E-06	2.36E-06	2.53E-06	2.60E-06
	M. oleifera	1.65E-06	2.35E-06	2.26E-06	2.43E-06	1.92E--06
Cr	*I. batatas*	4.38E-04	4.90E-04	5.02E-04	4.88E-04	5.94E-04
	M. oleifera	3.92E-04	3.94E-04	4.82E-04	4.19E-04	4.10E-04
Cu	*I. batatas*	2.62E-03	2.43E-03	2.15E-03	2.73E-03	2.10E-03
	M. oleifera	2.57E-03	2.38E-03	1.85E-03	1.59E-03	2.84E-03
Co	*I. batatas*	1.35E-03	2.47E-03	2.02E-03	3.23E-03	2.26E-03
	M. oleifera	1.04E-03	1.30E-03	1.97E-03	3.95E-03	2.94E-03
Fe	*I. batatas*	1.59E-02	6.94E-03	1.69E-02	1.91E-02	1.69E-02
	M. oleifera	7.45E-03	9.02E-03	1.40E-02	1.69E-02	1.38E-02
Mn	*I. batatas*	1.56E-02	1.78E-02	1.89E-02	2.01E-02	2.32E-02
	M. oleifera	1.65E-02	1.72E-02	1.77E-02	1.88E-02	2.07E-02
Zn	*I. batatas*	1.49E-03	2.69E-04	8.05E-04	6.16E-04	3.79E-04
	M. oleifera	6.53E-04	1.11E-03	7.70E-04	5.09E-04	4.28E-04

The EDI values for *M. oleifera* ranged from 1.65E-02 to 2.07E-02 for Mn, 7.45E-03 to 1.69E-02 for Fe, 1.59E-03 to 2.84E–03 for Cu, 1.04E-03 to 3.95E-03 for Co, 4.28E-04 to 1.11E-03 for Zn, 3.92E-04 to 4.82E-04 for Cr, and 1.65E-06 to 2.43E-06 for Cd. As illustrated in Figure 3, Mn and Fe collectively contributed 74-82% of the total EDI across localities because of their high concentrations in vegetables and their high consumption rates. This dominance underscores their role as primary exposure vectors, despite their lower toxicity than Cr or Cd. The figure further highlights locality-specific variations, such as elevated Zn EDI contributions in Malaybalay (15%) linked to local agrochemical use. Concentration-driven exposure amplifies risks from essential metals. Proportional contribution (%) of heavy metals to total EDI from consuming *I. batatas* and *M. oleifera*. Values derived from the mean EDI are shown in Table 3. The dominance of Mn/Fe reflects their high bioavailability and dietary significance, whereas Cr/Cd contributions indicate disproportionate carcinogenic risks per unit intake. Notably, metals such as Fe, Zn, Mn, and Cu are present in trace amounts [48]. A similar result was observed in the study by Nolos et al. [36]. The computed EDI was used to calculate the THQ and HHI with the RfD for each metal. The values for these indices were used to interpret the possible health hazards of the metals (Table 1).

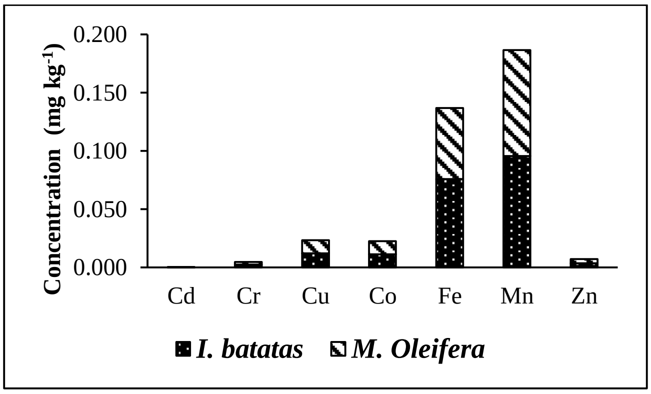


Figure 3 Contribution of metals to EDI *from I. batatas* and *M. oleifera* consumption along the Sayre Highway, Bukidnon.

