Journal of Agriculture and Food Research 25 (2026) 102575

Contents lists available at ScienceDirect

Journal of Agriculture and Food Research

journal homepage: www.sciencedirect.com/journal/journal-of-agriculture-and-food-research

Bioaccumulation of heavy metals in high Andean crops of the Peruvian Andes: comparative evaluation between irrigated and dry systems

Dennis Ccopi [a,b,*,1], Edilson Requena-Rojas [a], Kevin Ortega [b,c], Richard Solórzano-Acosta [d], Ronald Révolo-Acevedo [b], Samuel Pizarro [a]

[a] *Estación Experimental Agraria Santa Ana, Dirección De Servicios Estratégicos Agrarios, Instituto Nacional de Innovación Agraria (INIA), Carretera Saños Grande – Hualahoyo Km 8 Santa Ana, Huancayo, Junín, 12006, Peru*
[b] *Research Group on Nature Conservation and Climate Change (NCCC), Facultad de Ciencias Forestales y del Ambiente, Universidad Nacional del Centro del Perú, Av. Mariscal Castilla N° 3909-4089, Huancayo, Junín, 12006, Peru*
[c] *Estación Experimental Agraria Santa Ana, Dirección de Recursos Genéticos y Biotecnología, Instituto Nacional de Innovación Agraria (INIA), Carretera Saños Grande-Hualahoyo Km 8 Santa Ana, Huancayo, Junín, 12000, Peru*
[d] *Dirección De Servicios Estratégicos Agrarios, Instituto Nacional de Innovación Agraria (INIA), Av. La Molina N° 1981, Lima, 15024, Peru*

ARTICLE INFO

Keywords:
Heavy metals
Bioaccumulation factor
Food safety
Irrigated systems
Andean agriculture
Peru

ABSTRACT

Heavy metal contamination in Andean agricultural systems is a growing concern for food safety and environmental health. This study assessed the concentrations and bioaccumulation patterns of eleven metals (Cd, Pb, As, Cr, Ni, Cu, Zn, Mn, Fe, Hg, Mo) in seven representative crops cultivated under irrigated and rainfed conditions in the Mantaro Valley, central Peruvian Andes. Soil and foliar samples were collected from paired plots, and bioaccumulation factors (BAF) were calculated to evaluate metal transfer to plant tissues. Irrigated soils showed higher and more homogeneous concentrations of Cd, Pb, and As, reflecting long-term accumulation from historical mining activities and irrigation with contaminated water from the Mantaro River. Foliar concentrations exceeded Codex Alimentarius limits for Cd, Pb, and As in several crops, especially potato and broad bean. BAF analyses revealed distinct crop-specific behaviors: potato, quinoa, and broad bean frequently exhibited BAF >1 for metals such as Cd, Cu, Zn, and Mn, indicating active uptake and translocation. In contrast, cereals such as maize and barley maintained low BAF values (<1), suggesting conservative absorption patterns. Irrigation increased the bioavailability of several metals, resulting in higher foliar concentrations and elevated BAF values compared to rainfed systems. Multivariate analyses further differentiated metal accumulation profiles by crop type and water management system. These findings highlight the need for strengthened monitoring of high-accumulation crops and improved soil and water quality management in historically contaminated Andean agricultural regions.

1. Introduction

The intensifying anthropogenic activities have progressively compromised agricultural ecosystems, resulting in substantial degradation of their physical, chemical, and biological properties [1–3]. Among these environmental stressors, heavy metal (HM) contamination of agricultural soils has emerged as a particularly severe threat to global food security, with implications extending far beyond localized environmental degradation [4].

Irrigation systems, although essential for maintaining agricultural productivity, can paradoxically become critical pathways for the introduction of heavy metals into agroecosystems, particularly when contaminated water sources are used [5,6]. This issue is especially common in developing countries, where major rivers are frequently affected by wastewater discharges from formal and informal mining operations, industrial processes, and domestic effluents containing elevated concentrations of arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni), lead (Pb), and zinc (Zn), which are continuously used for agricultural irrigation [7,8]. Despite the existence of FAO water quality guidelines, weak

---

* Corresponding author. Estación Experimental Agraria Santa Ana, Dirección De Servicios Estratégicos Agrarios, Instituto Nacional de Innovación Agraria (INIA), Carretera Saños Grande – Hualahoyo Km 8 Santa Ana, Huancayo, Junín, 12006, Peru.

E-mail address: dennisccopit@gmail.com (D. Ccopi).

[1] first author of the manuscript.

https://doi.org/10.1016/j.jafr.2025.102575
Received 18 September 2025; Received in revised form 10 December 2025; Accepted 11 December 2025

environmental enforcement has allowed irrigation with contaminated water to persist under unsafe conditions [6,9]. In such scenarios, bioaccumulation plays a central role: this physiological process enables plants to absorb and concentrate chemical substances from their growth medium, progressively incorporating them into their structures and tissues [10]. When this mechanism involves heavy metals, it becomes a major environmental and agronomic concern, as these contaminants impair plant physiological functions and compromise agricultural productivity [11].

Quantitative evaluation of metal accumulation is commonly performed using the bioaccumulation factor (BAF), defined as the ratio between metal concentration in plant tissues and soil; values greater than one indicate high bioaccumulation potential [3,12]. Although crops possess natural mechanisms to limit metal uptake and translocation, these defenses are often exceeded under high contamination, permitting the accumulation of toxic metals in edible tissues and ultimately compromising the nutritional quality, safety, and marketability of agricultural products intended for human and livestock consumption [13].

The central region of Peru exemplifies these challenges, where agriculture serves as a fundamental economic cornerstone, particularly in high-altitude Andean zones such as the Mantaro Valley. This region supports diverse agricultural production systems, cultivating numerous food and forage crops throughout the year [14]. The agricultural landscape encompasses tubers including potato (*Solanum tuberosum*); legumes such as broad bean (*Vicia faba*); vegetables including garlic (*Allium sativum*), and carrot (*Daucus carota*); and cereals such as maize (*Zea mays*) and barley (*Hordeum vulgare*). Forage production includes leguminous species such as alfalfa (*Medicago sativa*) and native pastures [9,15].

However, agricultural activities in this region occur within an environment severely compromised by historical and ongoing contamination of the Mantaro River watershed, which has received industrial, urban, and predominantly mining discharges for several decades [16–18]. This chronic pollution has resulted in elevated heavy metal concentrations in both surface water and surrounding agricultural soils, severely compromising regional environmental quality, water security, and agricultural sustainability [19,20]. Despite documented contamination, river water continues to irrigate approximately 11,000 ha of agricultural land, exposing crops to toxic element uptake and promoting bioaccumulation in edible plant tissues [21]. Previous investigations have documented concentrations of Cd, Pb, Zn, and As exceeding permissible limits in tubers, leafy vegetables, and other locally consumed agricultural products, creating critical concerns regarding food quality and agricultural sustainability in the region [21–23]. However, a critical knowledge gap persists: the relative contribution of irrigation versus rainfed conditions to metal bioaccumulation in Andean crops has not been comparatively quantified. This information is needed to prioritize management and monitoring measures that reduce human exposure and strengthen food security.

Previous studies conducted in the Mantaro Valley and other Andean agricultural regions have documented the presence of heavy metal contamination in soils, water, and certain crops, generally associated with anthropogenic sources [21,24,25] However, most of this research has focused on a limited number of species or on only a few metals, thereby restricting a comprehensive understanding of risk within complex agricultural systems. In response to these limitations, the present study substantially broadens the traditional approach by simultaneously evaluating eleven heavy metals in multiple food and forage crops representative of the Mantaro Valley and a comparative analysis between irrigated and rainfed crops was carried out to determine the specific role of irrigation in intensifying metal bioaccumulation in high-altitude Andean agroecosystems. This approach provides a more complete and updated understanding of accumulation processes, allowing the identification of patterns, critical crops, and high-risk zones that had not been documented with this level of resolution in previous research.

We analyzed eleven elements based on their documented environmental presence and toxicological significance: lead (Pb), cadmium (Cd), arsenic (As), chromium (Cr), mercury (Hg), nickel (Ni), copper (Cu), zinc (Zn), manganese (Mn), iron (Fe), and molybdenum (Mo). Our primary objective is to determine whether irrigation practices intensify metal uptake compared with rainfed management and to identify the crop groups most prone to accumulation in this high-altitude Andean agroecosystem. We assume that the BAF and Contamination Factor (CF) of heavy metals in irrigated crops are significantly higher than those in rain-cultured crops. Consistently, we hypothesize that irrigated fields exhibit higher soil CF and higher plant Bioaccumulation Factor/Metal Pollution Index (BAF/MPI) values than rainfed fields due to chronic inputs from mining-affected waters. Ultimately, the findings are intended to guide management and monitoring actions to reduce human exposure and strengthen food security, contributing to the achievement of the Sustainable Development Goals, particularly SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-Being), and SDG 6 (Clean Water and Sanitation).

2. Materials and methods

2.1. Description of the study area

This study was conducted in the Mantaro Valley, located in the central region of the Peruvian Andes, in the department of Junín (Fig. 1). The valley extends between 11°30′–12°30′ S and 74°30′–76°00′ W, with elevations ranging from 3200 to 3800 m a.s.l. The climate is temperate sub-humid with a rainy season from November to April and a dry season from May to October [26]. According to the 2017 National Census, Junín Department has 2,370,582.58 ha of agricultural area distributed among 120,312 producers, with Huancayo Province concentrating over 27,000 producers (22.4 % of the regional total), making it one of Peru's most important agricultural regions [27].

The valley is predominantly composed of Acrisols, which cover more than 80 % of the area and are characterized by acidic conditions and low to moderate natural fertility. Fluvisols account for about 10 %, occurring mainly along the alluvial terraces of the Mantaro River. Smaller proportions of Phaeozems (5 %), associated with higher organic matter content, and Leptosols (4 %), typical of shallow and stony soils, are also present. This soil distribution influences nutrient availability, crop suitability, and patterns of land degradation across the valley [28–30].

Fig. 1 shows the distribution of prioritized crops in the Mantaro Valley under irrigated and rainfed systems, highlighting that maize and potato are fundamental crops in both agricultural water regimes. The study encompassed diverse crop categories including food crops (tubers, legumes, vegetables, and cereals/grains) and forage crops (forage legumes, grasses, and pastures) as detailed in Table 1.

Irrigated crops are predominantly concentrated in the central valley where water infrastructure is well-developed, while rainfed systems dominate higher elevation and peripheral areas, supporting crops such as quinoa, barley, native pastures, and ryegrass. This spatial distribution reflects the agricultural adaptation to topographic gradients and water availability, with crop selection varying according to elevation, irrigation access, and management intensity. The study encompassed a variety of crop groups commonly cultivated in the region. Food crops included tubers such as potato, legumes such as broad bean, and vegetables such as carrot. Cereal and grain crops were represented by maize, quinoa, and barley. In addition, alfalfa was included as a forage crop belonging to the forage legume group.

