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ORIGINAL

Assessment of the Environmental Load in the Trophic System of the Huanuni Sub-Basin, Oruro Department

Evaluación de la carga ambiental en el sistema trófico de la subcuenca Huanuni, departamento de Oruro

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ABSTRACT

The study in the Huanuni sub-basin, agricultural area (Pacopampa – Sora Sora), had the objective of "Evaluating the environmental load of the trophic system of heavy metals (As, Sn, Pb, Cd, Zn)". The results in the study waters (M2-2 and M3-1, irrigation system), have high concentrations of Cd (greater than maximum permissible limits, class C, Law 1333), and Na. As for the soils, Na, Zn and Cd (M1-1), the last two metals are above the Common Range (RC), proposed by Kloke, Critical Concentration proposed by the EC (2002). The plant part (Vicia Faba, Medicago sativa, and Distichlis humilis –the last two of forage interest–), the elements As, Cd, Pb, Zn, exceed the maximum allowable, being progressive the accumulation, which induces a biomagnification process, demonstrated in the environmental load in cattle, highlighting more than 15 g/day; 110g/week and 400 g/month of heavy metals that enter an animal unit (cattle). Apart from the fact that the body has routes of expulsion and/or counteracting the entry of foreign substances into its metabolism, the reality is undeniable in Pacopampa - Sora Sora, the presence of heavy metals in the food chain, a risk factor in the area, the existing mining activity.

Keywords: pollution, heavy metals, bioaccumulation, environmental load.

RESUMEN

El estudio en la subcuenca Huanuni, zona agropecuaria (Pacopampa – Sora Sora), tuvo el objetivo de "Evaluar la carga ambiental del sistema trófico de metales pesados (As, Sn, Pb, Cd, Zn)". Los resultados en las aguas de estudio (M2-2 y M3-1, sistema de riego), tiene concentraciones elevadas de Cd (mayor a límites máximos permisibles, clase C, Ley 1333), y de Na. En cuanto a los suelos, el Na, Zn y Cd (M1-1), los dos últimos metales están por encima del Rango Común (RC), propuesto por Kloke, Concentración Crítica propuesta por la CE (2002). La parte vegetal (Vicia Faba, Medicago sativa, y Distichlis humilis –los dos últimos de interés forrajero–), los elementos As, Cd, Pb, Zn, exceden los máximos permisibles, siendo progresivo la acumulación, lo cual induce a un proceso de biomagnificación, demostrado en la carga ambiental en ganado vacuno, resaltando más de 15 g/día; 110g/semana y 400 g/mes de metales pesados que ingresa a una unidad animal (vacuno). Al margen que el organismo tiene vías de expulsión y/o contrarrestar el ingreso de sustancias extrañas a su metabolismo, la realidad es innegable en Pacopampa - Sora Sora, la presencia de metales pesados en la cadena trófica, un factor de riesgo en la zona, la actividad minera existente.

Palabras clave: Palabras claves: contaminación, metales pesados, bioacumulación, carga ambiental.

INTRODUCTION

Mining is one of the main sources of pollution, generating waste that contains heavy metals (Rebollo, 2022). The intensification of anthropogenic activities over the past century, driven by industrialization, large-scale mining, intensive agriculture, and urban growth, has led to an accelerated release of these contaminants, often exceeding natural geochemical background levels (Leaño, 2025), as demonstrated by cases of Cd and Hg poisoning in Japan. Heavy metals are among the most toxic environmental pollutants (Förstner & Müller, 1973), and the study of heavy metal contamination, such as Hg, As, Pb, and Cd, represents a serious risk to human health, as well as to animals and ecosystems (Robles, 2024). The presence of metals in soils and sediments of the Altiplano, as shown by studies conducted by Orsag et al. (2013 and 2004), Zamora G. (2008), Swedish Geological AB Environmental Services (1996), Zapata and Fernández (1994), and Noras (1992), reveals varied and temporally dispersed results, which largely depend on human activities (mining and metallurgy), types of parent material (rocks), and their location in the landscape. This demonstrates a differentiation of heavy metals, mainly in aquatic biota, and although their concentrations are very low, they can be toxic like any other element (Calcina R.L. & Huaraya Ch.Fr., 2018; Molina C.I. et al., 2012; Montoya & Pérez, 2009; Calcina L., 2005-2006; Swedish Geological AB Environmental Services, 1996), and may accumulate in plant species, as shown in a study that determined the presence of heavy metals (Pb, Cd, and As) in agricultural soils and soils for Solanum tuberosum cultivation in the Inner Bay of Puno (Linarez et al., 2020). The growing impact of heavy metal pollution represents a significant threat to aquatic ecosystems and human health, as evaluated in fish from the Hatillo Dam – Dominican Republic (Altagracia M.M. & Altagracia U.Y., 2024). The danger of heavy metals is greater because they are neither chemically nor biologically degradable; their concentration in living beings increases as they are ingested by others, so the consumption of contaminated plants or animals can cause symptoms of poisoning (Plumlee et al., 1999), posing a threat to biodiversity and human health, as evidenced in the assessment of the degree of heavy metal contamination in the Mallorquín Marsh, located on the Caribbean coast of Colombia (Ojeda & Rhénals Quintana, 2025).

