

Multi-matrix baseline monitoring of toxic metals and targeted pesticide residues in a highland vegetable agroecosystem, southern Lao PDR: Implications for adaptive surveillance design

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Abstract

Vegetable production systems receive contaminants through interconnected environmental pathways, yet baseline evidence from data-scarce tropical highlands remains limited. This pilot study established an environmental baseline for toxic contaminants in a highland vegetable production system on the Bolaven Plateau, Pakxong District, Lao PDR. Fresh vegetables ($n = 45$) were screened for 213 target-analyte entries using LC–MS/MS multi-residue methods, while toxic metals (Pb, Cd, As, and Cr) were quantified across sub-sampled vegetables ($n = 27$), co-located cultivation soils ($n = 15$), and stored irrigation water ($n = 15$) using matrix-appropriate atomic spectrometric methods. Targeted pesticide screening yielded uniform non-detections ($< \text{LOD}$) for all monitored compounds. These non-detections should be interpreted within the analytical target-list boundary rather than as evidence of a pesticide-free production system, and they suggest a potential mismatch between fixed laboratory panels and locally relevant agrochemicals, particularly pyrethroids not included in the target list. Toxic metals occurred at low, matrix-dependent concentrations. Acidic cultivation soils (pH 5.2–5.5) contained measurable Pb (2.251–3.091 mg kg⁻¹ DW), As (0.688–1.011 mg kg⁻¹ DW), and total Cr (10.019–12.021 mg kg⁻¹ DW), whereas stored irrigation water contained detectable Pb (0.031–0.045 mg L⁻¹) and total Cr (0.024–0.038 mg L⁻¹). In vegetables, multi-element detections were mainly observed in coriander (Pb: 0.066–0.074; Cd: 0.011–0.012; As: 0.011–0.012; Cr: 0.032–0.037 mg kg⁻¹ FW), while heading cabbages showed minimal or non-detectable metal occurrence. This pattern is consistent with morphology-related exposure differences, although internal uptake and surface-associated contributions could not be fully separated. Overall, the study demonstrates the value of co-located crop–soil–water monitoring for interpreting contaminant occurrence, and provides an empirical basis for adaptive, context-informed, and matrix-prioritized surveillance in southern Lao PDR and comparable transboundary highland agricultural zones.

Introduction

Vegetable production systems in Southeast Asia function as open agroecosystems in which intensive management practices increasingly intersect with environmental transport pathways. Contaminant inputs within these systems are rarely confined to a single matrix; rather, they may be distributed across interconnected environmental compartments through crop protection practices, irrigation inputs, and cultivation substrates. In the Lao People's Democratic Republic (Lao PDR), vegetable cultivation is an important component of local subsistence, household livelihoods, and expanding transboundary trade. This is particularly relevant to the Bolaven Plateau, including Pakxong District, Champasak Province, which represents a highly productive tropical highland agroecosystem with favorable microclimatic conditions for continuous vegetable production (Department of Planning and Investment, 2010). Although previous monitoring in Pakxong District has confirmed the occurrence of pesticide residues in vegetables, available evidence remains largely constrained to the edible crop matrix (Vansavang et al., 2024). Because irrigation water, cultivation soils, and edible plant tissues provide an interconnected production continuum, multi-matrix surveillance is needed to interpret contaminant distribution more accurately and to distinguish potential input pathways from environmental reservoirs.

The need for a systematic multi-matrix approach is further supported by broader monitoring evidence from the Mekong subregion. In Thailand, studies have reported pesticide residues in agricultural and river-basin settings, together with heavy metal assessments in soils, surface waters, and associated crops (Chaikasem & Roi-et, 2020; Kladsomboon et al., 2020). In Vietnam, surveillance in the Mekong Delta has documented pesticide residues in commercial produce, as well as Cu, Pb, and Cd accumulation in leafy vegetables irrigated with wastewater (Nguyen et al., 2021; Thom et al., 2024). In Cambodia, recent studies have reported frequent pesticide occurrence in surface water and soils along the Mekong River corridor, indicating agricultural chemical runoff as an important regional concern (Ngin et al., 2024; Sokcheng et al., 2021). As Pakxong District is an export-linked vegetable production area supplying both domestic and neighboring Mekong markets, baseline environmental monitoring data from this zone have broader transboundary relevance. However, published multi-matrix monitoring data linking agricultural inputs, environmental compartments, and edible outputs in southern Lao PDR remain scarce. This knowledge gap limits the development of evidence-based and matrix-prioritized environmental surveillance frameworks for this important agricultural region.

Evaluating interconnected compartments provides a stronger diagnostic basis for environmental assessment than isolated crop analysis alone. Cultivation soils can act as long-term sinks or reservoirs for persistent toxic metals, whereas irrigation water may serve as a dynamic input pathway introducing trace elements into the rhizosphere. Monitoring these compartments simultaneously allows matrix-specific occurrence patterns to be interpreted more clearly and helps identify priority matrices for future surveillance (Sagagi et al., 2022). In addition, irrigation sources and soil physicochemical conditions can influence the phytoavailability and transfer behavior of metals in edible plant tissues (Ketema et al., 2023; Sharafi et al., 2024). For organic contaminants such as pesticides, environmental context is also important because residue occurrence can vary across crop types, crop phenological stages, and seasonal field conditions (Loha et al., 2020; Quansah et al., 2024). Recent field studies further indicate that pesticide residues in agricultural soils may show substantial spatial and temporal variability and may persist longer under field conditions than predicted by simplified laboratory degradation models (Veloso et al., 2025).

Although the present study screened pesticide residues only in vegetable matrices, the surrounding soil–water context remains essential for designing more comprehensive future monitoring programs.

To capture crop-matrix differences relevant to contaminant occurrence, this study included three commonly cultivated vegetables with contrasting edible-plant morphologies. Chinese cabbage and green cabbage were selected as heading *Brassica* vegetables. Their compact and overlapping foliar structures may reduce direct exposure of inner edible tissues to atmospheric deposition, irrigation splash, or resuspended soil particles. In contrast, coriander (*Coriandrum sativum*) is a non-heading leafy herb with finely divided leaves and a high surface-area-to-biomass ratio. This morphology increases potential contact with irrigation splash, dust, and fine soil particles, making coriander a useful comparative crop matrix for assessing external surface-associated contamination relative to uptake-related patterns.

Although localized pesticide occurrences in Pakxong vegetables have been documented (Vansavang et al., 2024), current surveillance evidence remains largely crop-centric. Integrated datasets that combine targeted pesticide screening with multi-matrix toxic metal monitoring are still limited for southern Lao PDR. The present study addresses this operational gap by establishing a pilot baseline dataset for an underrepresented highland vegetable production system, while explicitly distinguishing between targeted crop-matrix pesticide screening and multi-matrix toxic metal monitoring (Hassan et al., 2024; Sharafi et al., 2024). The primary contribution of this work lies in identifying matrix-specific occurrence patterns, improving transparency in the interpretation of non-detectable (ND) results across matrix-specific reporting limits, and highlighting potential target-list mismatches, in which routine laboratory screening panels may not fully cover agrochemicals that are locally relevant or previously reported in comparable vegetable systems, including pyrethroid insecticides (Loha et al., 2020; Vansavang et al., 2024). Given the pilot nature of this surveillance design, the dataset is intended to guide matrix-prioritized monitoring strategies rather than to establish definitive causal transfer kinetics.