2.2. Sample collection

Sampling was carried out between February and March 2023, covering the agricultural period in which the selected crops were at active growth stages. A total of 218 georeferenced samples were

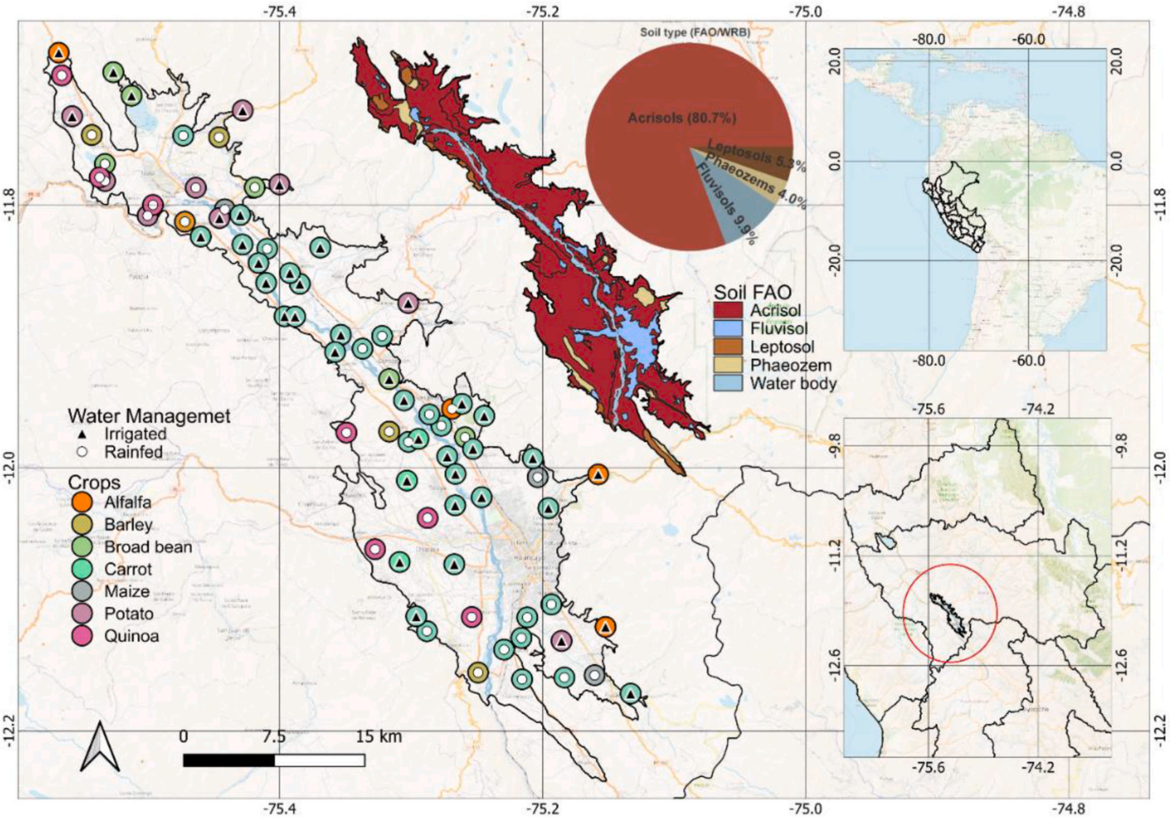

Fig. 1. Location map and geographic distribution of prioritized crops by water management in the Mantaro Valley.

collected across the Mantaro Valley following a regularized grid pattern with intervals of 2–5 km. The dataset includes 88 soil samples, 88 foliar samples from representative Andean crops, and 42 surface water samples from irrigation channels and natural watercourses. All sampling locations were georeferenced using UTM coordinates under the WGS 84 reference system. For soil sampling, each location consisted of five subsamples taken around the central point and homogenized to obtain a single composite soil sample. In the case of crop sampling, material from the aerial part of the plants was collected by taking tissue from five representative plants surrounding the sampling point; these subsamples were then combined and homogenized to generate a composite aerial-tissue sample. For water samples, the presence or absence of irrigation infrastructure in the associated agricultural plots was recorded to enable comparative analyses between irrigated and rainfed farming systems.

2.3. *Soil sampling*

Soil sampling was conducted following guidelines established in the Guide for Sampling of Contaminated Soils by Peru's Ministry of Environment [31], aligned with FAO methodological recommendations for contaminated soil assessment [32] systematic sampling design was applied in agricultural areas, collecting five surface subsamples (0–30 cm depth) at each site, which were homogenized to form representative composite samples for laboratory analysis. This approach ensures reliable data collection on contaminant distribution and concentration in agricultural soils while complying with international standards for contaminated site characterization.

2.4. *Water sampling*

Surface water sampling followed the National Protocol for Monitoring Natural Surface Water Body Quality [33], which establishes technical procedures to ensure sample representativeness and reliability. Samples were collected through direct immersion of high-density polyethylene bottles at approximately 20 cm depth below the water surface, avoiding contact with bottom sediments or channel margins. Containers were previously conditioned according to analytical parameter requirements. Each bottle was sealed with security tags, labeled with unique codes, and stored at 4 °C in thermal coolers following strict chain-of-custody protocols. This procedure was complemented by FAO [34] methodological recommendations, emphasizing cross-contamination prevention, proper preservation techniques, and ensuring that sampling reflects actual agricultural environment conditions.

2.5. *Foliar sampling*

For foliar samples, 100 m^2 plots were delineated, within which five subsamples were collected at each point to form composite samples of approximately 250 g fresh leaves. Leaves were washed with tap water and deionized water (three times each), then oven-dried at 80 °C for 4 h, ground, sieved through 0.075 mm mesh, and stored in sealed bags until laboratory analysis.

2.6. *Analytical method validation and quality assurance*

Heavy metal analysis of soil, irrigation water, and plant tissue samples was performed at the Laboratory of Soils, Water, and Foliar Analysis (LABSAF-Lima) of the National Institute of Agricultural Innovation (INIA), following standardized analytical procedures accredited by the National Institute of Quality (INACAL). Quantitative determination of Pb, Cd, As, Cr, Hg, Ni, Cu, Zn, Mn, Fe, and Mo was conducted using validated atomic absorption spectrometry (AAS) methods with flame and graphite furnace atomization techniques.

Sample preservation protocols adhered to established guidelines for each matrix type. Water samples were maintained under refrigerated

Table 1
Concentrations of heavy metals in irrigated (I) and rain-fed (R) agricultural soils in different crop areas.

HM	n	Alfalfa I	Alfalfa R	P Val.	n	Broad b. I	Broad b. R	P Val.	n	Maize I	Maize R	P Val.	n	Potato I	Potato R	P Val.	Quinoa R	Barley R	Carrot I
Cd	3	0.73 ± 0.37	0.91 ± 0.63	1.00	4	1.00 ± 0.62	2.63 ± 2.82	0.665	25–18	1.44 ± 2.36	2.42 ± 4.55	0.514	8–5	2.07 ± 3.91	4.86 ± 5.68	0.272	1.11 ± 1.93	1.09 ± 1.34	0.38 ± 0.25
Pb	3	36.3 ± 15.30	34.5 ± 2.38	0.663	4	40.0 ± 11.7	91.4 ± 52.3	0.193	25–18	116 ± 268	87.9 ± 162	0.179	8–5	189 ± 450	501 ± 700	0.048	177 ± 396	144 ± 219	22.9 ± 11.8
As	3	24.7 ± 8.42	36.7 ± 24.3	0.663	4	33.7 ± 3.61	47.9 ± 23.1	0.312	25–18	51.3 ± 73.2	46.4 ± 57.8	0.824	8–5	66.7 ± 120	162 ± 194	0.067	73.39 ± 114.50	45.9 ± 67.6	20.0 ± 9.55
Cr	3	23.2 ± 6.54	20.9 ± 4.11	1.00	4	26.5 ± 11.1	16.4 ± 4.98	0.112	25–18	22.2 ± 7.10	18.9 ± 6.88	0.112	8–5	20.9 ± 8.97	19.4 ± 8.90	0.608	20.5 ± 5.57	16.9 ± 4.13	25.1 ± 14.6
Hg	3	0.91 ± 0.86	0.50 ± 0.36	0.663	4	0.30 ± 0.35	1.26 ± 1.22	0.383	25–18	0.63 ± 1.18	0.77 ± 2.21	0.236	8–5	0.25 ± 0.17	0.98 ± 1.59	0.607	0.69 ± 1.48	0.40 ± 0.35	0.23 ± 0.19
Ni	3	25.1 ± 13.5	27.4 ± 10.0	0.663	4	38.9 ± 38.1	17.6 ± 1.57	0.312	25–18	19.95 ± 7.17	19.7 ± 6.80	0.990	8–5	18.9 ± 10.1	17.3 ± 3.59	0.714	18.3 ± 2.87	16.0 ± 4.33	26.7 ± 10.0
Cu	3	28.3 ± 8.92	28.2 ± 3.81	1.00	4	32.9 ± 4.37	48.1 ± 31.9	1.00	25–18	66.3 ± 107	55.8 ± 90.1	0.579	8–5	85.2 ± 170	278 ± 411	0.164	106 ± 213	67.5 ± 123	26.5 ± 11.3
Zn	3	156 ± 63	144 ± 54.7	0.663	4	184 ± 120	548 ± 511	0.470	25–18	540 ± 1204	487 ± 103	0.758	8–5	823 ± 1944	2413 ± 3280	0.164	893 ± 2269	569 ± 1134	88.3 ± 48.2
Mn	3	832 ± 371	745 ± 148	1.00	4	808 ± 213	755 ± 189	0.885	25–18	948 ± 734	954 ± 679	0.796	8–5	1040 ± 765	1746 ± 1986	0.608	676 ± 307	644 ± 176	765 ± 206
Fe	3	23607 ± 4529	27344 ± 5422	0.383	4	25080 ± 3051	23154 ± 2439	0.312	25–18	26984 ± 6250	28237 ± 6023	0.467	8–5	23328 ± 10102	35245 ± 20627	0.124	30584 ± 11873	25389 ± 8180	28102 ± 12715
Mo	3	2.13 ± 2.16	2.36 ± 2.35	0.383	4	4.58 ± 7.14	1.12 ± 0.32	1.00	25–18	1.46 ± 0.93	1.53 ± 1.07	0.423	8–5	2.58 ± 3.95	3.63 ± 4.78	0.420	1.29 ± 0.90	1.29 ± 0.82	1.21 ± 0.50

Note: Quinoa (n = 8), barley (n = 7) and carrot (n = 3) I = irrigated, R = rainfed. Statistical comparisons between systems were performed using the Wilcoxon (Mann–Whitney).

conditions (4 °C) and processed according to preservation and filtration protocols for natural waters [33]. Soil and plant tissue samples underwent acid digestion procedures following EPA-validated methods prior to instrumental analysis.

Quality assurance measures included systematic implementation of analytical blanks, certified reference materials, matrix spikes, and duplicate analyses for every analytical batch. The laboratory operates under ISO/IEC 17025 standards and undergoes regular proficiency testing and technical audits to ensure analytical traceability, accuracy, and precision. Method detection limits and quantification limits were established for each element and matrix combination, with recovery rates maintained within acceptable ranges (85–115 %) for all certified reference materials.

2.7. *Contamination Factor*

The Contamination Factor is an index that assesses the degree of contamination of a specific metal by comparing its concentration in a sample to a natural background value. It is calculated as the ratio between the metal concentration in soil or water and its reference value. A CF > 1 indicates contamination; the higher the value, the greater the level of impact.

$$CF = \frac{C_{metal\ in\ the\ sample}}{C_{metal\ in\ the\ background\ value}} \tag{1}$$

The CF is interpreted according to the classification proposed by Hakanson [35] and adopted in subsequent studies [36,37]. Contamination levels are categorized as follows: $CF < 1$ indicates no contamination; $1 \leq CF < 3$ corresponds to moderate contamination; $3 \leq CF < 6$ represents considerable contamination; and $CF \geq 6$ is classified as high contamination.