Organisms have well-developed mechanisms to absorb, metabolize, and excrete different elements, including metals at concentrations found naturally (Sánchez, 2025; Jarrín, 2023; Curtis & Barnes, 2001). These mechanisms can become saturated at high metal concentrations, and the absorption rate may exceed the rate of loss, a process that requires greater energy expenditure. Mining activity releases toxic metals into the environment, accumulating in plants and organic tissues. The annual flow of heavy metals in the Santa Fé and Huanuni rivers of the Huanuni sub-basin averages 1900 t/year (Swedish Geological AB Environmental Services, 1996), mainly Zn, Cu, Pb, As, Sb, and Cd. In this context, Empresa Minera Huanuni is responsible for the largest amount of effluent discharges into the river of the same name without prior treatment, with waters characterized by high acidity and high heavy metal content. The Huanuni River passes by water springs (Pacopampa sector), 60 m from the Huanuni River. One of the most important springs has a flow rate of up to 18 l/s in the dry season, affected by the Huanuni River. The water from this spring supplies the Machacamarca plant for metallurgical operations throughout the year. There is a canal that runs from Pacopampa, passes through Sora Sora, and reaches the plant. Along the irrigation canal, there are crops of alfalfa, barley, and broad beans, as well as native grasslands irrigated with water from the spring. There is livestock activity (sheep, cattle, llamas, and pigs), which feed on the forage crops grown in the area. In many cases, the animals consume water from the spring and the canal. It is important to assess the progressive or regressive environmental load in the trophic system, mainly that of heavy metals. This is to demonstrate that in Pacopampa - Sora Sora, the situation is conditioned by the effects of mining activity in the upper part of the sub-basin, mainly from the Huanuni River, such that the environmental load consists mainly of heavy metals (As, Sn, Pb, Cd, Zn).

METHODS

Bolivia has water resources—Hydrographic Basins—of the Amazon, the Plata, and the Closed Altiplano. The latter, of interest for this study, contains the Huanuni sub-basin (734.56 km2), fed by the river of the same name. At the height of the Aco Aco community, it receives contributions from the Santa Fe River, which collects water from the Japo and Morococala tributaries (areas of mining activity); it also receives input from small springs that irrigate the Pacopampa and Sora Sora areas.

These and other springs have generated agricultural and livestock activity, but are affected by the waters of the Huanuni River, originating from mining localities, causing environmental contamination by heavy metals, as indicated by Leaño (2025), constituting a global threat to human health and ecosystems, exacerbated by urbanization and industrialization. The average annual temperature in the area is 8.1 °C, with the mean thermal amplitude, the coldest month (June-July), and the warmest month (December-January) ranging from 11.4 to 13.4 °C. The significant difference occurs from August to December ($F_{11,539}$=7619.234; p<0.001). The temperature increase causes a water deficit throughout the year. The study area (Figure 1) is geographically located at 18°09'44'' S and 66°58'24'' W, at 18°12'30'' S and 66°56'08'' W, at 3780 masl. Sampling of water, soil, and plant species was carried out in the communities of Pacopampa and Sora Sora (Table 1).

Figure 1. Location of the study area

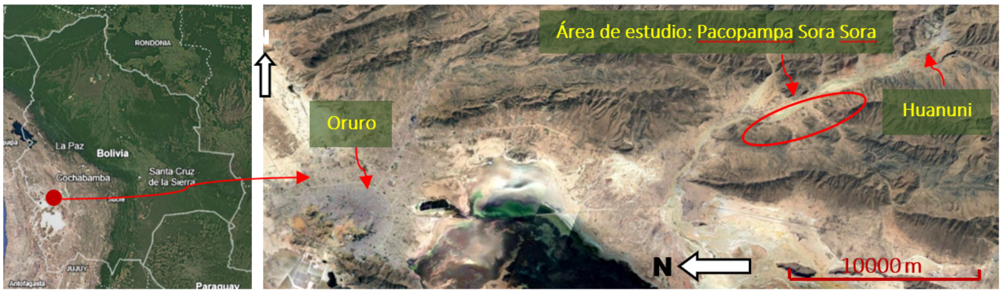


Table 1. Sampling points for water, soils, and plant species

Samples	Coordinates		Altitude masl	Sampling date	Area characteristics
	LS	LW			
M2-1	18°11´29.7"	66°56´32.4"	3743	10/09/2024	Water source, Pacopampa
M1-1	18°11´26.9"	66°56´29.7"	3780	10/09/2024	Upstream Sora Sora
M2-2	18°11´26.8"	66°56´30.4"	3785	10/09/2024	Sora Sora irrigation system
M3-1	18°11´09.4"	66°56´43.7"	3745	15/04/2025	Sora Sora irrigation system, alfalfa crops