Therefore, this pilot study aimed to assess targeted pesticide residues and toxic metals in a representative highland vegetable production system in Pakxong District, Champasak Province, Lao PDR. Pesticide residues were screened in fresh vegetable matrices, whereas total toxic metals, including Pb, Cd, As, and Cr, were quantified across co-located vegetables, cultivation soils, and stored irrigation water using matrix-specific analytical approaches. By pairing targeted crop-matrix pesticide screening with multi-matrix toxic-metal monitoring, this study provides empirical groundwork for context-informed and seasonally repeated environmental surveillance protocols in southern Lao PDR and related transboundary highland zones.

Materials and Methods

Study Area and Sampling Design

This pilot multi-matrix environmental monitoring study was conducted in Pakxong District, Champasak Province, Lao PDR, an important highland agricultural ecosystem on the Bolaven Plateau. The monitoring framework focused on tracking contaminant distribution across three interconnected environmental compartments within the vegetable production system: edible crops (fresh vegetables), environmental sinks (cultivation soils), and dynamic pathways (stored irrigation water). The locations and geographic coordinates of the three monitored sampling points are shown in Fig. 1, and the detailed sampling design matrix is summarized in Table 1.

Three commonly cultivated vegetable species, namely Chinese cabbage, green cabbage, and coriander, were collected from three agricultural plots during the active harvesting period from September to November 2024. The selected vegetables representing locally important crops with contrasting edible plant morphologies were designed to capture different surface-exposure pathways: Chinese cabbage and green cabbage were evaluated as compact heading *Brassica* vegetables, whereas coriander was evaluated as a non-heading leafy herb with finely dissected leaves providing a greater exposed edible surface area, which subject to atmospheric deposition and irrigation splash. For pesticide-residue screening, five individual samples of each vegetable species were collected from each plot, yielding 45 fresh vegetable samples in total. For toxic-metal analysis, a targeted sub-sampling strategy was used, which three individual samples of each vegetable species from each plot were randomly selected from the 45 collected samples, giving 27 vegetable samples. To evaluate associated environmental reservoirs and inputs, five soil samples were collected from each corresponding cultivation area, and five irrigation-water samples were collected from each associated on-farm storage pond, giving 15 soil samples and 15 irrigation-water samples. This sampling design was intended to provide pilot-scale baseline monitoring across co-located crop–soil–water matrices; accordingly, the three plots should be interpreted as monitored production sites rather than as statistically representative of all regional farms in Pakxong District. No formal statistical power calculation was performed because the study was explicitly designed as a pilot environmental monitoring investigation rather than a district-level prevalence survey or mechanistic transfer kinetics study.

Cultivated soil samples were collected from the corresponding vegetable-growing areas, yielding five soil samples from each of the three cultivation areas (n = 15). Irrigation water samples were collected from three on-farm water storage ponds used for vegetable cultivation.

These ponds received water diverted from the local irrigation network and functioned as primary agricultural inputs used by farmers for irrigation and related field activities. Five samples were collected from each pond, yielding a total of 15 irrigation water samples.

Table 1
Spatial sampling architecture, target analytes, and analytical configurations across co-located environmental matrices.

Environmental Matrix	Sampling Unit / Description	Spatial Sampling Configuration	Sample Size (n)	Target Contaminants	Analytical Instrumentation	Reporting Basis
Fresh Vegetables	Edible portions of <i>Brassica</i> varieties (Chinese cabbage, green cabbage) and leafy herbs (coriander)	Co-located sub-sampling during harvest season (Sept–Nov 2024) across 3 agricultural plots	$n = 45$	Pesticide residues (Targeted multi-residue screening)	QuEChERS extraction followed by LC–MS/MS	mg kg^{-1} FW
		Randomly stratified sub-selection from the primary crop pool	$n = 27$	Toxic metals (Pb, Cd, As, Cr)	AOAC 2015.01-based acid digestion followed by ICP-MS	mg kg^{-1} FW
Cultivation Soil	Rhizo-surface bulk soils (0–15 cm depth)	5 individual rhizosphere-zone soil samples per plot across 3 corresponding cultivation areas	$n = 15$	Toxic metals (Pb, Cd, As, Cr)	EPA 3050B-like hot-plate $\text{HNO}_3/\text{H}_2\text{O}_2$ digestion followed by ICP-MS	mg kg^{-1} DW
Irrigation Water	Volumetric profiles from on-farm surface storage ponds (0.3 m depth)	5 grab samples per pond across 3 independent on-farm storage units	$n = 15$	Toxic metals (Pb, Cd, As, Cr)	Acid digestion (HNO_3) followed by GFAAS	mg L^{-1}
Total Inventory			$N_{\text{total}} = 102$			

LC–MS/MS liquid chromatography–tandem mass spectrometry, ICP-MS inductively coupled plasma–mass spectrometry, GFAAS graphite furnace atomic absorption spectrophotometry, FW fresh weight, DW dry weight, Pb lead, Cd cadmium, As arsenic, Cr chromium. Total sample replication ($N_{\text{total}} = 102$) reflects distinct extraction protocols. Spatial plots serve as specific co-located monitoring nodes under shared field exposure conditions.

Sample Collection and Preparation

Fresh vegetable samples were collected using clean sampling tools, placed separately in clean polyethylene bags, labeled immediately in the field, and transported to the laboratory in closed, chilled containers. Pesticide-residue samples were prepared according to the accredited laboratory’s fresh-produce residue-testing SOP. For toxic-metal analysis, edible portions were prepared according to the laboratory’s validated procedure, including removal of adhering soil particles and rinsing with deionized water before homogenization. Vegetable toxic-metal results were reported on a fresh-weight basis (mg kg^{-1} FW).

Soil samples were collected from the upper root-zone bulk soil layer at approximately 0–15 cm depth using clean sampling tools. Samples from different cultivation areas were kept entirely separated, labeled, and transported to the laboratory to prevent cross-site contamination. Soil samples were air-dried, oven-dried at 105°C for 24 h to remove moisture variance, ground, homogenized, and sieved before toxic metal analysis. Soil chemical results were reported on a dry-weight basis (mg kg^{-1} DW) to ensure standardization across shifting environmental moisture regimes.

Irrigation water samples were collected from on-farm storage ponds at a uniform depth of approximately 0.3 m using clean polyethylene bottles. Samples from each pond were collected and stored separately, immediately preserved with concentrated HNO_3 to stabilize trace elements, kept at 4°C, and transported to the laboratory before analysis. Water chemistry results were reported as mg L^{-1} .

Field Quality Control and Uncertainty Framing

Field-level quality-control procedures were strictly implemented to minimize cross-contamination during sample collection, handling, transport, and storage. Clean sampling tools were dedicated to each specific matrix, samples from different sites and matrices were segregated in separate containers, and all samples were labeled immediately after collection. Irrigation-water samples were preserved with concentrated HNO_3 and kept at 4°C before analysis, while vegetable and soil samples were transported and processed separately according to standardized laboratory procedures.

Field blanks and field duplicate samples were not operationalized across all matrices due to logistical constraints in this data-scarce region. This represents an acknowledged field-level uncertainty in the present pilot monitoring design, particularly for independently evaluating micro-scale spatial variability, sampling precision, and potential field-level contamination. Consequently, the results were interpreted transparently as pilot baseline monitoring data for a data-limited vegetable-producing area rather than as a fully field-validated surveillance dataset or as evidence for definitive source attribution. This transparent framing ensures data integrity while establishing a baseline for future scale-up verification. Accordingly, laboratory QA/QC results support analytical reliability, but they do not fully resolve field-level uncertainty associated with sample collection, transport, and micro-scale spatial heterogeneity.