2.8. *Metal Pollution Index (MPI)*

The Metal Pollution Index (MPI) is a composite index that summarizes the total heavy metal load in a plant sample into a single value. Its main advantage is that it allows for a global comparison between different plant species in terms of their overall metal accumulation, without the need to assess each metal individually [38].

$$MPI = \left(\prod_{i=1}^{n} {}^{*}Ci \right)^{\frac{1}{n}} \tag{2}$$

Where.

- Ci = concentration of metal i in the plant (mg/kg).
- n = total number of analyzed metals.
- $\prod$. = product of the concentrations.

2.9. *Bioaccumulation factor (BAF)*

The estimation of heavy metal bioaccumulation in crops from the Mantaro Valley will be carried out using the BAF, defined as the ratio between the metal concentration in the plant (Cplant) and its concentration in the medium (Csoil or Cwater), according to Ref. [39,40]. This indicator allows quantifying the plant's ability to absorb metals, distinguishing between soil and irrigation water as sources of contamination.

$$BAF_{soil} = \frac{C_{Plant}}{C_{soil}} \quad and \quad BAF_{water} = \frac{C_{Plant}}{C_{water}} \tag{3}$$

A BAF >1 indicates a tendency for metal accumulation in the plant, whereas a BAF <1 reflects low uptake, typical of metal-excluding species [41].

2.10. *Statistical analysis*

Statistical analyses were conducted using R 4.3.0 [42] within RStudio. Data visualization and exploration utilized ggplot2 [43], dplyr [44], and FSA [45] packages. Data normality was assessed using the Shapiro-Wilk test implemented in car [46]. Due to non-normal distributions, non-parametric Wilcoxon (Mann–Whitney) tests assessed group differences between irrigated and rainfed systems. Pearson correlation analyses among heavy metals were performed using corrplot, PerformanceAnalytics, and Hmisc packages to identify relationships between elements. Correlation matrices and concentration patterns were visualized through heatmaps generated using pheatmap [47] and ComplexHeatmap. Principal component analysis was performed with FactoMineR [48] to identify underlying patterns in heavy metal accumulation across crop types and farming systems, with results visualized using factoextra [49]. Spatial analysis and mapping were conducted in QGIS [50] for geographic distribution assessment. Statistical significance was set at $p < 0.05$ for all analyses.

3. Results

3.1. *Concentrations of metals in crops*

The results shown in Table 1 indicate that soil metal concentrations differ between irrigation (I) and rainfed (R) conditions, although the pattern varies depending on the metal and the crop area. In soils associated with alfalfa, values under both systems are practically the same, for example Cd at 0.73 vs 0.91 mg/kg and Pb at 36.3 vs 34.5 mg/kg. This indicates that irrigation has very little influence on soil contamination levels in this crop. In soils linked to broad bean cultivation, some metals are higher under rainfed conditions, such as Zn increasing from 184 to 548 mg/kg and As from 33.7 to 47.9 mg/kg, although these differences are not statistically significant. This pattern suggests that natural soil variability may explain these values better than the presence or absence of irrigation.

Maize soils show a mixed response. Cd is higher under rainfed conditions (2.42 mg/kg) than under irrigation (1.44 mg/kg), while Pb decreases from 116 mg/kg under rainfed conditions to 87.9 mg/kg under irrigation. Other elements, such as Mn and Fe, remain similar between the two systems, indicating that irrigation does not consistently alter their concentrations in maize soils. The most marked case is observed in potato soils. Several metals increase substantially under irrigation, including Cd rising from 2.07 to 4.86 mg/kg, Pb increasing from 189 to 501 mg/kg (with a significant difference, $P = 0.048$), and Fe rising from 23,328 to 35,245 mg/kg. These differences suggest that irrigation water may act as an additional source of heavy metal inputs to these soils. In soils associated with quinoa, barley, and carrot, evaluated mainly under rainfed conditions, naturally high concentrations of some elements are observed, such as Zn at 893 mg/kg in quinoa and Mn ranging from 676 to 765 mg/kg. This indicates preexisting soil enrichment rather than the effect of irrigation.

3.2. *Concentrations of metals in crops*

Table 2 shows a comparison between foliar metal concentrations and the maximum levels established by the Codex Alimentarius for vegetables and leafy crops [51,52]. For cadmium, with a maximum permitted level of 0.2 mg/kg, most foliar samples remained below this threshold under both irrigation (I) and rainfed (R) conditions. However, exceedances were observed in potato (0.55 ± 0.55 mg/kg under irrigation and 0.53 ± 0.24 mg/kg under rainfed conditions) and in quinoa (0.30 ± 0.45 mg/kg). For lead, whose maximum level is 0.3 mg/kg, nearly all crops exhibited concentrations far above this limit. The highest values occurred in potato (11.1 ± 24.5 mg/kg under irrigation and 5.14 ± 5.67 mg/kg under rainfed conditions) and alfalfa (1.85 ± 1.94 mg/kg under irrigation). In maize, although concentrations were lower relative to

Table 2
Comparison of foliar heavy metal concentrations in crops under irrigated (I) and rainfed (R) conditions and Codex Alimentarius reference values.

HM	n	Alfalfa I	Alfalfa R	P Val.	n	Broad b. I	Broad b. R	P Val.	n	Maize I	Maize R	P Val.	n	Potato I	Potato R	P Val.	Quinoa R	Barley R	Carrot I	Maximum Level (mg/kg)
Cd	3	0.05 ± 0.01	0.12 ± 0.03	0.077	4	0.15 ± 0.12	0.14 ± 0.08	0.882	25–18	0.13 ± 0.12	0.06 ± 0.01	0.018	8–5	0.55 ± 0.55	0.53 ± 0.24	0.464	0.30 ± 0.45	0.16 ± 0.12	0.15 ± 0.09	0.2
Pb	3	1.85 ± 1.94	1.96 ± 1.16	1.000	4	8.40 ± 11.7	2.67 ± 0.84	0.471	25–18	2.43 ± 4.85	0.83 ± 0.87	0.012	8–5	11.1 ± 24.5	5.14 ± 5.67	0.608	0.33 ± 0.19	1.52 ± 0.95	1.27 ± 0.52	0.3
As	3	0.50 ± 0.09	1.07 ± 0.60	0.658	4	2.48 ± 2.32	3.27 ± 2.90	0.471	25–18	0.88 ± 1.46	0.41 ± 0.39	0.083	8–5	4.30 ± 7.36	2.79 ± 1.99	0.608	0.21 ± 0.07	0.88 ± 0.78	0.84 ± 0.14	0.1
Cr	3	1.21 ± 0.70	1.77 ± 0.98	0.383	4	3.65 ± 1.04	7.33 ± 9.23	0.885	25–18	1.67 ± 1.10	2.30 ± 2.55	0.343	8–5	2.40 ± 0.73	2.82 ± 1.12	0.341	1.54 ± 0.81	2.51 ± 0.85	2.38 ± 1.39	0.03
Hg	3	0.09 ± 0.00	0.09 ± 0.00		4	0.12 ± 0.06	0.09 ± 0.00	0.453	25–18	0.09 ± 0.00	0.09 ± 0.00	1.000	8–5	0.09 ± 0.00	0.09 ± 0.00	1.000	0.09 ± 0.00	0.09 ± 0.00	0.09 ± 0.00	–
Ni	3	1.08 ± 0.40	1.36 ± 0.84	0.825	4	3.56 ± 3.26	4.93 ± 4.59	0.665	25–18	1.01 ± 0.64	1.22 ± 0.73	0.228	8–5	2.42 ± 0.71	2.37 ± 1.05	0.714	2.47 ± 2.56	2.23 ± 0.82	1.73 ± 0.63	–
Cu	3	11.9 ± 2.59	16.3 ± 14.9	0.663	4	14.5 ± 5.45	16.1 ± 5.15	0.885	25–18	12.9 ± 7.66	12.1 ± 5.88	0.883	8–5	18.9 ± 14.7	14.8 ± 2.71	0.608	16.5 ± 10.4	14.9 ± 10.6	6.13 ± 2.43	–
Zn	3	32.1 ± 5.95	36.2 ± 2.47	0.663	4	109 ± 84.0	83.1 ± 47.5	0.885	25–18	76.9 ± 58.2	40.8 ± 13.4	0.023	8–5	91.2 ± 96.3	49.3 ± 20.4	0.421	48.4 ± 16.5	62.7 ± 46.2	22.5 ± 7.69	–
Mn	3	41.9 ± 18.6	64.6 ± 28.5	0.190	4	235 ± 356	169 ± 59.6	0.471	25–18	53.2 ± 27.0	65.1 ± 38.5	0.157	8–5	234 ± 223	224 ± 96.9	0.608	70.6 ± 30.8	87.1 ± 64.9	42.4 ± 20.0	–
Fe	3	443.1 ± 56.3	629 ± 352	0.663	4	1098 ± 958	1457 ± 833	0.471	25–18	216 ± 167	205 ± 118	0.971	8–5	1377 ± 708	1532 ± 684	0.714	143 ± 48.4	590 ± 462	541 ± 128	–
Mo	3	0.12 ± 0.03	0.13 ± 0.05	1.000	4	1.60 ± 2.18	0.09 ± 0.01	0.245	25–18	0.09 ± 0.03	0.08 ± 0.01	0.295	8–5	0.10 ± 0.05	0.10 ± 0.05	1.000	0.09 ± 0.02	0.10 ± 0.05	0.11 ± 0.04	–

Note: Quinoa (n = 8), barley (n = 7) and carrot (n = 3) I = irrigated, R = rainfed. Statistical comparisons between systems were performed using the Wilcoxon (Mann–Whitney). Codex Alimentarius [51,52], evaluation reports.

other crops, they still exceeded the Codex threshold (2.43 ± 4.85 mg/kg under irrigation and 0.83 ± 0.87 mg/kg under rainfed conditions).

For inorganic arsenic, with a maximum level of 0.1 mg/kg, foliar concentrations also exceeded the Codex limit in most crops. Again, potato (4.30 ± 7.36 mg/kg under irrigation) and broad bean (2.48 ± 2.32 mg/kg under irrigation) showed the highest values. In alfalfa and maize, some concentrations were closer to the limit but still above the reference value. For total mercury, although the Codex does not define a specific limit for vegetables [52], guidance suggests a reference range of 0.01–0.03 mg/kg. All samples showed concentrations of 0.09 mg/kg, exceeding this guideline. Foliar concentrations of other metals for which no international regulatory limits exist in vegetables, such as Cr, Ni, Cu, Zn, Mn, Fe, and Mo, also varied among crops and water management systems. Zinc reached notably high values in maize under irrigation (76.9 ± 58.2 mg/kg) and in quinoa (48.4 ± 16.5 mg/kg), while iron showed elevated levels in potato (1377 ± 708 mg/kg under irrigation).

3.3. Metal concentrations in irrigation water

The irrigation water analyses showed very low or non-detectable metal concentrations, remaining below the guideline values established by Ayers & Westcot [53]. Although current water quality appears acceptable, this does not rule out irrigation as a contamination pathway, since irrigated soils consistently show higher metal concentrations than rainfed soils. This pattern suggests that long-term irrigation with water from a mining-affected watershed may have contributed to the gradual accumulation of heavy metals in agricultural soils, even if current metal levels in water are minimal.