3) Target hazard quotient (THQ) and human hazard index (HHI)

The computed THQ, which shows the estimated risk associated with pollutant exposure [8–9], is shown in Table 4. The number of vegetables in the roadside samples recorded to have THQ values for *I. batatas* ranged from 1.90E-07 to 2.60E-07 for Cd, 2.92E-07 to 3.96E-07 for Cr, 5.26E-05 to 6.83E-05 for Cu, 6.75E-05 to1.61E-04 for Co, 9.92E-04 to 2.73E-03 for Fe, 1.11E-04 to 1.65E-04 for Mn, and 8.97E-05 to 2.68E-04 for Zn, whereas the THQ values for *M. oleifera* ranged from 1.65E-07 to 2.42E-07 for Cd, 2.61E-07 to 3.21E-07 for Cr, 3.96E-05 to 7.11E-05 for Cu, 5.19E-05 to 1.98E-04 for Co, 1.06E-03 to 2.41E-03 for Fe, 1.18E-07 to 1.48E-04 for Mn, and 1.43E-04 to 3.68E-04 for Co. All of the THQs are less than 1; hence, it is considered safe or has noncarcinogenic consequences for the human population from the consumption of roadside vegetables [8–9]. The computed potential HHIs of the metals present in the vegetables are shown in Figure 4. The computed HHI for each locality ranged from 0.001 to 0.005 for *I. batatas* and 0.002 to 0.003 for *M. oleifera*. Although THQ<1, Cd accumulation poses a renal risk (kidney), whereas Cr(VI) targets the respiratory system [49]. All of the computed cumulative HHI values were less than 1. Hence, the probability of danger is lower in all areas of the study.

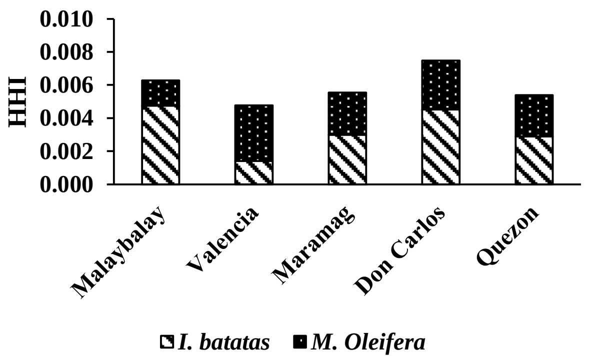


Figure 4 Potential HHI values for *I. batatas* and M. oleifera along the Sayre Highway, Bukidnon.

4) Cancer risk assessment (CR)

Carcinogenic risk assessment calculates the lifetime likelihood of developing cancer from a unit dosage of a likely carcinogen [33]. The cancer risk (CR) was used to quantify the likelihood of cancer hazard in the sample vegetables due to ingestion of carcinogenic heavy metals [34]. By computing the EDI × CFS or the cancer slope factor. In this study, Cd and Cr were the only elements with CFS values of 6.30 mg kg^{-1} and 4.10 mg kg^{-1}, respectively (Table 5). The CRs for Cd and Cr ranged from (1.20E-05 to 1.64E-05) and (1.80E-03 to 2.43E-03) for *I. batatas* and from (1.04E-05 to 1.53E-05) and (1.61E-03 to 1.98E-03) for *M. oleifera*, respectively. The calculated target CR (TCR: 4.02×10^{-2} to 4.94×10^{-2}) significantly exceeded the USEPA safety threshold (1×10^{-4}) across all localities, indicating a 4-5% probability of cancer development over a 70-year exposure period. Three primary factors drove these elevated risks. First, Cr(VI) dominance in high-traffic zones correlated with peak Cr concentrations in Quezon (21.93 mg kg^{-1}; 9.5× above limits), which was attributable to vehicular emissions along Sayre Highway's transport corridor. Hexavalent Cr deposition from brake/tire wear formed DNA-adducting carcinogens upon ingestion, explaining Quezon's maximal TCR (4.94×10^{-2}). Second, Cd's high cancer slope factor (CSF: 6.30) amplified risks despite subthreshold concentrations (0.069-0.101 mg kg^{-1}), particularly in Don Carlos, where mining activities increased soil bioavailability (bioconcentration factor: 1.80 for *M. oleifera*). Third, synergistic exposure pathways emerged from the concurrent consumption of both vegetables (>40 g day^{-1}), where *I. batatas* Cd accumulation (translocation factor: 1.2) and *M. oleifera* Cr retention (BCF: 0.9) create dual exposure vectors, increasing the TCR 2.3-fold for regular consumers. Buffer zones ≥30 m from roads demonstrated potential TCR reductions of 60-70% by mitigating Cr deposition.