Pesticide Residue Analysis in Fresh Vegetables

Pesticide residues were analyzed in all 45 individual fresh vegetable samples using targeted LC–MS/MS multi-residue screening methods. The screening covered 213 target analyte entries across four analytical suites. The 52-compound and 129-compound analyte sets were prepared using QuEChERS-based extraction, including solvent extraction, salting-out partitioning, clean-up, and LC–MS/MS determination, following EN 15662:2008 and the established QuEChERS method described by Anastassiades et al. (2003). These analyses corresponded to the laboratory in-house methods TM-T04-R05 and TM-T04-R08, respectively. Carbamate pesticides and additional targeted pesticide analytes listed in Supplementary Table S1 were analyzed using the in-house method TM-T04-R07 based on the ethyl acetate method of the European Union Reference Laboratory for Pesticide Residues in Fruits and Vegetables (EURL-FV). The internal method codes are retained for institutional traceability but should be interpreted together with the described extraction chemistry and instrumental setup.

The reported LOD and LOQ values were 0.004 and 0.010 mg kg⁻¹ FW for the 52-compound analyte set, respectively, and 0.005 and 0.010 mg kg⁻¹ FW for the carbamate, additional pesticide, and 129-compound analyte sets, respectively. Non-detectable (ND) results indicated that the analyte concentration was below the analyte-specific LOD. The pesticide-residue analysis was strictly a targeted multi-residue screening approach rather than an open-ended non-targeted screening. Therefore, ND results apply exclusively to compounds included in the analytical target list shown in Supplementary Table S1. Pesticide compounds not included in this target analyte list were not evaluated and cannot be inferred from the present ND results. Pesticide residues were analyzed only in fresh vegetable samples and were not evaluated in cultivation soil or irrigation-water samples; therefore, pesticide results were interpreted as targeted crop-matrix screening data, while cross-matrix interpretation was confined to the toxic-metal dataset.

Toxic Metal Analysis in Irrigation Water

Irrigation water samples were analyzed for Pb, Cd, As, and Cr to evaluate potential toxic metal inputs from water used in vegetable cultivation. For sample preparation, 500 mL of each water sample was acidified with 5 mL of concentrated HNO₃ and heated gently, without boiling, until the volume was reduced to approximately 10 mL. After cooling, the digest was filtered, transferred to a polyethylene container, and diluted to 100 mL with deionized water. Pb, Cd, As, and Cr concentrations in irrigation water were determined using graphite furnace atomic absorption spectrophotometry (GFAAS; PerkinElmer AAnalyst 400, PerkinElmer, USA). Instrument calibration, reagent blanks, and routine performance checks were conducted according to the laboratory standard operating procedure. Matrix-specific detection/reporting limits were applied for each element, as summarized in Supplementary Table S5. Replicate analyses were performed, and results were reported as mean ± standard deviation where applicable.

Batch-specific QA/QC information for irrigation-water analysis included calibration linearity, method blank results, CRM recovery, matrix-spike recovery, and duplicate precision, as summarized in Supplementary Table S5. Method blanks were consistently below the detection/reporting limit, CRM recovery ranged from 86% to 109%, matrix-spike recovery was 84.5%, and duplicate precision was 4.8% RPD. These results supported the validation of irrigation-water Pb, Cd, As, and Cr concentrations within the method-specific reporting limits. Therefore, the irrigation-water results were interpreted as baseline monitoring data supported by laboratory SOP-based QA/QC and matrix-specific detection/reporting limits. ND indicated concentrations below the corresponding detection/reporting limit, and final concentrations were corrected for the digestion and dilution factors. For chromium, the reported concentration represents total Cr, and chromium speciation was not performed.

Toxic Metal Analysis in Cultivation Soils

Cultivation soil samples were analyzed for Pb, Cd, As, and Cr to assess toxic-metal occurrence in the agricultural soil matrix. Before ICP-MS analysis, dried, ground, homogenized, and sieved soil samples were subjected to hot-plate acid digestion using an HNO₃/H₂O₂ procedure adapted from U.S. EPA Method 3050B for soil and sediment matrices, according to the analytical laboratory's validated SOP (U.S. EPA, 1996). Briefly, approximately 1.0 g of prepared dry soil was digested with concentrated HNO₃ and H₂O₂ under controlled heating conditions. After digestion and cooling, the digest was filtered where necessary, transferred to a volumetric flask, and diluted to a final volume of 100 mL with deionized water before instrumental analysis. Pb, Cd, As, and Cr concentrations in the digests were determined using inductively coupled plasma–mass spectrometry (ICP-MS). Results were expressed as mg kg⁻¹ dry weight (DW). For soil toxic-metal analysis, element-specific

LODs and LOQs were applied for each metal, as summarized in Supplementary Table S5. The soil LOD/LOQ values were 0.075/0.225 mg kg⁻¹ DW for Pb, 0.046/0.135 mg kg⁻¹ DW for Cd, 0.176/0.588 mg kg⁻¹ DW for As, and 0.064/0.380 mg kg⁻¹ DW for Cr. ND indicated concentrations below the corresponding element-specific LOD. Because this procedure was based on an EPA 3050B-type hot-plate acid digestion, the soil results should be interpreted as acid-digestible metal concentrations rather than complete mineral-lattice total concentrations.

As supplementary soil-context information, soil pH was measured for the three monitored cultivation plots using a 1:5 soil-to-water suspension and a calibrated immersion-type pH meter, according to the laboratory procedure. The pH meter was calibrated using standard buffer solutions before measurement. The measured soil pH values ranged from 5.2 to 5.5, indicating acidic to moderately acidic soil conditions across the monitored plots. Field observations during sampling indicated red-brown, fine-textured, friable highland cultivation soils with visible organic residues, possibly related to organic soil amendments or crop residues. These pH and field-observed soil characteristics were used to support qualitative interpretation of possible metal mobility and crop-level occurrence patterns. However, organic matter content, cation exchange capacity, laboratory-based texture classification, redox-related conditions, moisture regime, and plant-available metal fractions were not measured.

Toxic Metal Analysis in Fresh Vegetables

Toxic metals were analyzed in 27 fresh vegetable samples selected from the 45-sample pesticide-screening pool using a stratified random sub-sampling approach by crop species and plot. The selected subset comprised three samples of each vegetable species from each of the three agricultural plots, giving nine samples per species. Pb, Cd, As, and Cr were determined in the edible portions using the laboratory in-house method TCA-05 based on AOAC Official Method 2015.01 for heavy metals in food by inductively coupled plasma–mass spectrometry (AOAC International, 2019). Briefly, homogenized edible vegetable samples were subjected to acid digestion according to the laboratory's validated SOP before instrumental analysis. After digestion, the prepared solutions were analyzed using ICP-MS (PerkinElmer NexION 350D). Results were expressed as mg kg⁻¹ fresh weight (FW). For vegetable toxic-metal analysis, ND indicated concentrations below the corresponding vegetable-specific detection/reporting limit summarized in Supplementary Table S5.

Quality Assurance/Quality Control and Treatment of Non-Detects

Analytical quality assurance and quality control were rigorously evaluated based on the information provided in the accredited laboratory reports for each matrix. For pesticide-residue analysis, method performance was interpreted using the reported analyte-group-specific LODs and LOQs. The LODs ranged from 0.004 to 0.005 mg kg⁻¹ FW, whereas the LOQ was 0.010 mg kg⁻¹ FW for all pesticide groups. Because all targeted pesticide residues were reported as ND, the results were interpreted strictly as concentrations below the corresponding analyte-specific LODs and, consequently, below the reported LOQs.