In the water study, surface samples were collected and analyzed at SPECTROLAB (Table 2). The elements analyzed included As, Cd, Sn, Pb, and Zn, which are highly toxic, as well as non-critical elements such as Ca, Mg, K, and Na. Additional physical and chemical parameters, including pH, Ce, carbonates, bicarbonates, chlorides, and sulfates, were also assessed (2024 and 2025). The results were compared with the maximum permissible limits established by Law 1333 (1992) and its regulation on water pollution (1995). In soils, the content of heavy metals (As, Cd, Sn, Pb), exchangeable bases (Ca, Mg, K, Na), Zn, and S was evaluated (Table 2), and the results were compared with international standards: Common Range and Maximum Tolerable Concentration for Agriculture (MC) according to Kloke; Critical Levels (NC) of Kabata-Pendias (1995); Critical Total Concentration (CTC) of Rams and Steines (1994); and Critical Concentration (CC) of the European Commission (2002). In flora, heavy metals (Table 2) were analyzed in three plant species ("ch'iji" Distichlis humilis, "alfalfa" Medicago sativa, and "broad bean" Vicia faba), with the first two used as forage (native and introduced, respectively) and the latter for human consumption in Sora. The results were compared with parameters from PPO 9612 (1996) Plant Levels; LPS Chapman (1995); and WHO (1977).

Table 2. Analysis of water, soil, and plants

Parameters	Water	Unit	Standard/ Method	Soil	Unit	Standard/ Method	Plant	Unit	Standard/ Method
Arsenic	As	mg/l	ASTM D 2972-03B	As	mg/kg	EPA 7062	As	mg/kg	EPA 7062
Tin	Sn	mg/l	ASTM D 5185-18	Sn	mg/kg	EPA 3050B	Sn	mg/kg	EPA 3050B
Cadmium	Cd	mg/l	ASTM D 3557-02[a]	Cd	mg/kg	EPA 7130	Cd	mg/kg	EPA 7130
Lead	Pb	mg/l	ASTM D 3559-03[a]	Pb	mg/kg	EPA 7420	Pb	mg/kg	EPA 7420
Zinc	Zn	mg/l	ASTM D 1691-02[a]	Zn	mg/kg	EPA 7951	Zn	mg/kg	EPA 7951
pH			ASTM D 1293-99						
Conductivity	Ce	uS/cm	ASTM D 1125-95						
Calcium	Ca	mg/l	ASTM D 511-03	Ca	meq/100g	AAS			
Magnesium	Mg	mg/l	ASTM D 511-03	Mg	meq/100g	AAS			
Sodium	Na	mg/l	ASTM D 3561-02	Na	meq/100g	AAS			
Potassium	K	mg/l	ASTM D 4191-03	K	meq/100g	AAS			
Chloride	Cl-	mg/l	ASTM D 512-04						
Carbonates	CO3=	mg/l	ASTM D 3875-03						
Bicarbonates	HCO3-	mg/l	ASTM D 3875-03						
Sulfatos	SO4=	mg/l	ASTM D 516-02	SO4=	mg/kg	Fotometría			
Sulfates	SO4=	mg/L	ASTM D 516-02	SO4=	mg/kg	Photometric method			

Source: SPECTROLAB, 2024

The bioaccumulation of heavy metals in the water–soil–plant system was studied using cluster analysis, which employs mathematical algorithms to assess the similarity of characteristics among the variables (As, Sn, Cd, Pb, and Zn). The data were organized in a matrix (Table 3) with n rows (compartments) containing the p characteristics (variables).

Table 3. Data organization in the bioaccumulation of heavy metals

Individuals	V1	V2		Vj		Vp
1	X11	X12	...	X1j	...	X1p
2	X21	X22	...	X2j	...	X2p
n	Xn1	Xn2	...	Xnj	...	Xnp

To analyze the interdependence of the variables (As, Sn, Cd, Pb, and Zn) and to obtain an optimal graphical representation of data variability—differentiating the compartments: water, soil, and plant—principal component analysis (PCA) was used. PCA reveals the structure of variation in the compartments water, soil, and plant species—stem+leaves and root—through a scatter plot of the variables, providing optimal properties for interpreting the underlying variability and covariability.

For the assessment of environmental load (amount of contaminants entering a system) in cattle, a daily feed intake of 10% of live weight was considered for animal nutrition studies. Water intake in cattle is considered ad libitum; however, studies indicate that an average cattle unit consumes 50 l of water daily (one animal unit of 250 kg live weight). The main forages in the area are Medicago sativa and Distichlis humilis.