5) Relationships of metal concentrations in vegetables

As shown in Table 6, the correlation analysis revealed significant relationships between specific metals in plant tissues, highlighting both synergistic and antagonistic interactions. Zn was strongly positively correlated with Fe (0.453*) ($p < 0.05$), suggesting potential coaccumulation or shared physiological roles in plant metabolism. For example, the synergistic effects of Zn and Fe in plants may arise from their roles in enzyme cofactors and chlorophyll synthesis [50-51].

Table 4 Target hazard quotient (THQ) of metals (mg kg^{-1} day$^{-1)}$ through vegetables (*I. batatas and M. oleifera*) along the Sayre Highway, Bukidnon

Metal(oids)	Vegetables	Location/sites				
		Malaybalay	Valencia	Maramag	Don Carlos	Quezon
Cd	*I. batatas*	1.90E-07	2.15E-07	2.35E-07	2.52E-07	2.60E-07
	M. oleifera	1.65E-07	2.35E-07	2.26E-07	2.42E-07	1.92E-07
Cr	*I. batatas*	2.92E-07	3.27E-07	3.35E-07	3.25E-07	3.96E-07
	M. oleifera	2.61E-07	2.63E-07	3.21E-07	2.79E-07	2.73E-07
Cu	*I. batatas*	6.55E-05	6.08E-05	5.37E-05	6.83E-05	5.26E-05
	M. oleifera	6.42E-05	5.94E-05	4.64E-05	3.96E-05	7.11E-05
Co	*I. batatas*	6.75E-05	1.24E-04	1.01E-04	1.61E-04	1.13E-04
	M. oleifera	5.19E-05	6.50E-05	9.86E-05	1.98E-04	1.47E-04
Fe	*I. batatas*	2.27E-03	9.92E-04	2.41E-03	2.73E-03	2.41E-03
	M. oleifera	1.06E-03	1.29E-03	1.99E-03	2.41E-03	1.97E-03
Mn	*I. batatas*	1.11E-04	1.27E-04	1.35E-04	1.44E-04	1.65E-04
	M. oleifera	1.18E-04	1.23E-04	1.26E-04	1.35E-04	1.48E-04
Zn	*I. batatas*	4.98E-04	8.97E-05	2.68E-04	2.05E-04	1.26E-04
	M. oleifera	2.18E-04	3.68E-04	2.57E-04	1.70E-04	1.43E-04

Table 5 Metal cancer risk assessment (CR) and target cancer risk (TCR) values for vegetables (*I. batatas and M. oleifera*) along the Sayre Highway, Bukidnon

Location/sites	CR				TCR	
	Cd		Cr			
	I. batatas	*M. oleifera*	*I. batatas*	*M. oleifera*	*I. batatas*	*M. oleifera*
Malaybalay	1.20E-05	1.04E-05	1.80E-03	1.61E-03	4.25E-02	4.02E-02
Valencia	1.36E-05	1.48E-05	2.01E-03	1.62E-03	4.50E-02	4.03E-02
Maramag	1.48E-05	1.42E-05	2.06E-03	1.98E-03	4.55E-02	4.46E-02
Don Carlos	1.59E-05	1.53E-05	2.00E-03	1.72E-03	4.49E-02	4.16E-02
Quezon	1.64E-05	1.21E-05	2.43E-03	1.68E-03	4.94E-02	4.11E-02

Remark: The TCR exceeded the USEPA [31] maximum threshold value (1.00E-4) for the risk of developing cancer.