3.4. Principal component analysis (PCA) of heavy metal bioaccumulation in andean crops

The principal component analysis (PCA) shows differentiated patterns in the distribution of heavy metals according to irrigation system, physical medium, and crop type. Fig. 2 shows that the first two components explain most of the total variability, with PC1 accounting for 65.3 percent and PC2 for 18.2 percent, indicating that the separation observed in the two-dimensional plane adequately captures the main trends in the dataset. PC1 is primarily influenced by As, Cd, Cu, Pb, and Zn, whose vectors project toward the lower right quadrant of the biplot, while PC2 is dominated by Ni, Cr, Fe, Mo, and Mn, oriented toward the upper region. Hg displays a more independent behavior, projecting in the opposite direction from the main metal clusters, suggesting distinct variability relative to the other elements.

Fig. 2a shows a separation between irrigated and rainfed samples. The irrigation observations cluster near the PCA origin, extending slightly toward the zone associated with As, Pb, Zn, and Cu, suggesting a greater affinity of irrigated systems with these metals. In contrast, rainfed samples present much greater dispersion along PC1 and PC2, aligning with the vectors of Ni, Cr, Fe, and Mn.

Fig. 2b shows that soil displays the greatest amplitude of dispersion in both dimensions, reflecting its heterogeneous nature and its role as the main reservoir of metals. Water concentrates toward the lower right quadrant, close to the vectors of As, Pb, and Zn, indicating that these metallic species dominate the chemical variability of this matrix. Foliage samples, on the other hand, cluster around the PCA origin, suggesting lower variability and more stable behavior in terms of relative metal accumulation.

Finally, in Fig. 2c, clear differences are observed between functional groups. Crops such as barley and quinoa project toward the upper part of

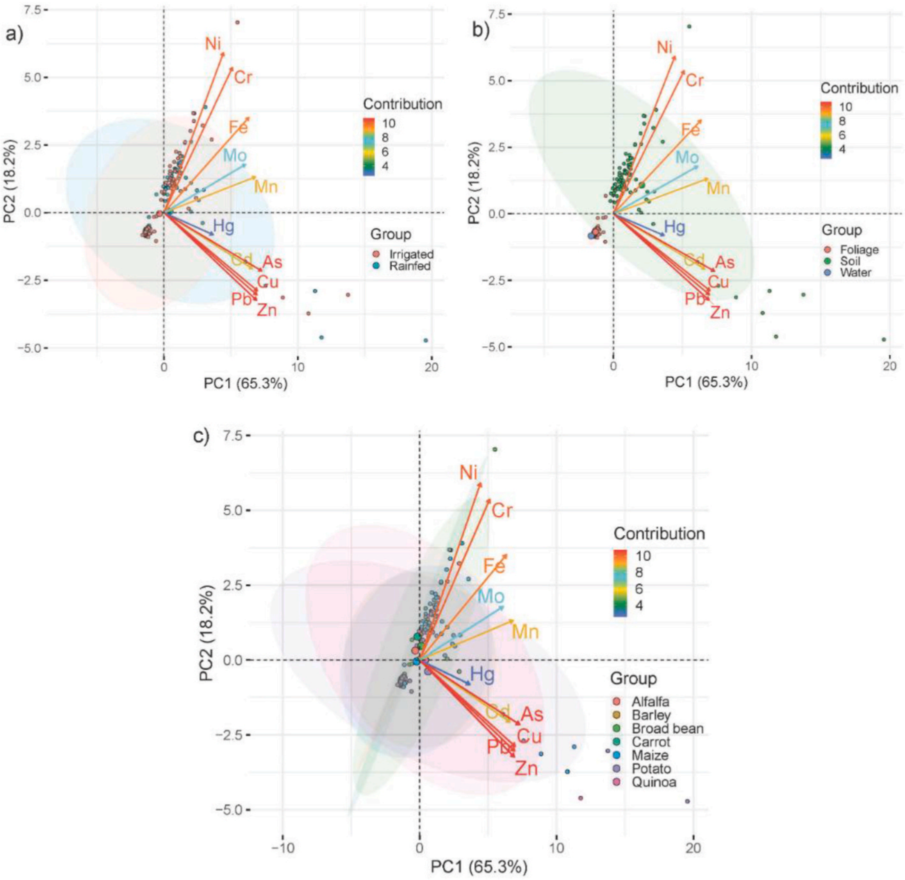

Fig. 2. Principal component analysis (PCA) of heavy metal distribution by a) irrigation regime, b) environmental matrix, and c) crop type.

the graph, in the direction of Ni, Cr, Fe, and Mn, evidencing affinity with these metals. Carrot shows considerable dispersion across the biplot, with some samples extending toward negative PC1 values, while potato appears in the lower part, close to the vectors of As and Pb. Maize is situated in an intermediate region, sharing influence from various metals, while alfalfa is positioned near the center of the biplot, showing a more neutral pattern. Broad bean, although with greater dispersion, tends toward the region associated with Cu and Zn. Overall, these patterns indicate that metal accumulation differs between crop types in a manner consistent with their physiology and absorption strategies.

3.5. Spatial distribution of Contamination Factor

Fig. 3 shows the spatial distribution of CF values for eleven heavy metals in the Mantaro Valley, calculated using the reference levels proposed by Hakanson [35]. The map exhibits marked spatial variability, with As (arsenic) showing the most extensive and severe contamination pattern, dominated by red symbols indicating “High” contamination across large portions of the valley. Cu, Pb, Zn, and Hg show the highest CF values concentrated in the northern sector of the valley, where “High” and “Considerable” contamination classifications are recorded (red and orange symbols). Essential elements such as Fe, Mn, Ni, and Cr display predominantly low values, with most sampling points classified as “No contamination” (green symbols).

Cadmium shows elevated values distributed across portions of the valley, with multiple points classified between “Moderate” and “Considerable”. Molybdenum exhibits predominantly low contamination levels throughout the study area.

The spatial pattern observed in Fig. 3 is explained by the strong concentration of mining and metallurgical activities throughout the Mantaro Valley, particularly the historical influence of the La Oroya Metallurgical Complex [54,55], located in the central-northern region, one of the main sources of atmospheric emissions and effluents containing Pb, As, Cd, Zn, Cu, and Hg. Atmospheric deposition, particle transport, and wastewater discharges into the Mantaro River contribute to the progressive accumulation of metals in affected areas. The high CF values for Cu, Pb, Zn, and Hg in the northern sector coincide with proximity to the La Oroya complex and intensive mining activities in this zone. Additionally, the common agricultural practice of using polluted water from the Mantaro River for irrigation in the northern and central sectors contributes significantly to metal accumulation in soils, as contaminated water continuously introduces heavy metals into agricultural lands. The widespread distribution of arsenic contamination reflects its mobility through atmospheric and fluvial transport mechanisms, as well as its incorporation through irrigation practices. In areas where industrial influence is comparatively lower, low and moderate CF values predominate, reflecting reduced pressure from direct pollution sources.

3.6. MPI and BAF metrics for assessing heavy metal bioaccumulation in crops

Fig. 4 shows the Metal Pollution Index (MPI) for the evaluated crops. Broad bean and potato present the highest MPI values, with medians around 5.0 and wide interquartile ranges extending between approximately 4.0 and 7.0. Broad bean shows the greatest variability, reaching values close to 8.0 and presenting some outliers above this range, while potato exhibits a similar but slightly more compact range. Barley presents an intermediate median of approximately 3.5 with moderate dispersion, while carrot shows moderate values (median ∼2.5) with low

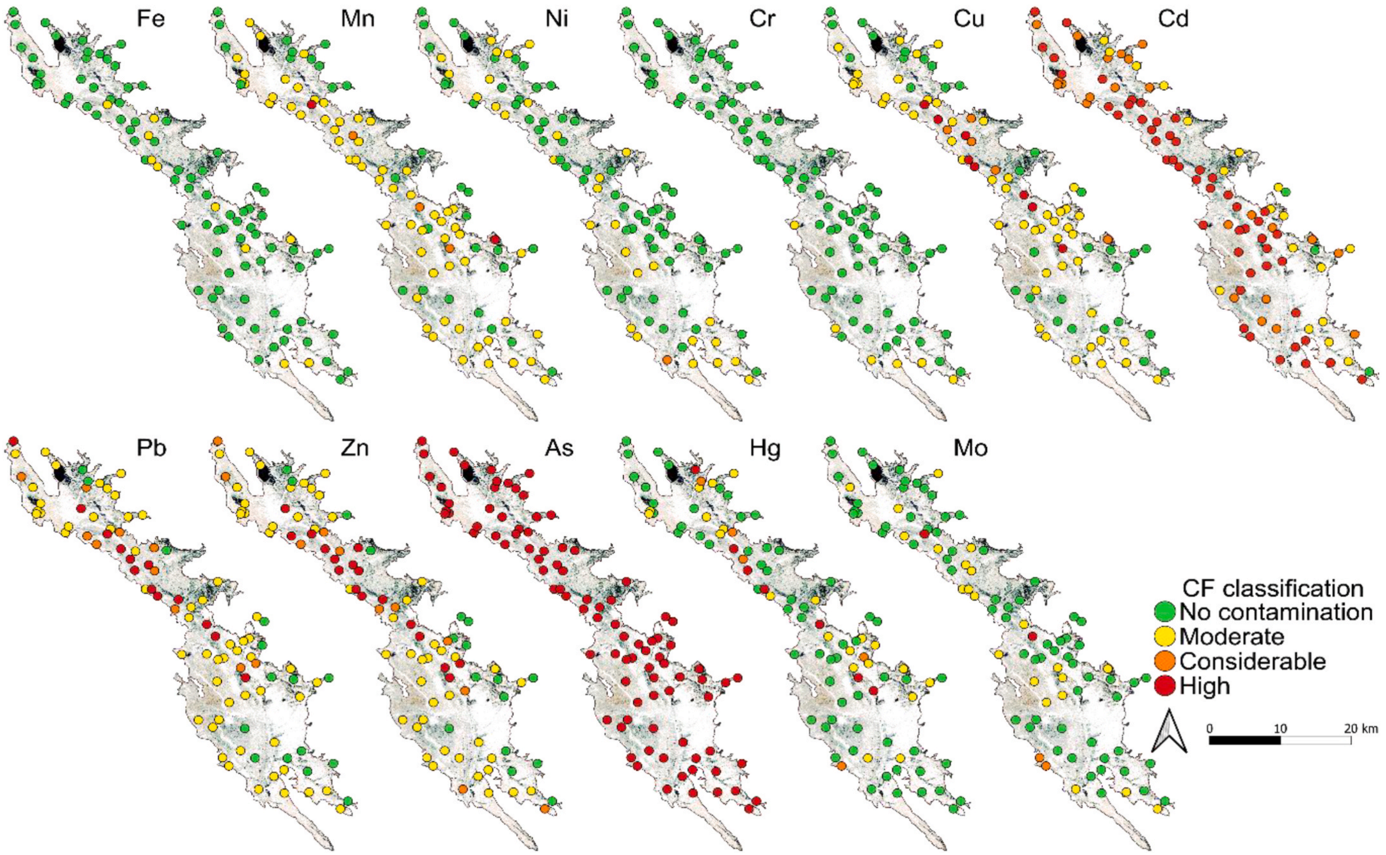

Fig. 3. Spatial distribution of the Contamination Factor (CF) for eleven potentially toxic elements in agricultural soils of the Mantaro Valley, Peru, classified according to Hakanson [35] thresholds. The maps show the variation in contamination levels (no, low, moderate, and high) and highlight element-specific hotspots across the region.