RESULTS

Water assessment

The chemical elements were grouped according to their solubility, frequency, and toxicity to the environment (Table 4). In the Pacopampa and Sora Sora area (2024-2025), 4 samples were collected (M2-1, M1-1, M2-2, M3-1; Table 1).

The cells highlighted in Table 5 indicate substances that exceed the maximum permissible limits, class B and C, Law 1333 (1992). As at the sampling points M2-1, M1-1, M2-2, and M3-1 does not exceed the maximum permissible concentration (0.05 mg/l; class C, Law 1333) (Table 5, Figure 3), with values well below 0.002 mg/l.

In the Pacopampa area, the elements As, Sn, and Pb, with values <0.002, 0.5, and 0.03 mg/l, respectively, are below the maximum permissible concentration (As = 0.05, Sn = 2, Pb = 0.05 mg/l), class C, Law 1333 (Table 5, Figure 3). However, it should be noted that the recorded concentrations of heavy metals may accumulate in local organisms over time and cause harm, especially As, which is a potentially carcinogenic element. For Cd, the recorded value (1.89 mg/l) exceeds the maximum permissible concentration (Cd = 0.005 mg/l), class C, Law 1333, posing a risk of accumulation in living organisms (flora and fauna).

Table 4. Grouping of chemical elements according to their solubility, frequency, and toxicity to the environment

Non-critical			Toxic but insoluble or infrequent		Highly toxic and relatively bioavailable		
Na K Mg Ca H O	C P Fe S Cl Br N	F Li Rb Sr (Al)* Si	Ti Hf Zr W Nb Ta Re	Ga La Os Rh Ir Ru Ba	Be Co Ni Cu Zn Sn	As Se Te Pd Ag Cd Cr	Au Hg Tl Pb Sb Bi Pt

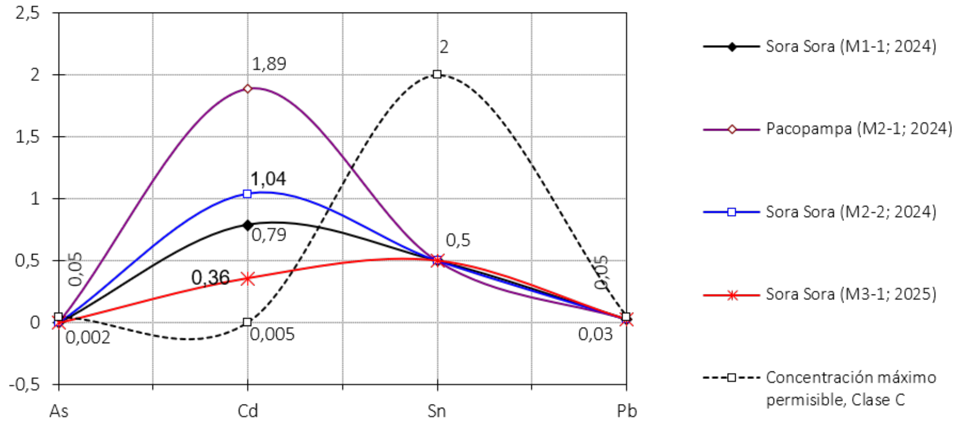
Source: Franken Margot (2005), Limnology Laboratory - UMSA
* Aluminum is toxic to soil and aquatic organisms

In the locality of Sora Sora, three samples were collected (two in 2024 and one in 2025). In both years, the elements As, Sn, and Pb have values below the maximum permissible concentration, class C, Law 1333 (Table 5, Figure 3). Cd in both Pacopampa and Sora Sora exceeds the maximum permissible concentration, class C, Law 1333, with values ranging from 0.79 mg/l in 2024 (M1-1) to 1.04 mg/l in the same year (M2-2), decreasing to 0.36 mg/l in 2025 (M3-1).

Parameter	Units	Pacopampa	Sora Sora		
		2024, M"-1	2024 M1-1	2024 M2-2	2025, M3-1
Arsenic	mg/l	<0,002	<0,002	<0,002	0,002
Cadmium	mg/l	1,89	0,79	1,04	0,36
Calcium	mg/l	163,5	201,2	143,1	145,1
Tin	mg/l	<0,5	<0,5	<0,5	<0,5
Magnesium	mg/l	89,98	82,06	69,04	63,77
Lead	mg/l	<0,03	<0,03	<0,03	<0,03
Potassium	mg/l	12,13	10,62	10,47	13,03
Sodium	mg/l	22,7	62,1	84,7	102,7
Zinc	mg/l		75,43		10,36
pH	mg/l	4,42 - 6,06	3,8 - 7,5		
Ce	μS/cm	1706	1375	1313	1283
Carbonates	mg/l	<3	<3	6	<3
Bicarbonates	mg/l	6	24	46	37
Chlorides	mg/l	100	98	80	73,5
Sulfates	mg/l	784,6	260,8	216,4	490,5