Table 6 Correlation analysis of metal concentrations in plant tissues

	Cd	Cr	Cu	Co	Fe	Mn	Zn
Cd	1						
Cr	0.197	1					
Cu	-0.024	-0.080	1				
Co	0.244	0.010	0.384	1			
Fe	0.055	-0.228	-0.276	-0.076	1		
Mn	0.226	0.325	-0.063	0.314	-0.105	1	
Zn	-0.020	-0.417*	-0.104	-0.388	0.453*	-0.427*	1

Remark: * Correlation is significant at the 0.05 level.

Conversely, Zn was significantly negatively correlated with Cr (-0.417*) and Mn (-0.427*) ($p< 0.05$), suggesting competitive uptake or inhibitory interactions between these metals [50]. Nonsignificant positive trends, such as Cd-Cr (0.197), Cd-Co (0.244), Cd-Fe (0.055), Cd-Mn (0.226), Cr-Co (0.010), Cr-Mn (0.325), Cu-Co (0.384), and Co-Mn (0.314), hint at weak coassociation patterns, possibly influenced by independent uptake pathways or external factors such as atmospheric deposition, which bypass soil–root transfer [50, 52]. Weak negative correlations were observed for Cd-Cu (-0.024), Cd-Zn (-0.020), Cr-Cu (-0.080), Cr-Fe (-0.228), Cr-Mn (-0.417), Cu-Fe (-0.276), Cu-Mn (-0.063), Cu-Zn (0.104), Co-Fe (-0.076), Co-Zn (-0.388), and Fe-Mn (-0.105), suggesting no strong antagonism but may reflect variability in uptake pathways or external soil conditions. The complexity of metal interactions in plants, where significant relationships may arise from shared transport mechanisms, competition for binding sites, or divergent environmental sources, and weaker associations likely reflect multifactorial influences that require further investigation.

Conclusions and recommendations

This study revealed significant heavy metal contamination in roadside vegetables across Bukidnon's urbanized localities, with Mn (up to 862.17 mg kg^{-1}), Fe (up to 706.68 mg kg^{-1}), and Cr (9.5× above limits in Quezon) exceeding FAO/WHO thresholds due to natural soil properties and anthropogenic activities. While noncarcinogenic risks (THQ<1) were negligible, lifetime carcinogenic risks (TCR: 4.02×10^{-2} to 4.94×10^{-2}) surpassed safety limits, primarily driven by Cd/Cr ingestion. The key metal interactions included Zn–Fe synergy (0.453*) and Zn–Cr antagonism (-0.417*), indicating complex uptake dynamics. Urgent mitigation requires implementing 30-100 m roadside buffer zones, deploying *Moringa oleifera* for Cd/Co phytoextraction in hotspots, and integrating TCR thresholds into national food safety policies. These actions must prioritize support for low-income communities (<$ 5 per day) reliant on contaminated vegetables through subsidized safe farming training and alternative livelihood programs.

Limitations include unanalyzed soil–plant transfer mechanisms and single-season sampling bias, which may lead to an underestimate of bioavailability and temporal variations. Future research should investigate soil-metal bioavailability through sequential extraction, conduct multiseason monitoring of accumulation patterns, and pilot community-led phytoremediation trials. Additionally, longitudinal health impact studies on vulnerable populations exposed to Cd/Cr are critical. These efforts will enable targeted interventions that balance agricultural productivity with public health safeguards in rapidly urbanizing regions, transforming scientific insights into actionable solutions for sustainable food systems.

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