For toxic metal analysis, matrix-specific detection/reporting limits and batch-specific laboratory QA/QC information are summarized in Supplementary Table S5. Calibration linearity values were $R^2 = 0.9992$ for fresh vegetables, $R^2 = 0.9950$ for irrigation water, and $R^2 = 0.9985$ for cultivation soils. Method blanks were below the corresponding detection/reporting limits for all matrices. CRM recoveries were 94.5% for fresh vegetables, 86–109% for irrigation water, and 90–110% for cultivation soils. Matrix-spike recoveries were 88.3%, 84.5%, and 90.5% for fresh vegetables, irrigation water, and cultivation soils, respectively. Duplicate precision values, expressed as relative percent difference (RPD), were 6.5%, 4.8%, and 8.7% for fresh vegetables, irrigation water, and cultivation soils, respectively. These batch-specific laboratory QA/QC results support the high reliability of the toxic-metal data within the analytical scope.

To prevent the introduction of artificial numerical artifacts into the descriptive environmental summaries, non-detect (ND) values were retained strictly as ND and were not substituted with zero, one-half of the LOD, or one-half of the LOQ. ND therefore indicates concentrations below the corresponding analyte-specific or matrix-specific detection/reporting limits, depending on the analytical method and matrix.

Data Analysis and Comparison with Guideline Values

Contaminant concentrations were summarized using descriptive statistics, including concentration ranges and mean $\pm$ standard deviation where appropriate. Descriptive statistics were calculated from the raw analytical dataset organized in Microsoft Excel. Exploratory one-way ANOVA followed by Tukey's HSD post-hoc test was performed using Python 3.13.5 with SciPy 1.17.0 and statsmodels 0.14.6, with statistical significance set at $p < 0.05$. Statistical comparisons were conducted only for element–matrix combinations with sufficient detected numerical values and were interpreted as local site-level comparisons rather than regional-scale environmental inference. Accordingly, differences in Pb and total Cr concentrations among irrigation-water ponds and differences in Pb, As, and total Cr concentrations among cultivation soil areas were evaluated only as exploratory comparisons. Cd and As in irrigation water and Cd in soils were excluded from statistical comparison because all values were reported as ND. Statistical comparison among vegetable species was not performed because the vegetable dataset contained censored ND values and some species–metal combinations had all values reported as ND. ND values were retained as censored observations and were not replaced with zero or fractional LOD/LOQ values.

Detected concentrations were compared with selected national and international guideline or regulatory values where available and applicable, as specified in the footnotes to the corresponding result tables. Irrigation-water results were compared with selected FAO and PCD guideline values, soil results were compared with selected PCD soil quality standards, and fresh-vegetable results were compared with selected FAO/WHO, EU, and Thai MoPH comparison values. Because Cr was measured as total Cr and not as Cr(VI), chromium was excluded from direct comparison with Cr(VI)-specific PCD criteria and was interpreted only as an occurrence-monitoring parameter. These comparisons were used only for screening-level contextual interpretation because the study was designed as baseline multi-matrix monitoring rather than a full exposure or human-health risk assessment.

Results and Discussion

Overview of Multi-Matrix Contaminant Monitoring

This investigation provides baseline empirical evidence on targeted pesticide residues and toxic metals in an intensive highland vegetable production system in Pakxong District, Champasak Province, Lao PDR. The study area represents an agriculturally important highland zone where integrated environmental monitoring data across edible crops, cultivation soils, and irrigation water remain limited. By characterizing fresh vegetable tissues, cultivation soils, and stored irrigation water within the same production system, this study moves beyond single-matrix food-safety reporting and applies a co-located multi-matrix framework for interpreting contaminant occurrence.

In accordance with the system-boundary framework presented in Fig. 2, contaminant profiles were interpreted within matrix-specific analytical and reporting limits. Because sampling represented a discrete environmental monitoring window, the following analysis focuses on occurrence patterns, concentration ranges, matrix-specific non-detectable (ND) results, and screening-level comparison with relevant guideline values where applicable. The study was not designed to perform contaminant fate modelling, source apportionment, or empirical bioaccumulation assessment. Instead, the multi-matrix design was used as a diagnostic monitoring approach to distinguish crop-matrix occurrence from potential environmental input and reservoir matrices. Because pesticide screening was conducted only in fresh vegetable samples, cross-matrix interpretation was applied primarily to the toxic-metal dataset.

Target-list-specific Pesticide Non-detections and Surveillance Implications

Targeted multi-residue pesticide screening of 45 fresh vegetable samples, including Chinese cabbage, green cabbage, and coriander, yielded uniform non-detections (< LOD) for all monitored compounds (Table 2). The analytical coverage comprised 213 target analyte entries across four LC–MS/MS analytical suites, including a 52-compound multi-residue suite using QuEChERS EN 15662:2008, carbamate and targeted agrochemical suites using ethyl acetate extraction, and an expanded 129-compound multi-residue suite using QuEChERS EN 15662:2008. The reported detection limits were 0.004 mg kg⁻¹ FW for the 52-compound suite and 0.005 mg kg⁻¹ FW for the carbamate, targeted agrochemical, and 129-compound suites, with a uniform LOQ of 0.010 mg kg⁻¹ FW.

Table 2

Analytical scope, validation boundaries, and screening profiles for targeted pesticide multi-residue analysis in fresh vegetables ($N_{\text{total}} = 45$).

Pesticide Analytical Suite	No. of Target Compounds	Extraction & Clean-up Protocol	Instrumental Configuration	Sample Allocation per Species (n)*	Detection Frequency (%)	Screening Result (mg kg^{-1} FW)	LOD (mg kg^{-1} FW)	LOQ (mg kg^{-1} FW)
Multi-residue Suite I (EN 15662:2008)	52	QuEChERS (Acetonitrile/Salting-out/d-SPE)	LC–MS/MS	CC ($n = 15$) GC ($n = 15$) CR ($n = 15$)	0%	< LOD	0.004	0.010
Carbamates Array	16	Ethyl Acetate Partitioning	LC–MS/MS	CC ($n = 15$) GC ($n = 15$) CR ($n = 15$)	0%	< LOD	0.005	0.010
Targeted Agrochemicals (Supplementary Table S1)	16	Ethyl Acetate Partitioning	LC–MS/MS	CC ($n = 15$) GC ($n = 15$) CR ($n = 15$)	0%	< LOD	0.005	0.010
Multi-residue Suite II (EN 15662:2008)	129	QuEChERS (Acetonitrile/Salting-out/d-SPE)	LC–MS/MS	CC ($n = 15$) GC ($n = 15$) CR ($n = 15$)	0%	< LOD	0.005	0.010

CC Chinese cabbage, GC green cabbage, CR coriander, LOD limit of detection, LOQ limit of quantification, FW fresh weight, LC–MS/MS liquid chromatography–tandem mass spectrometry. * Total crop screening repository consists of 45 independent operational samples. Screening results are strictly applicable to the targeted analyte boundaries detailed in Supplementary Table S1; non-targeted chemical pressures remain uncharacterized.

The uniform non-detection observed in the present screening should be interpreted as target-list-specific evidence rather than as confirmation of a pesticide-free production system. This distinction is important because analytical outcomes are constrained by the compounds included in the laboratory target list. Therefore, a 0% detection frequency within a fixed LC–MS/MS panel may reflect the absence of monitored residues above the applicable detection limits, but it does not exclude the possible use or occurrence of compounds outside the analytical scope. The contrast between the present non-detection pattern and prior evidence of pesticide occurrence in Pakxong vegetables is therefore best interpreted as a monitoring-coverage issue rather than a direct contradiction in environmental conditions. In particular, pyrethroid insecticides previously reported or locally relevant in Pakxong vegetable systems, including beta-cyhalothrin, lambda-cyhalothrin, and cypermethrin, were not included in the present target list (Vansavang et al., 2024). Future pesticide surveillance in this production system should therefore incorporate farmer pesticide-use inventories, local agrochemical retail information, seasonal sampling, and adaptive target-list updates before laboratory analysis (Veloso et al., 2025).