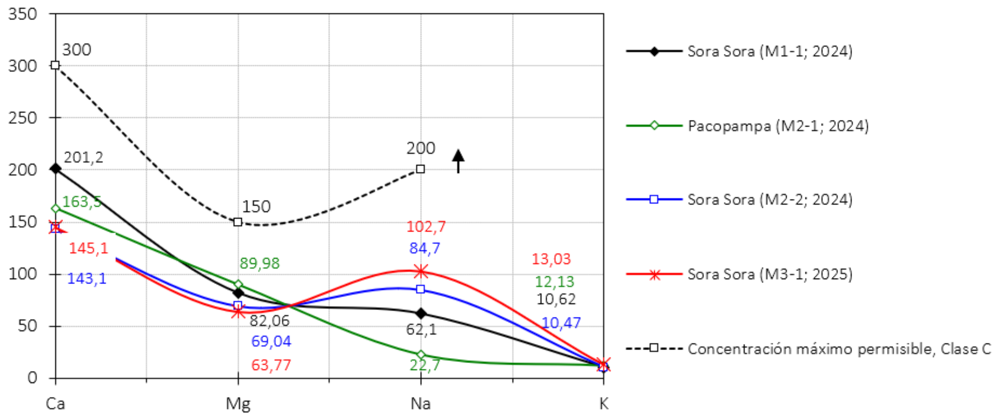
Source: SPECTROLAB, 2024

Figure 3. Heavy metals (As, Cd, Sn, Pb; mg/l)



The elements Ca, Mg, and Na have values below the maximum permissible concentration (Ca = 300, Mg = 150, Na = 200 mg/l), class C, Law 1333 (Table 5, Figure 4), in Sora Sora. K in Pacopampa and Sora Sora has a ratio of 1:15 ([K]water : [K]soil), considered a medium level. Na records 22.7 mg/l in M2-1 and 62.1 mg/l in M1-1; up to 84.7 mg/l in the same year in M2-2; increasing to 102.7 mg/l in M3-1, which represents a 40% increase in Na concentration.

Figure 4. Non-critical elements (Ca, Mg, Na, K; mg/l)



Regarding the concentration of CO3= and HCO3-, there is a ratio of 1:2 in M2-1, 1:8 in M1-1, 1:7.6 in M2-2, and 1:12.3 in M3-1. There is a greater difference in Sora Sora compared to Pacopampa (Figure 5). For SO4=, it exceeds the maximum permissible limit in M2-1 and M3-1 (Figure 6).

Figure 5. Carbonates: Bicarbonates (CO3= : HCO3-)

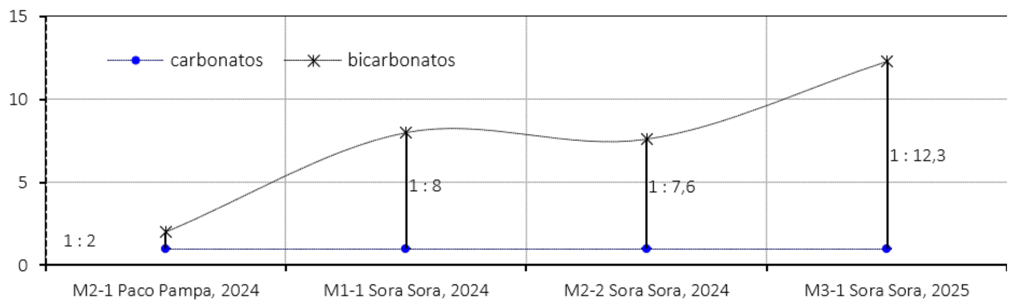
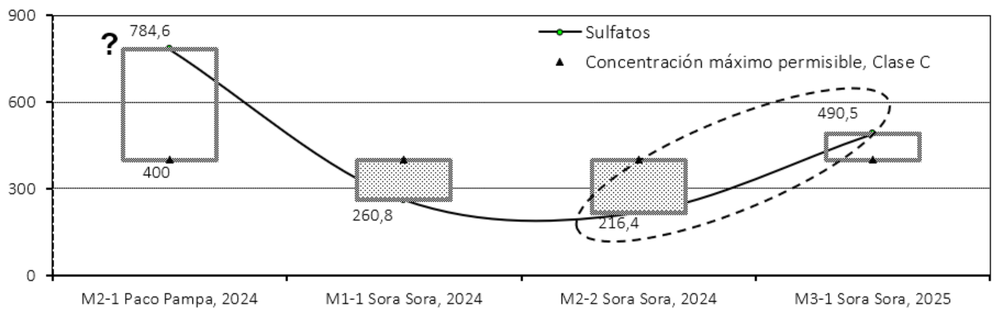