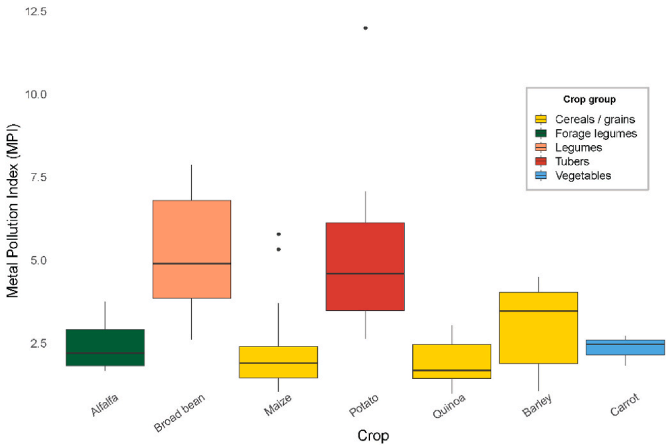

Fig. 4. Metal Pollution Index (MPI) variability in foliage of Andean crops cultivated in heavy metal-contaminated agricultural soils, Mantaro Valley, Peru.

variability.

In contrast, maize, quinoa, and alfalfa present the lowest MPI values, with medians between 1.5 and 2.3. These crops exhibit more compact distributions and lower variability, indicating significantly lower metal accumulation. The results show that tubers and grain legumes tend to accumulate higher concentrations of heavy metals, while cereals such as maize and quinoa, along with forages like alfalfa, present considerably lower levels. This variability reflects physiological differences in the mechanisms of absorption, translocation, and metal accumulation, being consistent with the specific nutritional and morphological strategies of each crop type.

Fig. 5 shows the variation of the Bioaccumulation Factor (BAF, $\log_{10}$ scale) for eleven metals (As, Cd, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Pb, and Zn) in seven representative crops from the Mantaro Valley, including alfalfa, broad bean, maize, carrot, potato, quinoa, and barley. Two water management systems are compared: irrigated conditions (Fig. 5a) and rainfed conditions (Fig. 5b). The red dashed line indicates $\log_{10}(\mathrm{BAF}) = 0$, which corresponds to BAF $= 1$ and represents the point where the metal concentration in the plant equals that of the soil. Values above this line indicate net accumulation in plant tissues, while negative values indicate limited or inhibited uptake.

Under irrigated conditions (Fig. 5a), most crops show negative $\log_{10}(\mathrm{BAF})$ values for most metals, suggesting restricted transfer from soil to plant. However, some crops display values near zero or slightly positive for specific elements, particularly broad bean and potato. These crops show a greater tendency to accumulate metals such as Cu, Mn, Mo, Ni, and Zn. Some relatively high values of Hg are also observed in certain crops, reflecting its mobility and ease of translocation. In contrast, cereals such as maize and quinoa have some of the lowest $\log_{10}(\mathrm{BAF})$ values across metals, which indicates a lower susceptibility to bioaccumulation under irrigation.

Under rainfed conditions (Fig. 5b), $\log_{10}(\mathrm{BAF})$ values tend to be even lower for most crops and metals. This pattern suggests reduced metal availability in the absence of irrigation inputs that could enhance metal mobility in the soil. Even so, metals such as Cu, Mn, Mo, and Zn show moderately elevated values in crops such as broad bean, potato, and carrot. This indicates that these species maintain physiological pathways that facilitate the uptake of micronutrients that share transport mechanisms with toxic metals. In contrast, maize and quinoa show consistently low values across most elements, confirming their conservative absorption behavior.

The comparison between the two systems indicates that irrigation increases bioaccumulation for several metals, especially those that are more mobile or associated with soil organic matter, such as Cu, Mn, Mo, and Zn. The irrigated system also displays greater variability, which may be related to differences in water quality, soil heterogeneity, and crop management. The rainfed system shows lower and more uniform values, suggesting that limited water availability acts as a barrier to metal mobilization and uptake in the evaluated crops.

3.7. *Correlation analysis of crop bioaccumulation factors under irrigated and rainfed conditions*

Fig. 6 presents the correlation matrix among crops based on average BAF values for all evaluated metals, considering both water management systems: irrigation (I) and rainfed (R). The dendrogram shows that water availability exerts a strong enough influence to separate crops according to their management system, since in most cases the irrigated and rainfed conditions of a given crop do not cluster together. This indicates that hydrological management modifies the metal bioaccumulation patterns of each crop in a distinct way. A particularly clear grouping appears among cereals grown under rainfed conditions, specifically maize (Maize_R) and barley (Barley_R), which cluster closely together. This suggests that both crops share a similar relative metal accumulation profile under rainfed management, whereas their irrigated counterparts show more divergent patterns and appear more distant in the dendrogram.

For potato, irrigated (Potato_I) and rainfed (Potato_R) conditions form separate branches of the hierarchical tree, reflecting substantial shifts in their metal accumulation behavior depending on water supply. This observation is consistent with the wide variations found in their foliar metal concentrations. Similarly, broad bean and alfalfa do not cluster their irrigated and rainfed conditions together, indicating that both crops respond differently to water management, although with a smaller contrast than that observed in potato. Finally, carrot under irrigation (Carrot_I) appears relatively isolated, suggesting a distinct correlation pattern that does not align closely with other crops. Quinoa under rainfed conditions (Quinoa_R) also shows a unique behavior, positioned on an independent branch of the dendrogram.

4. Discussion

4.1. *Heavy metal toxicity and physiological impact on crops*

The presence of heavy metals such as Cd, Pb, and As in agricultural soils represents a silent yet profound threat to crop health and, by extension, to food security. Once absorbed through the roots, these elements can disrupt key physiological processes, reduce crop yields, and accumulate in edible plant tissues at concentrations exceeding international safety thresholds, as observed in crops from the Mantaro Valley. Studies such as those by Faouzi et al. [56] and Victoria & Nnebini [57] have shown that even moderate concentrations of these metals can impair plant development and facilitate their entry into the human food chain.

4.2. *Implications for human health associated with the consumption of crops containing elevated levels of heavy metals (HM)*

Elevated concentrations of cadmium (Cd), lead (Pb) and arsenic (As) detected in several crops from the Mantaro Valley represent serious concern for both human and animal health, particularly in rural communities that rely almost entirely on local produce for subsistence, either through direct consumption or market sales. Our findings indicate that highly important food crops such as potato and maize, among others, exhibited Pb and As levels exceeding the maximum permissible limits established by international references, which may suggest a potential risk of chronic dietary exposure [1].

Chronic exposure to Cd is associated with nephrotoxicity, bone disorders and an increased risk of cancer. In this regard, the Tolerable Weekly Intake for Cd is estimated at approximately 2.5 μg/kg body weight/week [58], a threshold that could be exceeded in populations

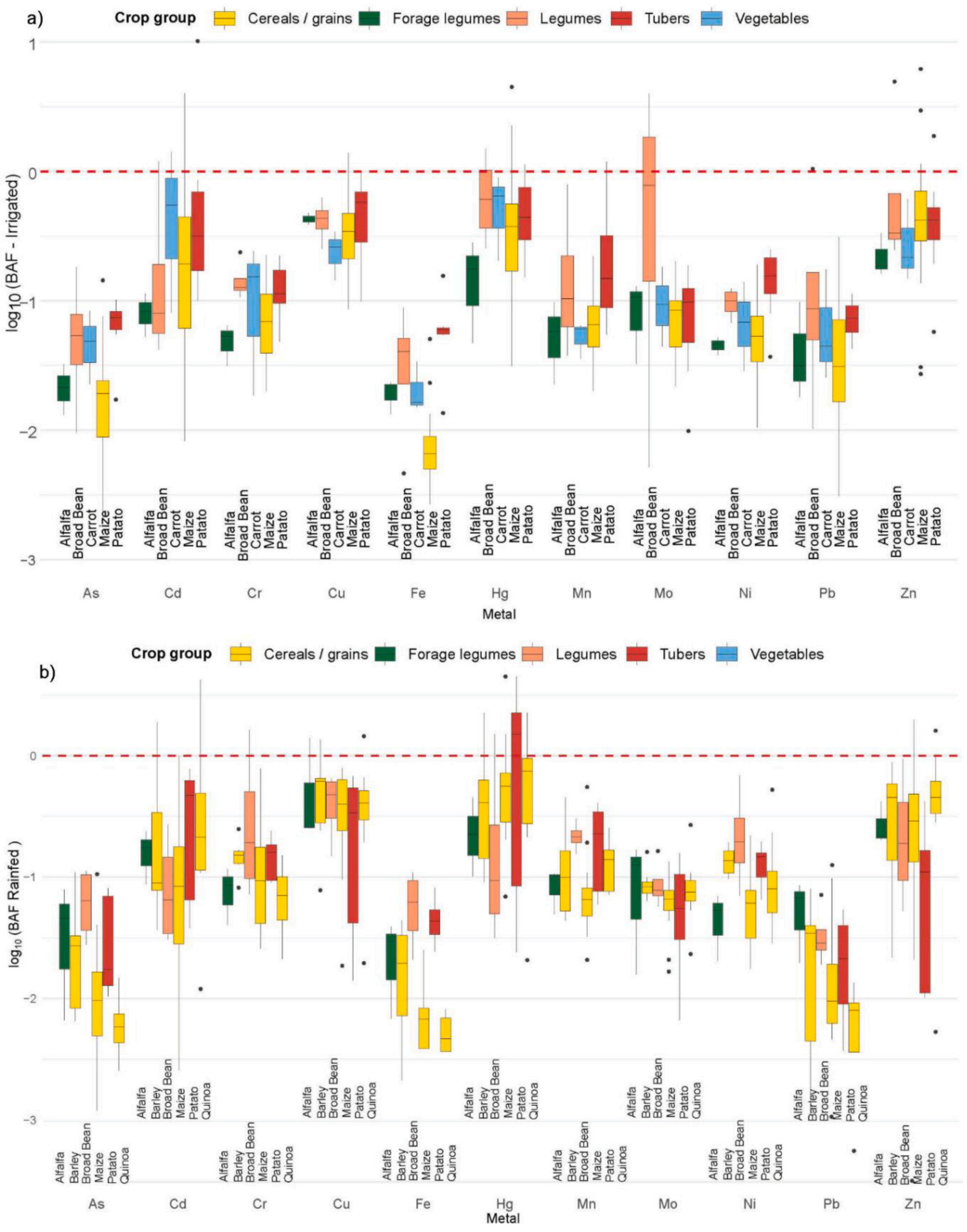

Fig. 5. Bioaccumulation factor for heavy metals in Andean crops under (a) irrigated and (b) rainfed cultivation systems, Mantaro Valley.