Inorganic Trace Elements in Irrigation Inputs

Hydro-chemical profiling of the on-farm water storage ponds revealed repeated low-level detections of lead (Pb) and total chromium (Cr), whereas cadmium (Cd) and arsenic (As) remained below analytical detection limits across all samples (Table 3, Supplementary Table S2). Total Pb concentrations ranged from 0.031 to 0.045 mg L^{-1} across the monitored ponds (WA: 0.031–0.035 mg L^{-1} ; WB: 0.042–0.045 mg L^{-1} ; WC: 0.034–0.038 mg L^{-1}). Total Cr concentrations ranged from 0.024 to 0.038 mg L^{-1} (WA: 0.024–0.026 mg L^{-1} ; WB: 0.032–0.035 mg L^{-1} ; WC: 0.035–0.038 mg L^{-1}). One-way ANOVA indicated statistically significant differences among the three storage ponds for both Pb ($F(2,12)$

= 71.52, $p = 2.15 \times 10^{-7}$) and total Cr ($F(2,12) = 131.76, p = 6.83 \times 10^{-9}$). Tukey's HSD post-hoc comparisons further indicated distinct pond-level concentration patterns, with Pb following the order WB > WC > WA and total Cr following the order WC > WB > WA.

The repeated detection of Pb and total Cr suggests that stored irrigation water represents a relevant monitoring matrix for potential input characterization within the monitored production system. However, these detections should not be interpreted as definitive evidence of specific transport mechanisms or source origins. Potential contributing factors may include suspended fine sediments, storm-driven runoff, erosion of metal-bearing particles from surrounding agricultural areas, or locally variable water-storage conditions (Ketema et al., 2023; Sharafi et al., 2024). Because upstream geochemical fingerprinting, suspended-solid characterization, and source apportionment were not included in this baseline monitoring phase, the water results are best interpreted as occurrence-based indicators for future surveillance rather than as evidence of confirmed geogenic or anthropogenic sources.

When compared with the guideline values summarized in Table 3, all observed Pb concentrations were below the FAO agricultural irrigation guideline value of 5 mg L⁻¹ and below the PCD surface-water baseline value of 0.05 mg L⁻¹. Because the present analytical framework quantified total elemental Cr rather than Cr speciation, direct comparison with Cr(VI)-specific regulatory criteria was intentionally avoided. Total Cr was therefore retained as an environmental occurrence parameter rather than as a direct regulatory-compliance indicator. Overall, the recurrence of Pb and total Cr across all irrigation-water nodes indicates that stored irrigation water should be retained as a priority matrix in repeated monitoring of this highland vegetable production system.

Table 3
Toxic metal profiles in on-farm irrigation water storage units compared with selected international agricultural and surface-water quality values.

Water Source / Pond ID	Sample Size (n)	Pb (mg L ⁻¹)	Cd (mg L ⁻¹)	As (mg L ⁻¹)	Total Cr* (mg L ⁻¹)
WA	5	0.033 ± 0.002 ^a (0.031–0.035)	ND	ND	0.025 ± 0.001 ^a (0.024–0.026)
WB	5	0.043 ± 0.001 ^b (0.042–0.045)	ND	ND	0.033 ± 0.001 ^b (0.032–0.035)
WC	5	0.036 ± 0.001 ^b (0.034–0.038)	ND	ND	0.037 ± 0.001 ^b (0.035–0.038)
Overall Range Matrix	15	0.031–0.045	ND	ND	0.024–0.038
FAO Irrigation Threshold [1]	—	5	0.01	0.10	0.10
PCD Surface Water Standard [2]	—	0.05	0.05	0.01	NA†

Data are presented as mean ± standard deviation (SD) with absolute minimum–maximum ranges in parentheses. Values within the same column followed by different superscript letters (a–c) indicate statistically significant differences among monitored ponds based on exploratory one-way ANOVA followed by Tukey's HSD post-hoc test ($p < 0.05$). ND denotes non-detectable concentrations below the matrix-specific laboratory limits of detection (LOD). [1] FAO threshold based on recommended maximum concentrations of trace elements in agricultural irrigation water (Ayers & Westcot, 1985). [2] PCD standard based on the Thai National Surface Water Quality Standards (National Environmental Board, 1994). † Direct regulatory compliance evaluation was omitted for chromium because the analytical setup measured total Cr, whereas the local PCD regulatory baseline targets hexavalent chromium (Cr(VI)) exclusively. Total Cr is presented strictly as an environmental occurrence parameter.

Edaphic Trace Element Reservoirs and Rhizosphere Context

Cultivation soils represented the main accumulation matrix within the multi-matrix monitoring framework. Soil profiling confirmed measurable concentrations of Pb, As, and Cr across all monitored agricultural plots, whereas Cd remained below the analytical detection limit (Table 4, Supplementary Table S3). Total soil concentrations ranged from 2.251 to 3.091 mg kg⁻¹ DW for Pb, 0.688 to 1.011 mg kg⁻¹ DW for As, and 10.019 to 12.021 mg kg⁻¹ DW for Cr. One-way ANOVA indicated statistically significant site-level variation among the three cultivation plots for all detected elements: Pb ($F(2,12) = 783.20, p = 1.93 \times 10^{-13}$), As ($F(2,12) = 177.66, p = 1.22 \times 10^{-9}$), and Cr ($F(2,12) = 1737.27, p = 1.66 \times 10^{-15}$). Tukey's HSD post-hoc comparisons showed element-specific spatial patterns, with Pb and Cr showing higher concentrations in plot B (SB > SA > SC), while As followed a different ranking pattern (SB > SC > SA).

Across the monitored soils, total trace-element concentrations followed the general order Cr > Pb > As. The predominance of total Cr among the detected soil elements should also be interpreted within the regional geogenic context of the Bolaven Plateau. The Bolaven Volcanic Field

is characterized by extensive basaltic lava sequences (Verolino et al., 2022), and soils developed on mafic or basaltic parent materials may naturally contain higher background levels of Cr and Ni than soils derived from more felsic or sedimentary materials (Izbicki & Groover, 2023). Therefore, the observed Cr-dominant pattern in the cultivation soils may partly reflect lithogenic background inputs associated with basalt-derived parent materials rather than agricultural contamination alone. However, owing to Ni was not analyzed and mineralogical characterization, Fe/Al normalization, and geochemical fingerprinting were not performed, the present dataset cannot definitively separate geogenic and anthropogenic contributions. The Cr results should therefore be interpreted as baseline acid-digestible occurrence data within a basalt-influenced highland setting. Pb and As concentrations were below the PCD soil quality screening values used for comparison. Similar to the irrigation-water analysis, total soil Cr was treated as an environmental occurrence indicator and was not directly benchmarked against Cr(VI)-specific criteria. Although the observed total concentrations indicate low baseline levels relative to available screening values, total elemental concentrations alone cannot define ecological risk or plant-uptake potential because they do not account for chemical speciation, mineral phase association, soil retention capacity, or bioavailability (Camacho-Alcantar et al., 2025; Sharafi et al., 2024).

Field and laboratory soil-context observations indicated red-brown, fine-textured highland soils with acidic to moderately acidic pH values ranging from 5.2 to 5.5. This pH range provides relevant geochemical context because acidic conditions may influence the mobility and retention of some trace metal cations in the rhizosphere. However, plant-available metal fractions were not directly measured. In addition, mineralogical characterization, cation exchange capacity, organic matter content, texture quantification, and sequential extraction were outside the scope of this baseline phase. Therefore, the soil results should be interpreted as total or acid-digestible occurrence data for environmental monitoring, not as direct evidence of soil-to-plant transfer potential. This interpretive boundary is particularly important when evaluating downstream detections in leafy or morphologically complex vegetable matrices.