Figure 6. Variation of SO4= (mg/l) in the study area



Soil Evaluation

The content of heavy metals (As, Cd, Pb), exchangeable bases (Ca, Mg, K, Na), Zn, and S (Table 6) was compared with international parameters. Regarding As content: As = <0.003 ppm in M2-1, As = 4.602 in M1-1, As = <0.003 in M2-2, and As = 0.042 in M3-1, all are below the Common Range (CR, As = 2 to 20 ppm), Kloke, (Figure 7). Regarding Cd in the study area, all sampling points are above the Common Range (CR, Cd = 0.1 to 1 ppm) and Maximum Tolerable (MT, Cd = 3 ppm), proposed by Kloke, and the Critical Concentration (CC, Cd = 3 ppm), proposed by the European Commission (2002). According to the Critical Total Concentration (CTC, Cd = 8 ppm) proposed by Rams and Steines (1994), the Cd content in zone M3-1 is below this standard; however, the other study zones (M2-1, M1-1, M2-2) are above the reference value (Figure 8).

Table 6. Physical and chemical analysis of soils

Parameter	Units	Pacopampa	Sora Sora		
		2024	2024		2025
		M2-1	M1-1	M2-2	M3-1
Arsenic	ppm	<0,003	4,602	<0,003	0,042
Cadmium	ppm	8,3	13,9	16	3,87
Tin	ppm	< 10	10	<10	<1
Lead	ppm	21	8	4	2,8
Calcium	meq/100 g	4,7	5	21,5	4,7
Magnesium	meq/100 g				1,4
Sodium	meq/100 g	0,9	0,4	2,8	0,6
Potassium	meq/100 g				0,9
Zinc	ppm		195,87		32,43
Sulfur	ppm			1,95	0,01

Source: SPECTROLAB, 2024

Figure 7. Variation of As (mg/l) in the study area

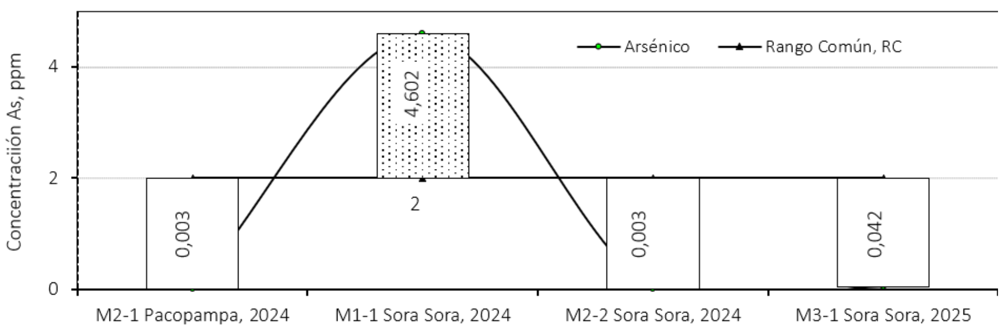
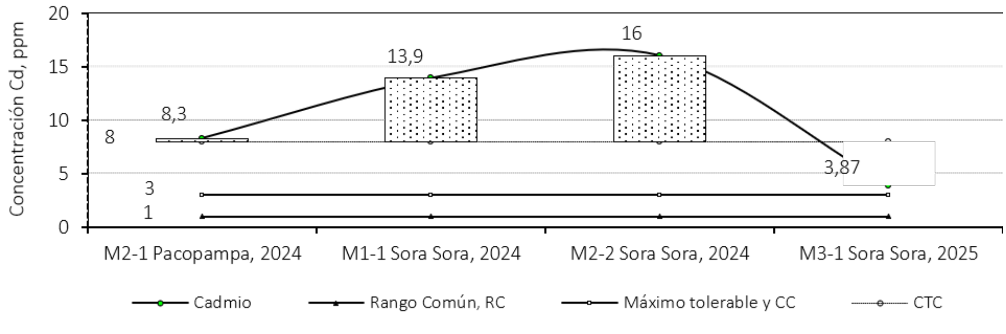


Figure 8. Variation of Cd (mg/l) in the study area



The Sn content (Table 6) in zones M2-1, M1-1, and M2-2 shows similar values, except for zone M3-1, which is lower than the others. Unfortunately, for Sn and other elements, there are no reference values available. The Pb contents in all study zones are below the Critical Concentration (CC, Pb = 50 to 300 ppm), European Commission (2002), and below the Critical Total Concentration (CTC, Pb = 200 ppm), Rams and Steines (1994). Regarding calcium (Table 6), zones M2-1, M1-1, and M3-1 show similar values except for M2-2, which has a value 4 times higher. The Na content in M2-1, M1-1, and M3-1 shows similar values except for M2-2, which is 3 to 7 times higher than the other zones.