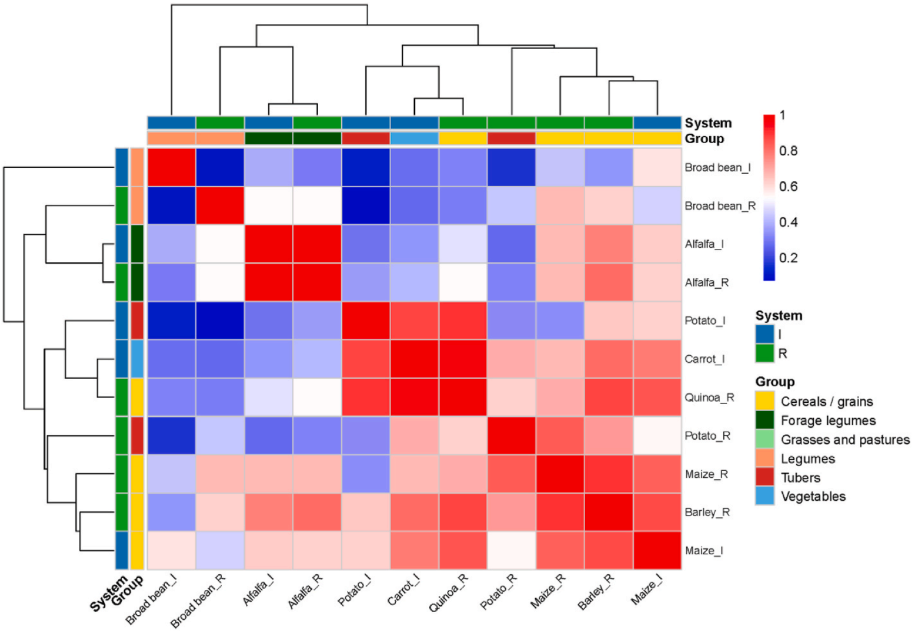

Fig. 6. Correlation matrix and hierarchical clustering of crops based on mean BAF values for all evaluated metals under irrigated (I) and rainfed (R) management. The dendrogram illustrates how water management differentiates the metal bioaccumulation profiles of each crop, with irrigated and rainfed conditions often forming separate clusters.

whose diets rely heavily on tubers and cereals grown in contaminated soils, posing a latent health risk and highlighting the urgent need for remediation measures [10]. In a more local context [3], reported that native Peruvian potatoes do not exceed reference Cd levels; however, they noted that Cd exposure may represent a greater risk for children, who are more susceptible to heavy metal intoxication due to the ongoing development of their neurological systems.

Lead (Pb) poses an even greater risk, as no safe threshold of exposure has been identified, particularly for children, according to international agencies such as the CDC [59] and the European Food Safety Authority, which has indicated that it is not possible to establish a tolerable weekly intake for this metal [60]. Its presence has been linked to neurological impairment, especially in children, as well as kidney damage and cardiovascular diseases in adults [61]. In the Mantaro River basin, elevated Pb concentrations have been reported in soils, water and crops, suggesting a potential direct source of exposure for the local population [62].

Arsenic (As), classified as a carcinogen, is associated with skin lesions, cardiovascular diseases, diabetes and various types of cancer. In this study, As concentrations in potato, barley and legume crops exceeded reference values, which may indicate that dietary intake could surpass the recommended limits for inorganic arsenic [41]. This pattern has also been documented in Andean regions affected by mining activities, such as in the Arequipa region, where the presence of As in rice was likely linked to mining operations [63].

4.3. Species-specific bioaccumulation patterns in andean crops

The bioaccumulation of heavy metals in Andean crops from the Mantaro Valley showed species-specific patterns, with elevated concentrations observed in food crops such as potato (*Solanum tuberosum*), artichoke, and maize (*Zea mays*), as well as in certain forage species. In these cases, BAF exceeded the threshold of 1 for elements such as Cd, Pb, and As across multiple sampling sites. These findings are consistent with Xiang et al. [64], who reported that grain crops tend to accumulate higher levels of heavy metals compared to fruits and vegetables, with significant bioaccumulation of Cr, Ni, and Cd. Similarly, Alhaj Hamoud et al. [65] observed elevated concentrations of Zn and Cu in traditional highland crops such as barley, reflecting the susceptibility of Andean species to metal accumulation, particularly in foliar tissues.

Moreover, Pachura et al. [66] demonstrated that Cd exhibits high mobility within plants, reaching translocation rates to aerial parts above 70 percent, while Pb remains predominantly retained in the roots, with translocation rates below 10 percent, which aligns with the patterns observed in this study. This behavior was further supported by Bhatti et al. [67], who reported limited Pb transfer to edible tissues, in contrast to other more mobile metals. Likewise, Raja et al. [68] found that food crops such as spinach, cabbage, and berseem exhibited high concentrations of Cd, Cr, and Ni, with BAF values that pose a threat to food safety.

4.4. Irrigation effects on heavy metal mobilization and distribution

Irrigation plays a key role in the mobilization, distribution, and accumulation of heavy metals in crops cultivated in the Mantaro Valley. The results indicate that irrigated plots exhibited a more homogeneous distribution of metal concentrations in the soil and a more consistent accumulation in plant tissues, in contrast to rainfed areas, which showed greater heterogeneity in both soil and crop metal levels.

This pattern is consistent with findings by Du et al. [69] and Wan et al. [70], who reported that frequent irrigation increases the bioavailability of metals through surface runoff and leaching, particularly in acidic soils or those with low organic matter content. However, they also noted that, in some cases, this process may enhance the surface washing of metals, thereby reducing localized accumulation depending on the metal type and cropping system. Complementary findings by Tong et al. [71] in Tibetan soils demonstrated that irrigation can significantly alter the bioavailable fraction of metals and their translocation within plants.

4.5. Chronic accumulation through historical irrigation practices

In the present study, although irrigation water did not show concerning concentrations of heavy metals according to current quality standards [53], irrigated plots had consistently higher levels of these elements in both surface soils and plant tissues compared to rainfed systems. This paradoxical finding suggests that decades of irrigation with water from the mining-affected Mantaro River watershed have contributed to progressive soil metal accumulation through chronic deposition. Even trace metal concentrations in irrigation water can result in significant soil contamination over extended periods, a dynamic that appears to be influenced by the physicochemical properties of the irrigation water, including pH, electrical conductivity, and dissolved organic matter content.

These factors have been shown to promote the solubility and mobility of metals in irrigated agricultural systems, as documented by Nowwar et al. [72] and Victoria & Nnebini [57]. Overall, the findings suggest that irrigation acts as a primary vector in the redistribution and accumulation of heavy metals, increasing crop exposure to persistent contaminants in high-altitude agroecosystems.

4.6. Water management influence on metal bioaccumulation patterns

The bioaccumulation of heavy metals in crops from the Mantaro Valley is closely shaped by the water management system. Irrigated fields exhibit more homogeneous patterns of metal concentrations in both soils and plant tissues, while rainfed areas show greater variability across species and plots. This contrast reflects not only crop-specific physiological differences but also the long-term influence of historically accumulated mining and metallurgical residues in high-Andean soils. Importantly, even though irrigation water may currently comply with environmental quality standards, the sustained application of water over decades can enhance the redistribution and mobilization of legacy metals within the soil profile. This mechanism has been widely documented in high-altitude agroecosystems, where irrigation acts as a driver of metal transport, altering their bioavailable fractions and facilitating plant uptake. Studies such as Custodio et al. [9] and Zárate-Quiñones et al. [73] report substantial accumulations of Pb, Cd, and As in edible tissues of both food and forage crops, frequently exceeding international guideline values. Likewise, Bedriñana et al. [74] and Orellana et al. [75] describe elevated CF and BAF indices in Andean crops, even in areas without clear point-source contamination. Together, these findings help explain the seemingly paradoxical scenario highlighted in the manuscript, in which irrigation water meets quality standards while the surrounding soils and crops exhibit significant contamination levels driven by cumulative and legacy effects.

4.7. Systematic contamination and regional food security implications

The findings of the present study reinforce this concerning trend, evidencing critical levels of metallic accumulation in prioritized crops such as potato, maize, broad bean, and alfalfa, both in irrigated and rainfed systems. Principal component analysis effectively discriminated between irrigation regimes, with irrigated systems showing greater association with toxic elements (As, Pb, Zn) compared to essential micronutrients (Ni, Cr, Fe, Mn). The spatial distribution analysis revealed distinct contamination hotspots in the northern sector of the valley, particularly for Cu, Pb, Zn, and Hg, while Cd and As displayed more widespread distribution across the agricultural landscape.

This situation highlights the urgent need to implement a permanent monitoring system in the high-Andean agroecosystems of the region. Particularly, the MPI and BAF analyses evidence a marked tendency of forage and leguminous crops to accumulate higher metallic concentrations. This phenomenon represents a significant potential risk for both local food security and the integrity of the forage chain in this agricultural region of high environmental sensitivity.

Finally, although this study provides robust evidence of the potential bioaccumulation of heavy metals in representative Andean crops of Peru, it is important to acknowledge certain factors that may influence the interpretation of the observed patterns. While irrigated and rainfed systems were compared, these agricultural environments may intrinsically differ in soil characteristics such as texture, organic matter content, cation exchange capacity, or land-use history, all of which can influence metal mobility and retention. Likewise, agronomic management practices including fertilization regimes, crop rotations, and tillage intensity may alter the availability and behavior of heavy metals in the soil, thereby affecting plant uptake. These aspects may act as potential confounding factors. Although the study design allows the identification of clear trends, future research, including ongoing efforts by our team, should more explicitly account for natural soil variability and differences in agricultural management. Such improvements will help refine the interpretation of bioaccumulation patterns, enhance the accuracy of risk assessments, and expand the geographic scope of analysis.

5. Conclusions

This study provides an integrated assessment of heavy metal contamination and bioaccumulation in major Andean crops cultivated in the Mantaro Valley under irrigated and rainfed management systems. The results demonstrate that agricultural soils across the region contain elevated concentrations of Cd, Pb, and As, reflecting the long-term influence of historical mining and metallurgical activities. Although irrigation water met current quality standards, irrigated fields consistently showed higher soil and foliar metal concentrations than rainfed fields, indicating a cumulative effect from decades of irrigation with water originating from contaminated watersheds. This pattern highlights the importance of considering chronic, low-dose inputs when evaluating agricultural contamination in high-altitude Andean environments.

Species-specific bioaccumulation patterns were evident. Potato, broad bean, and carrot exhibited the highest foliar concentrations and frequently exceeded international guideline values for Cd, Pb, and As, while cereals such as maize, barley, and quinoa showed comparatively conservative uptake. Multivariate analyses confirmed that water management strongly influences metal mobility and plant uptake, producing distinct correlation structures between irrigated and rainfed crops. These findings emphasize that irrigation practices can modulate bioavailability and redistribution of metals in agricultural soils, even when irrigation water appears compliant with regulatory standards.

The integration of concentration metrics, bioaccumulation factor (BAF), and contamination indices (CF, MPI) offers a comprehensive understanding of contamination pathways in the region. The combined evidence underscores the need for continued monitoring of soils, irrigation water, and high-accumulation crops, particularly in areas where mining legacies intersect with intensive agriculture. Strengthening surveillance systems and improving agricultural management strategies will be critical to mitigate exposure risks and safeguard food security in the Mantaro Valley.

CRediT authorship contribution statement

Dennis Ccopi: Writing – review & editing, Validation, Methodology, Investigation, Formal analysis. **Edilson Requena-Rojas:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation. **Kevin Ortega:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Conceptualization. **Richard Solórzano-Acosta:** Visualization, Validation, Software, Conceptualization. **Ronald Révolo-Acevedo:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Samuel Pizarro:** Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization.

Ethics statement

Not applicable: This manuscript does not include human or animal research.