Table 4
Total elemental concentrations of toxic metals in highland cultivation soils compared with national edaphic quality criteria.

Soil Management Area / Plot ID	Sample Size (n)	Pb (mg kg ⁻¹ DW)	Cd (mg kg ⁻¹ DW)	As (mg kg ⁻¹ DW)	Total Cr* (mg kg ⁻¹ DW)
SA	5	2.589 ± 0.031 [Ⓜ] (2.551–2.627)	ND	0.722 ± 0.031 [Ⓜ] (0.688–0.761)	10.512 ± 0.038 [Ⓜ] (10.474–10.554)
SB	5	3.068 ± 0.034 [Ⓜ] (3.011–3.091)	ND	0.992 ± 0.021 [Ⓜ] (0.958–1.011)	11.989 ± 0.056 [Ⓜ] (11.889–12.021)
SC	5	2.283 ± 0.030 [Ⓜ] (2.251–2.318)	ND	0.892 ± 0.013 [Ⓜ] (0.875–0.907)	10.115 ± 0.062 [Ⓜ] (10.019–10.192)
Overall Edaphic Range	15	2.251–3.091	ND	0.688–1.011	10.019–12.021
PCD Soil Quality Standard [1]	—	800	762	25	NA†

Data are presented as mean ± standard deviation (SD) with absolute minimum–maximum ranges in parentheses. Values within the same analytical column followed by different superscript letters indicate statistically significant differences among the monitored plots based on exploratory one-way ANOVA followed by Tukey’s HSD post-hoc test ($p < 0.05$). ND implies non-detectable levels below the validated matrix-specific laboratory limits of detection (LOD). [1] PCD standard threshold based on the Thai Soil Quality Standards for Agricultural, Commercial, and Other Land-Use Categories (National Environment Board, 2021). † Direct compliance benchmarking was intentionally omitted for chromium because this investigation quantified total elemental Cr, whereas the local PCD regulatory soil threshold is tailored specifically to hexavalent chromium (Cr(VI)). Total Cr concentrations are retained here strictly as baseline environmental occurrence indicator values.

Crop-Specific Metal Occurrence and Morphology-Related Exposure Patterns

Trace-metal assessment within the edible vegetable subset ($n = 27$) showed clear crop-specific occurrence patterns across the three monitored species (Table 5, Supplementary Table S4). Across all fresh vegetable samples, measured concentrations ranged from ND to 0.074 mg kg⁻¹ FW for Pb, ND to 0.012 mg kg⁻¹ FW for Cd, ND to 0.012 mg kg⁻¹ FW for As, and ND to 0.037 mg kg⁻¹ FW for total Cr.

Table 5

Toxic metal occurrence profiles in edible vegetable tissues compared with selected international and national comparison values.

Vegetable Species	Taxonomic Group / Morphology	Pb (mg kg ⁻¹ FW)	Cd (mg kg ⁻¹ FW)	As (mg kg ⁻¹ FW)	Total Cr* (mg kg ⁻¹ FW)
Chinese cabbage	Compact heading <i>Brassica</i>	ND–0.022	ND	ND	ND
Green cabbage	Compact heading <i>Brassica</i>	ND	ND	ND	ND
Coriander	Non-heading leafy herb	0.069 ± 0.003 (0.066–0.074)	0.012 ± 0.001 (0.011–0.012)	0.011 ± 0.001 (0.011–0.012)	0.034 ± 0.002 (0.032–0.037)
Overall Exposure Range	Matrix Continuum	ND–0.074	ND–0.012	ND–0.012	ND–0.037
FAO/WHO Codex Limit [1]	Maximum Allowable Level	0.3	0.2	-	-
European Union (EU) [2]	Regulatory Threshold	0.1–0.3	0.04–0.2	-	-
Thai MoPH Criteria [3]	National Standard	0.1–0.3	0.05–0.2	2	-

Data are reported descriptively as mean ± standard deviation (SD) with observed minimum–maximum ranges in parentheses for crop–metal combinations with fully detected numerical values. ND denotes concentrations below the matrix-specific laboratory detection/reporting limits. Statistical comparison among vegetable species was not performed because the dataset contained censored ND values and some species–metal combinations had all values reported as ND. For Pb in Chinese cabbage, only the censored occurrence range (ND–0.022 mg kg⁻¹ FW) is reported because one sample was below the detection/reporting limit; ND was retained to represent the full observed occurrence profile. For Cd, the matrix-specific LOD/reporting limits were 0.005 mg kg⁻¹ FW for fresh vegetables, 0.046 mg kg⁻¹ DW for cultivation soil, and 0.010 mg L⁻¹ for irrigation water. The soil Cd LOQ was 0.135 mg kg⁻¹ DW. Therefore, Cd detection in coriander despite ND results in soil and irrigation water should be interpreted within matrix-specific analytical boundaries and should not be considered direct evidence of soil-to-plant transfer. [1] FAO/WHO comparison values based on Codex Alimentarius CXS 193–1995 (Codex Alimentarius Commission, 2025). [2] EU thresholds based on Commission Regulation (EU) 2023/915 (European Commission, 2023). [3] Thai MoPH values based on the Notification of the Ministry of Public Health (No. 414) B.E. 2563 (Ministry of Public Health, 2020). * Total Cr is presented strictly as an ecological occurrence parameter because specific fresh-vegetable regulatory thresholds for total chromium were not available within the applied comparison frameworks.

The observed differences among vegetable species suggest that crop morphology may influence exposure to metal-bearing environmental materials, although this pilot dataset does not establish a definitive mechanism of uptake. The two heading *Brassica* vegetables, Chinese cabbage and green cabbage, showed limited metal occurrence. Green cabbage returned non-detectable results for all four elements, whereas Chinese cabbage showed only sporadic low-level Pb detections (ND–0.022 mg kg⁻¹ FW). This pattern is consistent with the compact heading structure of these crops, which may reduce direct exposure of inner edible tissues to irrigation splash, soil particles, and dust deposition.

In contrast, coriander (*Coriandrum sativum*) showed quantifiable concentrations of Pb, Cd, As, and total Cr in all analyzed replicates. The higher detection frequency in coriander may be associated with its non-heading morphology, finely divided leaves, low growth habit, and relatively high surface-area-to-biomass ratio. These characteristics may increase contact with irrigation droplets, fine soil particles, splash-derived residues, and atmospheric or field dust. Similar morphology-related exposure considerations have been reported for leafy vegetables and herbs in contaminated agricultural settings (Hassan et al., 2024; Sharafi et al., 2024). Therefore, coriander may represent a useful candidate sentinel crop for future field surveillance, but it should not be interpreted as a confirmed bioaccumulation based on the present dataset alone.

Interpretation of the coriander pattern requires particular caution because internal uptake and surface-associated contributions could not be fully separated. Although all vegetable samples were rinsed with deionized water prior to digestion, no formal washing-loss validation experiment was conducted. Consequently, residual fine particles or surface-associated metals may have contributed partly to the measured concentrations. The acidic soil conditions observed in the monitored plots (pH 5.2–5.5) provide a plausible geochemical context for increased metal mobility, but plant-available metal fractions were not measured. Therefore, the observed coriander metal profile should be interpreted as a morphology-related occurrence pattern rather than direct evidence of systemic root uptake or internal bioaccumulation.