Regarding K content (Table 6), there is only one value in M3-1 (K = 0.9 meq/100 g), which is higher than the Na value at the same sampling point, indicating alkaline soil behavior.

The Zn content = 195.87 ppm in M1-1 is above the Common Range (CR, Zn = 3 to 50 ppm), Kloke, Critical Concentration (CC, Zn = 150 to 300 ppm), European Commission (2002), and below the Critical Total Concentration (CTC, Zn = 400 ppm), Rams and Steines (1994), and Maximum Tolerable (MT, Zn = 300 ppm), Kloke. Conversely, the Zn content = 32.43 ppm in M3-1 is below the Common Range, CR and Maximum Tolerable, MT, Kloke, and is also below the Critical Concentration, CC, European Commission (2022), and Critical Total Concentration, CTC, Rams and Steines (1994). The S content in M2-2 is 1.95 ppm, much higher than in M3-1 (0.01 mg/l).

Analysis of heavy metals in plant species

The content of heavy metals (As, Cd, Sn, Pb, Zn) in plant species ("ch'iji" Distichlis humilis, "alfalfa" Medicago sativa, and "broad bean" Vicia faba) (Table 7) was compared with reference parameters and studies conducted by authors and institutions. Regarding As content in the 3 plant species evaluated ("alfalfa" Medicago sativa, "broad bean" Vicia faba, and "ch'iji" Distichlis humilis), in the leaf+stem part, Distichlis humilis accumulates the highest As = 5.137 ppm, followed by Medicago sativa and Vicia faba, both with 4.667 ppm. Considering the size and leaf area of each plant species studied, Distichlis humilis shows clear evidence of adaptation to higher As contents in its plant tissues; obviously, it is a native species (autochthonous) and not introduced like Medicago sativa and Vicia faba. It can also be indicated that none of the evaluated species exceeds the Upper Permissible Limit (As = 10 ppm), as considered by Chapman (1995). However, studies conducted in the Bolivian Altiplano by PPO 9612 (1996) indicate that common levels in plant species should be in the range of As = 0.5 to 1.5 ppm, which is much lower than the values found in the present study.

Table 7. Heavy metal content in plant species, Sora Sora

Parameter	Units	Sora Sora			
		2024			2025
		alfalfa (leaf + stem)	haba (leaf + stem)	ch'iji (leaf + stem)	alfalfa (root)
Arsénico	ppm	4,667	4,667	5,137	4,042
Cadmio	ppm	4,7	25,2	27,2	0,78
Estaño	ppm	<10	<10	<10	<1
Plomo	ppm	18	27	15	80,3
Zinc	ppm	162,27	1064,39	830,75	320,24

Regarding Cd, it shows the same behavior as As in accumulation in leaf+stem of the plant species under study: ch'iji has the highest concentration (27.2 ppm), followed by broad bean (25.2 ppm) and alfalfa (4.7 ppm). Except for the latter, the others exceed the value mentioned by AAFCO, the maximum value for Cd = 10 ppm. Regarding Sn, the values found in alfalfa, broad bean, and ch'iji show similar contents in leaf+stem (< 10 ppm) (Table 7, Figure 9).

The Pb concentration in leaf and stem of Vicia faba is the highest (27 ppm), followed by Medicago sativa (18 ppm) and Distichlis humilis (15 ppm) (Table 7, Figure 9), exceeding the maximum values permitted by WHO (1977) (Pb < 1.3 ppm), by FAO (Pb = 2 ppm), and the common values in plants recommended by PPO 9612 (1996) (Pb = 0.07 - 5.4 ppm). Regarding Pb content in roots of Medicago sativa (Pb = 80.3 ppm), it is far above the aforementioned limits.

Zn in leaf+stem, Vicia faba has the highest content (1064.39 ppm), followed by Distichlis humilis (830.75 ppm), with Medicago sativa having the lowest Zn content (162.27 ppm) (Table 7, Figure 9). These values are above those reported by PPO 9612 (1996), which mention common Zn levels (20 - 150 ppm) in plant species.

The analysis of heavy metal content in alfalfa (root) was also carried out in order to evaluate the difference in heavy metal accumulation (As, Cd, Sn, Pb, Zn), both in leaves+stem and root. Regarding As, Medicago sativa accumulates a higher concentration in leaves+stem (4,667 ppm) compared to the root (4,042 ppm); similarly, and of greater concern, Cd accumulates more in leaves+stem (4,7 ppm) than in the root (0,78 ppm).