Funding

This research was funded by the INIA project “Mejoramiento de los servicios de investigación y transferencia tecnológica en el manejo y recuperación de suelos agrícolas degradados y aguas para riego en la pequeña y mediana agricultura en los departamentos de Lima, Áncash, San Martín, Cajamarca, Lambayeque, Junín, Ayacucho, Arequipa, Puno y Ucayali” CUI 2487112, of the Ministry of Agrarian Development and Irrigation (MIDAGRI) of the Peruvian Government.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We would like to express our deepest gratitude to everyone who contributed to this research at the Santa Ana Experimental Station – Huancayo.

Data availability

Data will be made available on request.

References

[1] P.J. Alegbe, M. Appiah-Brempong, E. Awuah, Heavy metal contamination in vegetables and associated health risks, Sci. Afr. 27 (2025), https://doi.org/10.1016/j.sciaf.2025.e02603.

[2] B.J. Manegabe, T.A.M. Msagati, A. Adeyemi Ojutalayo, M.M.K. Ntabugi, J. B. Dewar, K. De Bryun, Assessment of heavy metals pollution in vegetables grown on irrigated soil and their potential threat to human health and global food security, in: Hygiene and Environmental Health Advances, vol. 14, Elsevier B.V, 2025, https://doi.org/10.1016/j.heha.2025.100129.

[3] E. Orellana-Mendoza, V. Camel, L. Yallico, V. Quispe-Coquil, R. Cosme, Effect of fertilization on the accumulation and health risk for heavy metals in native Andean potatoes in the highlands of Perú, Toxicol. Rep. 12 (2024) 594–606, https://doi.org/10.1016/j.toxrep.2024.05.006.

[4] C. Yao, Y. Yang, C. Li, Z. Shen, J. Li, N. Mei, C. Luo, Y. Wang, C. Zhang, D. Wang, Heavy metal pollution in agricultural soils from surrounding industries with low emissions: assessing contamination levels and sources, Sci. Total Environ. 917 (2024) 170610, https://doi.org/10.1016/J.SCITOTENV.2024.170610.

[5] O.O. Alegbeleye, A.S. Sant’Ana, Risks associated with the consumption of irrigation water contaminated produce: on the role of quantitative microbial risk assessment, Curr. Opin. Food Sci. 41 (2021) 88–98, https://doi.org/10.1016/J.COFS.2021.03.013.

[6] R.Z. Marques, N. Wistuba, J.C.M. Brito, V. Bernardoni, D.C. Rocha, M.P. Gomes, Crop irrigation (soybean, bean, and corn) with enrofloxacin-contaminated water leads to yield reductions and antibiotic accumulation, Ecotoxicol. Environ. Saf. 216 (2021) 112193, https://doi.org/10.1016/J.ECOENV.2021.112193.

[7] J.G. Balengayabo, G.R. Kassenga, S.M. Mgana, F. Salukele, Impact of recurring irrigation with treated domestic wastewater on heavy metal accumulation in the soil, Agric. Water Manag. 297 (2024) 108814, https://doi.org/10.1016/J.AGWAT.2024.108814.

[8] I. Ugulu, Z.I. Khan, A.F. Alrefaei, S. Bibi, K. Ahmad, H. Memona, S. Mahpara, N. Mehmood, M.H. Almutairi, A.I. Batool, A. Ashfaq, I.R. Noorka, Influence of industrial wastewater irrigation on heavy metal content in coriander (Coriandrum sativum L.): ecological and health risk assessment, Plants 12 (20) (2023) 3652, https://doi.org/10.3390/plants12203652.

[9] M. Custodio, R. Peñaloza, S. Ochoa, W. Cuadrado, Human risk associated with the ingestion of artichokes grown in soils irrigated with water contaminated by potentially toxic elements, Junin, Peru, Saudi J. Biol. Sci. 28 (10) (2021) 5952–5962, https://doi.org/10.1016/J.SJBS.2021.06.054.

[10] M. Sabir, E. Baltrėnaitė-Gedienė, A. Ditta, H. Ullah, A. Kanwal, S. Ullah, T.K. Faraj, Bioaccumulation of heavy metals in a soil–plant system from an open dumpsite and the associated health risks through multiple routes, Sustainability 14 (20) (2022), https://doi.org/10.3390/su142013223.

[11] S. Anwar, A. Naz, M.Y. Ashraf, A. Malik, Evaluation of inorganic contaminants emitted from automobiles and dynamics in soil, dust, and vegetations from major highways in Pakistan, Environ. Sci. Pollut. Control Ser. 27 (26) (2020) 32494–32508, https://doi.org/10.1007/S11356-020-09198-X.

[12] A. Sani, K.M. Idris, B.A. Abdullahi, A.I. Darma, Bioaccumulation and health risks of some heavy metals in Oreochromis niloticus, sediment and water of Challawa river, Kano, Northwestern Nigeria, Environ. Adv. 7 (2022) 100172, https://doi.org/10.1016/J.ENVADV.2022.100172.

[13] Mendieta Webster Carla, Taisigüe López Katerine, Acumulación y traslocación de metales, metaloides y no metales en plantas nativas de la zona minera de Chontales: Implicaciones para el potencial de fito-remediación, 2014. *Appear*.

[14] A.H. Gamarra Moreno, J.A. Taipe Castro, M.A. Arellano Vilchez, Y.D. Lozano Paulino, Á.C. Suazo Maldonado, IoT-based monitoring system for irrigation water quality measurement, Prospectiva Universitaria 20 (1) (2024) 31–39, https://doi.org/10.26490/uncp.prospectivauniversitaria.2023.20.1972.

[15] C. óscar Garay, A. álex Ochoa, First approach to identifying different types of agricultural soil in the Mantaro River Valley, in: Instituto Geofísico del Perú, 2010.

[16] J. Apaéstegui, C. Romero, M. Vuille, J. Sulca, A. Ampuero, Moisture sources and rainfall δ18O variability over the central andes of Peru—A case Study from the mantaro River Basin, Water 15 (10) (2023) 1867, https://doi.org/10.3390/w15101867.

[17] A. Delgado, J. Culqui, M. Lazo, V. Guerrero, I. Delgado, Grey systems model to assess water quality in mantaro River in Peru, Computation 11 (11) (2023) 223, https://doi.org/10.3390/computation11110223.

[18] J.A. Ramos-Guivar, N.-R. Checca-Huaman, F.J. Litterst, E.C. Passamani, Surface adsorption mechanism between Lead(II,IV) and nanomaghemite studied on polluted water samples collected from the Peruvian Rivers mantaro and cumbaza, Nanomaterials 13 (10) (2023) 1684, https://doi.org/10.3390/nano13101684.

[19] D. Chirinos-Peinado, J. Castro-Bedriñana, E. García-Olarte, R. Quispe-Ramos, S. Gordillo-Espinal, Transfer of lead from soil to pasture grass and milk near a metallurgical complex in the Peruvian Andes, Translat. Animal Sci. 5 (1) (2021), https://doi.org/10.1093/tas/txab003.

[20] S. Pizarro, M. Custodio, R. Solórzano-Acosta, D. Contreras, P. Verástegui-Martínez, Water storage–discharge relationship with water quality parameters of Carhuacocha and Vichecocha Lagoons in the Peruvian puna highlands, Water 16 (17) (2024) 2505, https://doi.org/10.3390/w16172505.

[21] M. Custodio, W. Cuadrado, R. Peñaloza, R. Montalvo, S. Ochoa, J. Quispe, Human risk from exposure to heavy metals and arsenic in water from rivers with mining influence in the Central Andes of Peru, Water (Switzerland) 12 (7) (2020), https://doi.org/10.3390/w12071946.

[22] D. Chirinos-Peinado, J. Castro-Bedriñana, E. Ríos-Ríos, G. Mamani-Gamarra, E. Quijada-Caro, A. Huacho-Jurado, W. Nuñez-Rojas, Lead and cadmium bioaccumulation in fresh cow’s milk in an intermediate area of the central andes of Peru and risk to human health, Toxics 10 (6) (2022) 317, https://doi.org/10.3390/toxics10060317.

[23] L. Giráldez, Y. Silva, R. Zubieta, J. Sulca, Change of the rainfall seasonality over central Peruvian andes: onset, end, duration and its relationship with large-scale atmospheric circulation, Climate 8 (2) (2020) 23, https://doi.org/10.3390/cli8020023.

[24] D.F. Cushquicullma-Colcha, M.V. González-Cabrera, C.S. Tapia-Ramírez, M. Y. Brito-Mancero, E.D. Guilcapi-Pacheco, G.M. Ati-Cutiupala, P.V. Vaca-Cárdenas, E.A. Muñoz-Jácome, M.L. Vaca-Cárdenas, Bioaccumulation and tolerance of metals in floristic species of the high andean wetlands of the Ichubamba Yasepan protected area: identification of groups and discriminant markers, Sustainability 17 (15) (2025) 6805, https://doi.org/10.3390/su17156805.

[25] E. Orellana, C. Bastos, B. Sotelo, V. Sarapura, M. Custodio, W. Cuadrado, Potential risk of Pb to children’s health from consumption of cow’s milk in areas irrigated with river water contaminated by mining activity, Sci. Agropecu. 10 (3) (2019) 377–382, https://doi.org/10.17268/sci.agropecu.2019.03.08.

[26] SENAMHI, Climate change scenario in the mantaro River Basin by the year 2100. http://www.minam.gob.pe, 2010.

[27] INEI, Junín final results. https://www.inei.gob.pe/media/MenuRecursivo/publicaciones_digitales/Est/Lib1576/.

[28] ANA, Suelos y Capacidad de Uso Mayor, Suelos y Capacidad de Uso Mayor (2015). https://www.ana.gob.pe/2019/consejo-de-cuenca/mantaro/OS.

[29] FAO, World reference base for soil resources 2014 international soil classification system for naming soils and creating legends for soil maps, Food Agric. Organiz. United Nations (2015). https://openknowledge.fao.org/server/api/core/bitstreams/bcdecec7-f45f-4dc5-beb1-97022d29fab4/content.

[30] C. óscar Garay, Primera aproximación para la identificación de los diferentes tipos de suelo agrícola en el valle del río Mantaro. https://surl.li/cgmlzl, 2010.

[31] MINAM, Guía Para Muestreo De Suelos, Ministerio del Ambiente, 2014, p. 38.

[32] F. Fao, agriculture organization of the united nations, Standard Operating Handling and Preparation of Soil Samples for Chemical and Physical Analyses, 2019.

[33] A.N.D.A. Ana, National Protocol for Monitoring the Quality of Natural Surface Water Bodies, 2016.

[34] FAO, Irrigation Technology Transfer in Support of Food Security, WORLD BANK IPTRID, 1997.

[35] L. Hakanson, An ecological risk index for aquatic pollution control. A sedimentological approach, Water Res. 14 (8) (1980) 975–1001, https://doi.org/10.1016/0043-1354(80)90143-8.

[36] G.M.S. Abrahim, R.J. Parker, Assessment of heavy metal enrichment factors and the degree of contamination in marine sediments from Tamaki Estuary, Auckland, New Zealand, Environ. Monit. Assess. 136 (1–3) (2007) 227–238, https://doi.org/10.1007/s10661-007-9678-2.

[37] W. Ahmad, R.D. Alharthy, M. Zubair, M. Ahmed, A. Hameed, S. Rafique, Toxic and heavy metals contamination assessment in soil and water to evaluate human health risk, Sci. Rep. 11 (1) (2021) 17006, https://doi.org/10.1038/s41598-021-94616-4.