The low-level Cd detection in coriander (0.011–0.012 mg kg⁻¹ FW), despite non-detectable Cd in bulk cultivation soils and stored irrigation water, represents an important cross-matrix observation that must be interpreted in relation to matrix-specific analytical boundaries. The Cd detection/reporting limits were 0.025 mg kg⁻¹ DW for cultivation soil, 0.010 mg L⁻¹ for irrigation water, and 0.005 mg kg⁻¹ FW for fresh vegetables. Therefore, Cd reported as ND in soil or irrigation water indicates concentrations below the corresponding matrix-specific reporting limit, not absolute absence from the monitored system. Direct numerical equivalence across matrices is also limited by differences in units, digestion procedures, sample preparation, and reporting basis. Accordingly, the coriander Cd signal should be interpreted as a matrix-specific occurrence pattern within a censored monitoring dataset rather than as definitive evidence of soil-to-plant Cd transfer. Possible explanations include localized root-zone heterogeneity, low-level Cd pools below the bulk-soil reporting boundary, unmeasured agricultural inputs, and surface-associated contributions related to coriander morphology. Because plant-available Cd fractions, sequential extraction, organic matter, cation exchange capacity, and washing-loss validation were not assessed, the Cd signal in coriander should be considered a targeted follow-up priority rather than conclusive evidence of bioconcentration.

Several explanations may account for this asymmetry. Low-level Cd pools below the bulk-soil reporting limit may occur in localized rhizosphere microsites or in labile fractions not captured by total bulk-soil measurements. Unmeasured agricultural inputs, including fertilizers or foliar agrochemical products, may also contribute trace Cd at levels difficult to detect in bulk environmental matrices. In addition, coriander's leaf architecture may favor surface retention of fine particles or residues. Because plant-available Cd fractions, sequential extraction, organic matter, cation exchange capacity, and washing-loss validation were not assessed, the Cd signal in coriander should be interpreted as a matrix-specific occurrence pattern requiring targeted follow-up rather than as conclusive evidence of bioconcentration.

Systems-Based Cross-Matrix Synthesis

The main contribution of the multi-matrix framework is its ability to integrate separate environmental compartments into a coherent baseline monitoring interpretation. When evaluated together, the crop–soil–water dataset indicates a compartment-specific contaminant pattern: cultivation soils acted as measurable reservoirs for Pb, As, and total Cr; stored irrigation water represented a potential low-level input matrix for Pb and total Cr; and edible vegetable tissues showed crop-specific responses, with heading cabbages exhibiting minimal or non-detectable metal occurrence and coriander showing more frequent low-level multi-element detections. This cross-matrix pattern highlights the diagnostic value of co-located sampling, because crop results cannot be fully interpreted without considering the surrounding soil and irrigation-water matrices.

The Cd asymmetry further illustrates the importance of interpreting contaminant data across matrices rather than relying on isolated soil or crop monitoring. Cd was detected at low levels in coriander, whereas Cd remained non-detectable in bulk cultivation soils and stored irrigation water. This pattern should not be interpreted as definitive evidence of soil-to-plant Cd transfer or as proof of an external Cd pollution source. Instead, it reflects a matrix-specific occurrence pattern within a censored monitoring dataset, where ND values indicate concentrations below matrix-specific reporting limits rather than absolute absence. Possible explanations include localized rhizosphere-scale heterogeneity, low-level Cd pools below the soil reporting limit, crop-specific exposure characteristics, and surface-associated contributions related to coriander morphology (Hassan et al., 2024; Sharafi et al., 2024). However, because plant-available metal fractions, sequential extraction, soil organic matter, cation exchange capacity, and washing-loss validation were not measured, the mechanism responsible for the Cd signal cannot be confirmed.

Accordingly, the present pilot configuration should be viewed as a baseline surveillance framework rather than a definitive source-apportionment or transfer-modeling study. The dataset is not sufficiently extensive to support robust bioaccumulation-factor estimation or mechanistic modeling of soil–water–crop transfer pathways. Nevertheless, the results demonstrate that co-located vegetable, soil, and irrigation-water monitoring can improve interpretation of contaminant occurrence by distinguishing probable reservoir matrices, potential input matrices, and crop-specific signal matrices. This systems-based approach provides a practical foundation for future seasonal, spatially replicated, and analytically expanded agroecosystem surveillance in Pakxong District and comparable highland vegetable production zones.

Environmental Monitoring Implications and Strategic Future Directions

This pilot study provides a baseline multi-matrix monitoring framework for a data-limited highland vegetable production zone in southern Lao PDR. Rather than replacing conventional commodity-based food-safety surveys, the crop–soil–water design complements them by providing environmental context for interpreting contaminant occurrence across interconnected production matrices (Ketema et al., 2023; Lazović et al., 2023). Based on the matrix-specific detection patterns observed in this study, future surveillance on the Bolaven Plateau could be organized around three complementary monitoring nodes.

The first is a crop-exposure node, in which morphologically different vegetable species are monitored together. Non-heading species such as *Coriandrum sativum* may serve as useful candidate sentinel crops for detecting surface-associated or morphology-related contaminant occurrence, whereas heading cabbages remain relevant for dietary-exposure-oriented interpretation. The second is a dynamic input node,

focused on repeated monitoring of on-farm stored irrigation water, particularly during periods when runoff, pond storage conditions, or irrigation practices may change seasonally. The third is an environmental reservoir node, based on routine soil monitoring in cultivation and rhizosphere-adjacent zones to track longer-term inorganic contaminant accumulation. Together, these nodes provide a practical structure for improving diagnostic sensitivity while avoiding overinterpretation of a single-season pilot dataset.

Several uncertainties should be addressed before this baseline framework can be scaled into a broader regional monitoring program. First, the present dataset represents a single monitoring window; therefore, seasonal variation between wet and dry cultivation periods remains unresolved. Future studies should include stratified sampling across additional farms, production cycles, and hydrological conditions. Second, the vegetable metal dataset should be expanded to increase the number of independent replicate samples per crop species and plot, allowing more robust inferential statistics and stronger crop-specific comparisons. Third, future designs should include more detailed soil characterization, including total organic carbon, cation exchange capacity, particle-size distribution, and plant-available or selectively extractable metal fractions. These measurements would help distinguish total metal occurrence from potentially mobile or bioaccessible fractions. Fourth, synchronized soil–rhizosphere–plant sampling and washing-loss validation experiments are needed to better separate internal uptake from surface-associated contamination. Finally, field-level QA/QC should be strengthened through routine field blanks, travel blanks, and field duplicates to better quantify sampling uncertainty and micro-scale spatial heterogeneity.

For pesticide monitoring, future surveillance should move beyond fixed historical target lists and incorporate locally updated information on farmer pesticide-use patterns, agrochemical retail availability, and previously reported compounds in comparable vegetable systems (Loha et al., 2020; Quansah et al., 2024). For toxic metals, total concentration data should be complemented with selective extraction and soil-property measurements to improve interpretation of mobility and potential plant availability. With these additions, the present baseline can support the development of an adaptive, context-informed environmental monitoring framework for highland vegetable production systems in the Bolaven Plateau and related transboundary agricultural zones in the Mekong subregion and other highland agroecosystems' countries.

Conclusions

This pilot study established a co-located crop–soil–water monitoring baseline for toxic metals and targeted pesticide residues in a highland vegetable production system in Pakxong District, Lao PDR. The uniform non-detection of 213 target-analyte entries should be interpreted within the boundary of the applied LC–MS/MS target list rather than as evidence of a pesticide-free production system. This finding highlights the need to align analytical panels with locally relevant agrochemical-use information, particularly for compounds that may be used in the field but are not included in routine target lists.

Toxic metals occurred at low and matrix-dependent concentrations. Cultivation soils contained measurable Pb, As, and total Cr, stored irrigation water contained detectable Pb and total Cr, and coriander showed more frequent multi-element detections than heading cabbages. These patterns support the value of co-located multi-matrix monitoring for distinguishing contaminant occurrence across environmental and edible matrices. However, the Cd occurrence in coriander despite ND results in bulk soil and stored irrigation water should be interpreted cautiously as a matrix-specific occurrence pattern influenced by reporting-limit constraints, not as definitive evidence of soil-to-plant transfer or internal bioaccumulation.

Future surveillance in the Bolaven Plateau should incorporate seasonal replication, farmer pesticide-use inventories, expanded pyrethroid coverage, field blanks and duplicate samples, and soil indicators related to metal mobility, including organic matter, cation exchange capacity, texture, and plant-available metal fractions. Such improvements would strengthen adaptive environmental monitoring for vegetable production systems in southern Lao PDR and comparable transboundary highland agroecosystems.

Declarations

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Author Contributions

A.W. and P.P.: Conceptualization, Methodology, Study design, Project administration, Supervision, Data interpretation, Writing – original draft, Writing – review & editing.

H.S.: H.S.: Scientific consultation, Critical intellectual input, Writing – review & editing, and Critical revision.

W.B., N.K., J.J., S.T., S.S., K.L., P.K., S.K., K.P., and B.S.: Investigation, Field sampling, Resources, Laboratory coordination, Sample processing, Data acquisition, and Preliminary data verification.

All authors actively reviewed and edited the manuscript draft, approved the final version for submission, and hold themselves mutually accountable for the integrity of the reported datasets.

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Data Availability

The datasets generated and analyzed during the current study are included in the main manuscript and supplementary information files.

Ethics Approval

Not applicable. This environmental monitoring study did not involve human participants, human-derived clinical data, or experimental trials utilizing animal subjects.

Conflict of Interest

The authors declare that they have no known competing financial interests, institutional conflicts, or personal relationships that could have appeared to influence or bias the scientific work, analytical interpretations, or conclusions reported in this manuscript.

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Figures

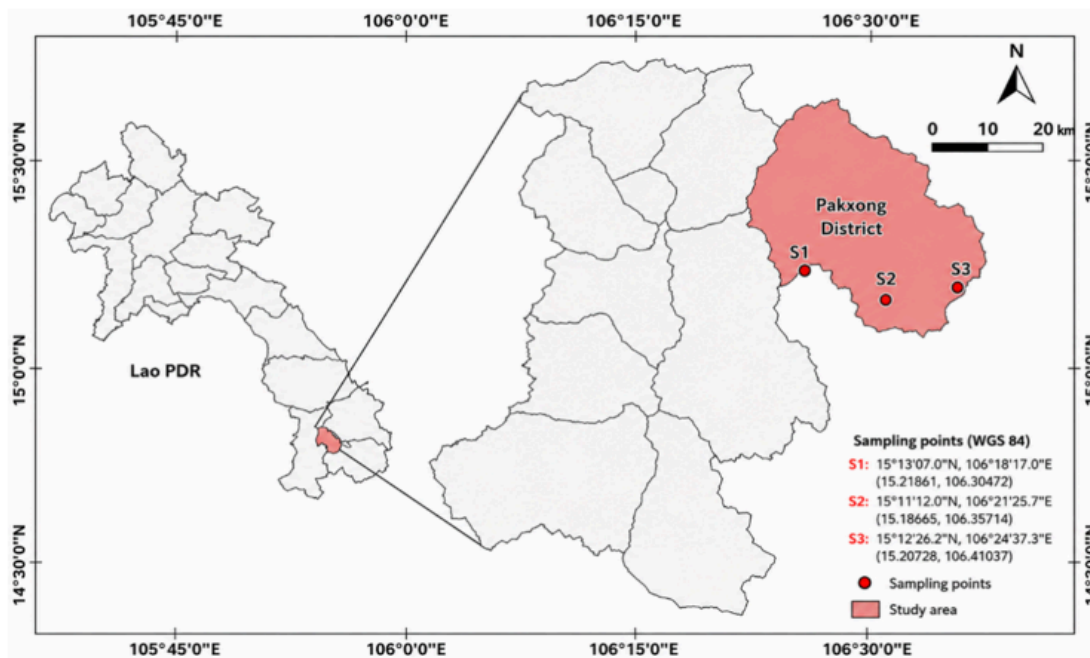


Figure 1

Geographic location and spatial architecture of the monitored intensive highland agroecosystem in Pakxong District, Champasak Province, Lao PDR. The red-shaded boundary defines the administrative sector of Pakxong District within the southern Laotian transboundary corridor.

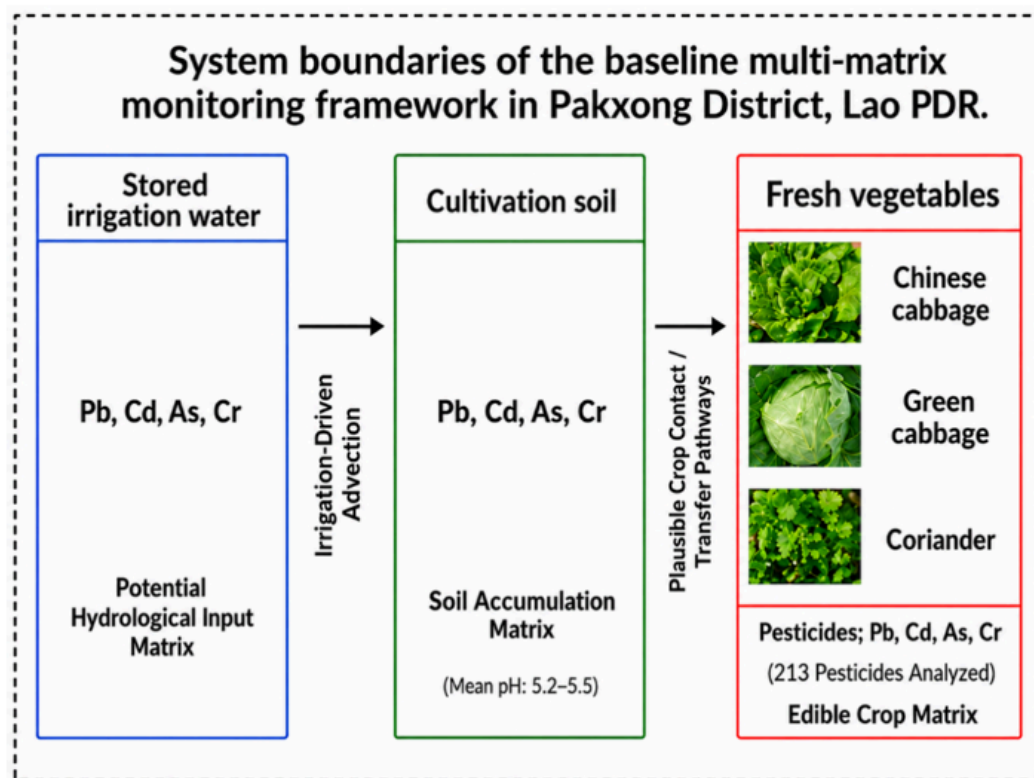


Figure 2

Conceptual framework defining the system boundaries of the baseline multi-matrix monitoring design in Pakxong District, Lao PDR. Stored irrigation water was interpreted as a potential hydrological input matrix, cultivation soil as an accumulation matrix, and fresh vegetables as

edible crop matrices. Arrows indicate plausible contaminant movement relationships within the monitored production system rather than confirmed transfer pathways. Pesticide screening was conducted only in vegetable samples, whereas toxic metals were monitored across vegetable, soil, and irrigation-water matrices.

Supplementary Files

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