[38] G. Mawari, N. Kumar, S. Sarkar, M.K. Daga, M.M. Singh, T.K. Joshi, N.A. Khan, Heavy metal accumulation in fruits and vegetables and human health risk assessment: findings from Maharashtra, India, Environ. Health Insights 16 (2022), https://doi.org/10.1177/11786302221119151.

[39] N.P. Castro-González, R. Moreno-Rojas, F. Calderón-Sánchez, A. Moreno-Orteg, J.V. Tamariz-Flores, Heavy metals in milk from cows fed alfalfa produced in soils irrigated with wastewater in Puebla and Tlaxcala, Mexico, Revista Mexicana De Ciencias Pecuarias 9 (3) (2018) 466–485, https://doi.org/10.22319/rmcp.v9i3.4358.

[40] A. Kicińska, Arsenic, cadmium, and Thallium content in the plants growing in close proximity to a Zinc works - long-term observations, J. Ecol. Eng. 20 (7) (2019) 61–69, https://doi.org/10.12911/22998993/109866.

[41] R.Z. Afriyie, E.K. Arthur, E. Gikunoo, D.S. Baah, E. Dziafa, Potential health risk of heavy metals in some selected vegetable crops at an artisanal gold mining site: a case study at Moseaso in the Wassa Amenfi West District of Ghana, J. Trace Element. Mineral. 4 (2023) 100075, https://doi.org/10.1016/J.JTEMIN.2023.100075.

[42] R Core Team, *R: a Language and Environment for Statistical Computing* (Version 4.x, R Foundation for Statistical Computing, 2024. https://www.r-project.org/.

[43] H. Wickham, M. Averick, J. Bryan, W. Chang, L. McGowan, R. François, G. Grolemund, A. Hayes, L. Henry, J. Hester, M. Kuhn, T. Pedersen, E. Miller, S. Bache, K. Müller, J. Ooms, D. Robinson, D. Seidel, V. Spinu, H. Yutani, Welcome to the tidyverse, J. Open Source Softw. 4 (43) (2019) 1686, https://doi.org/10.21105/joss.01686.

[44] H. Wickham, R. François, L. Henry, K. Müller, D. Vaughan, Dplyr: a grammar of data manipulation, in: CRAN: Contributed Packages, 2014, https://doi.org/10.32614/CRAN.package.dplyr.

[45] D.H. Ogle, J.C. Doll, A.P. Wheeler, A. Dinno, FSA: simple fisheries stock assessment methods, in: CRAN: Contributed Packages, FSA, 2015, https://doi.org/10.32614/CRAN.package.

[46] Z. Gu, R. Eils, M. Schlesner, Complex heatmaps reveal patterns and correlations in multidimensional genomic data, Bioinformatics 32 (18) (2016) 2847–2849, https://doi.org/10.1093/bioinformatics/btw313.

[47] R. Kolde, Pheatmap: pretty heatmaps, in: CRAN: Contributed Packages, 2010, https://doi.org/10.32614/CRAN.package.pheatmap.

[48] S. Lê, J. Josse, A. Rennes, F. Husson, FactoMineR: an R package for multivariate analysis, in: JSS Journal of Statistical Software, vol. 25, 2008. http://www.jstatsoft.org/.

[49] A. Kassambara, F. Mundt, Factoextra: Extract and visualize the results of multivariate data analyses. Contributed Packages, CRAN, 2016, https://doi.org/10.32614/CRAN.package.factoextra.

[50] QGIS Development Team, QGIS Development Team. (2024), QGIS Geographic Information System (Versión 3.36). Open Source Geospatial Foundation. (Versión 3.36), 2024. https://qgis.org.

[51] CODEX STAN, General Standard for Contaminants and Toxins in Food and Feed, FAO/WHO, 1993, 1995, https://www.fao.org/fao-who-codexalimentarius/sh-proxy/en/?lnk=1&url=https://workspace.fao.org/sites/codex/Standards/CXS%20193-1995/CXS_193e.pdf.

[52] FAO/WHO, Codex Alimentarius Commission; FAO/WHO. General Standard for Contaminants and Toxins in Food and Feed, 2024 (2024). *(CODEX STAN 193-1995)*, https://www.fao.org/fileadmin/user_upload/livestockgov/documents/CXS_193s.pdf.

[53] R.S. Ayers, D.W. Westcot, Water quality for agriculture – FAO irrigation and drainage paper, Food Agric. Organiz. United Nations 29 (1985). ISBN 92-5-102263-1.

[54] A. Arrieta, J. Guillen, The birthweight toll of mining pollution: evidence from the most contaminated mine site in the Andean region, BJOG Int. J. Obstet. Gynaecol. 125 (10) (2018) 1272–1278, https://doi.org/10.1111/1471-0528.15257.

[55] M.K. Reuer, N.W. Bower, J.H. Koball, E. Hinostroza, M.E. De la Torre Marcas, J.A.H. Surichaqui, S. Echevarria, Lead, Arsenic, and Cadmium Contamination and Its Impact on Children's Health in La Oroya, Peru, ISRN Publ. Health 2012 (2012) 1–12, https://doi.org/10.5402/2012/231458.

[56] J. Faouzi, S. Kaioua, A. Allali, N. Eloutassi, A. Lahkimi, Impact of irrigation water on heavy metal content in irrigated soils and plants – spatial and vertical distribution, Ecol. Eng. Environ. Technol. 23 (5) (2022) 91–98, https://doi.org/10.12912/27197050/151759.

[57] A. Victoria, D.N. Nnebini, A systematic review of heavy metals in irrigation water and their effects on agricultural soil quality and crop production in Ghana, J. Geosci. Environ. Protect. 13 (1) (2025) 48–70, https://doi.org/10.4236/gep.2025.131004.

[58] EFSA, Statement on tolerable weekly intake for cadmium, EFSA J. 9 (2) (2011), https://doi.org/10.2903/j.efsa.2011.1975.

[59] CDC, C. for D. C. and Prevention, About childhood lead poisoning prevention, About Childhood Lead Poison. Prevent. (2025, August 21). https://www.cdc.gov/lead-prevention/about/index.html.

[60] EFSA, Scientific opinion on lead in food, EFSA J. 8 (4) (2010), https://doi.org/10.2903/j.efsa.2010.1570.

[61] B.R. Stern, M. Solioz, D. Krewski, P. Aggett, T.-C. Aw, S. Baker, K. Crump, M. Dourson, L. Haber, R. Hertzberg, C. Keen, B. Meek, L. Rudenko, R. Schoeny, W. Slob, T. Starr, Copper and human health: biochemistry, genetics, and strategies for modeling dose-response relationships, J. Toxicol. Environ. Health, Part A B 10 (3) (2007) 157–222, https://doi.org/10.1080/10937400600755911.

[62] E. Orellana, M. Custodio, M. Bastos, J. Ascencion, Heavy metals in agriculture soils from high andean zones and potential ecological risk assessment in Peru's central andes, J. Ecol. Eng. 21 (8) (2020) 108–119, https://doi.org/10.12911/22998993/127094.

[63] Y. Román-Ochoa, G.T. Choque Delgado, T.R. Tejada, H.R. Yucra, A.E. Durand, B.R. Hamaker, Heavy metal contamination and health risk assessment in grains and grain-based processed food in Arequipa region of Peru, Chemosphere 274 (2021) 129792, https://doi.org/10.1016/j.chemosphere.2021.129792.

[64] M. Xiang, J. Ma, J. Cheng, K. Lei, F. Li, Z. Shi, Y. Li, Collaborative evaluation of heavy metal pollution of soil-crop system in the southeast of Yangtze River Delta, China, Ecol. Indic. 143 (2022), https://doi.org/10.1016/j.ecolind.2022.109412.

[65] Y. Alhaj Hamoud, H. Shaghaleh, M. Zia-ur-Rehman, M. Rizwan, M. Umair, M. Usman, M.A. Ayub, U. Riaz, G.S.H. Alnusairi, S.M.S. Alghanem, Cadmium and lead accumulation in important food crops due to wastewater irrigation: pollution index and health risks assessment, Heliyon 10 (3) (2024) e24712, https://doi.org/10.1016/j.heliyon.2024.e24712.

[66] P. Pachura, A. Ociepa-Kubicka, B. Skowron-Grabowska, Assessment of the availability of heavy metals to plants based on the translocation index and the bioaccumulation factor, Desalination Water Treat. 57 (3) (2016) 1469–1477, https://doi.org/10.1080/19443994.2015.1017330.

[67] S.S. Bhatti, V. Kumar, N. Singh, V. Sambyal, J. Singh, J.K. Katnoria, A.K. Nagpal, Physico-chemical properties and heavy metal contents of soils and kharif crops of Punjab, India, Procedia Environ. Sci. 35 (2016) 801–808, https://doi.org/10.1016/j.proenv.2016.07.096.

[68] S. Raja, H.M.N. Cheema, S. Babar, A.A. Khan, G. Murtaza, U. Aslam, Socio-economic background of wastewater irrigation and bioaccumulation of heavy metals in crops and vegetables, Agric. Water Manag. 158 (2015) 26–34, https://doi.org/10.1016/j.agwat.2015.04.004.

[69] Y. Du, K. Luo, R. Ni, R. Hussain, Selenium and hazardous elements distribution in plant–soil–water system and human health risk assessment of Lower Cambrian, Southern Shaanxi, China, Environ. Geochem. Health 40 (5) (2018) 2049–2069, https://doi.org/10.1007/s10653-018-0082-3.

[70] M. Wan, W. Hu, H. Wang, K. Tian, B. Huang, Comprehensive assessment of heavy metal risk in soil-crop systems along the Yangtze River in Nanjing, Southeast China, Sci. Total Environ. 780 (2021) 146567, https://doi.org/10.1016/j.scitotenv.2021.146567.

[71] S. Tong, L. Yang, H. Gong, L. Wang, H. Li, J. Yu, Y. Li, Y. Deji, C. Nima, S. Zhao, Z. Gesang, C. Kong, X. Wang, Z. Men, Bioaccumulation characteristics, transfer model of heavy metals in soil-crop system and health assessment in plateau region, China, Ecotoxicol. Environ. Saf. 241 (2022), https://doi.org/10.1016/j.ecoenv.2022.113733.

[72] A.I. Nowwar, I.I. Farghal, M.A. Ismail, M.A. Amin, Impact of irrigation with wastewater on accumulation of heavy metals in Phaseolus vulgaris L. and its remediation, J. Soil Sci. Plant Nutr. 23 (1) (2023) 761–777, https://doi.org/10.1007/s42729-022-01080-8.

[73] R.H. Zárate-Quiñones, M. Custodio, E. Orellana-Mendoza, W.J. Cuadrado-Campó, P.L. Grijalva-Aroni, R. Peñaloza, Determination of toxic metals in commonly consumed medicinal plants largely used in Peru by ICP-MS and their impact on human health, Chem. Data Collect. 33 (2021) 100711, https://doi.org/10.1016/j.cdc.2021.100711.

[74] J.C. Bedriñana, D.C. Peinado, R. Peñaloza-Fernández, Lead bioaccumulation in root and aerial part of natural and cultivated pastures in highly contaminated soils in Central Andes of Peru, Adv. Sci. Technol. Eng. Syst. 5 (2) (2020) 126–132, https://doi.org/10.25046/aj050216.

[75] E. Orellana, M. Custodio, M.C. Bastos, W. Cuadrado, Lead in agricultural soils and cultivated pastures irrigated with river water contaminated by mining activity, J. Ecol. Eng. 20 (8) (2019) 238–244, https://doi.org/10.12911/22998993/111715.