Figure 9. Heavy metals (As, Cd, Sn, Pb, Zn; ppm) in water-soil-plant

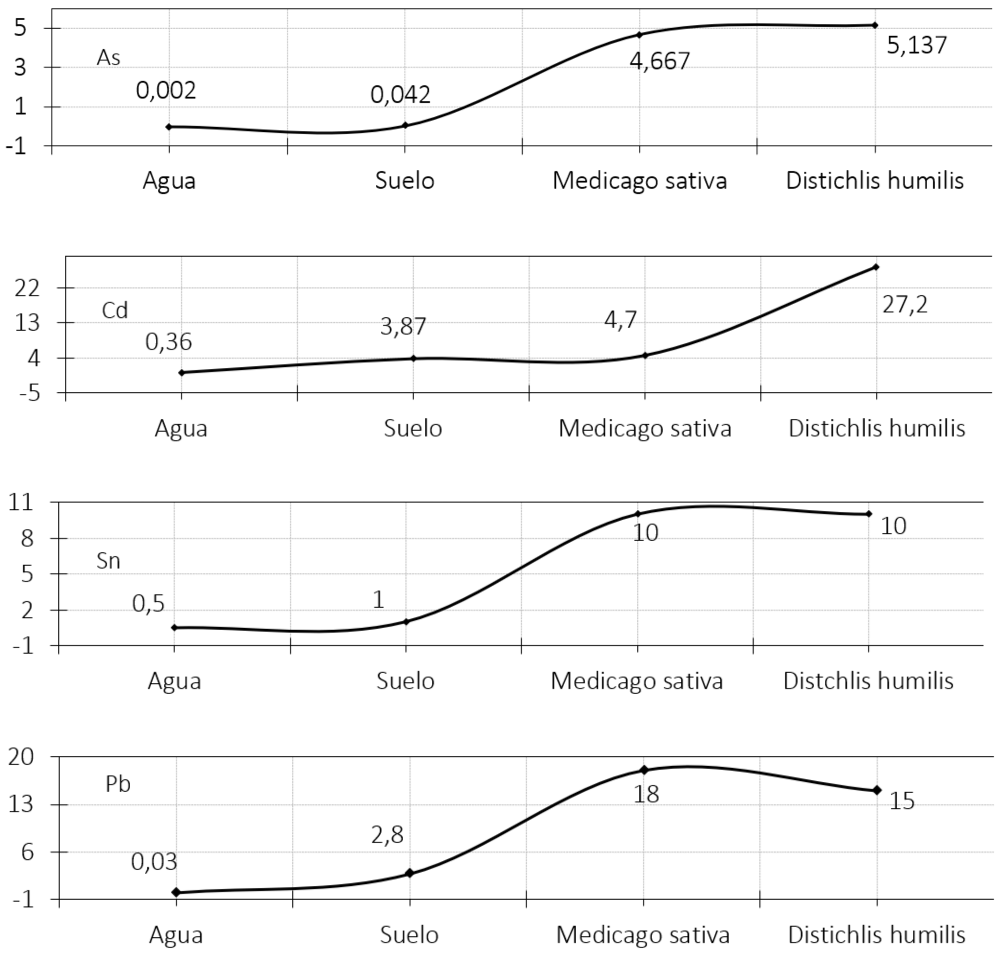
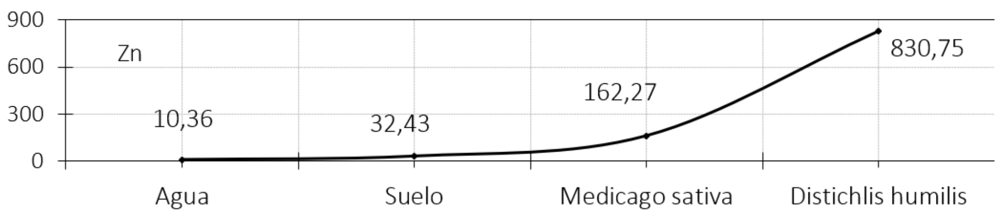


Figure 10. Clusters in water-soil-plant of heavy metals (As, Cd, Sn, Pb, Zn; ppm)



Medicago sativa is a forage species of importance, mainly for its foliar area, which serves as a food source for livestock; As and Cd show greater accumulation in leaves+stem (Table 7, Figure 9). As, Cd, Sn, Pb, and Zn show a progressive behavior in the water-soil-plant system (Figure 9).

Through cluster analysis, a clear difference is observed between the water and soil compartments and those of the plant species, the latter being a risk for consumption mainly as a forage resource for livestock activity (Figure 10). On the other hand, principal component analysis, as shown in Figure 11, evidences the bioaccumulation process with greater predominance in Distichlis humilis than in Medicago sativa in leaves+stem, being much lower in the root of the latter plant species, with the risk being much higher due to the presence of Cd.

Figure 11. Clusters in water-soil-plant of heavy metals (As, Cd, Sn, Pb, Zn; ppm)

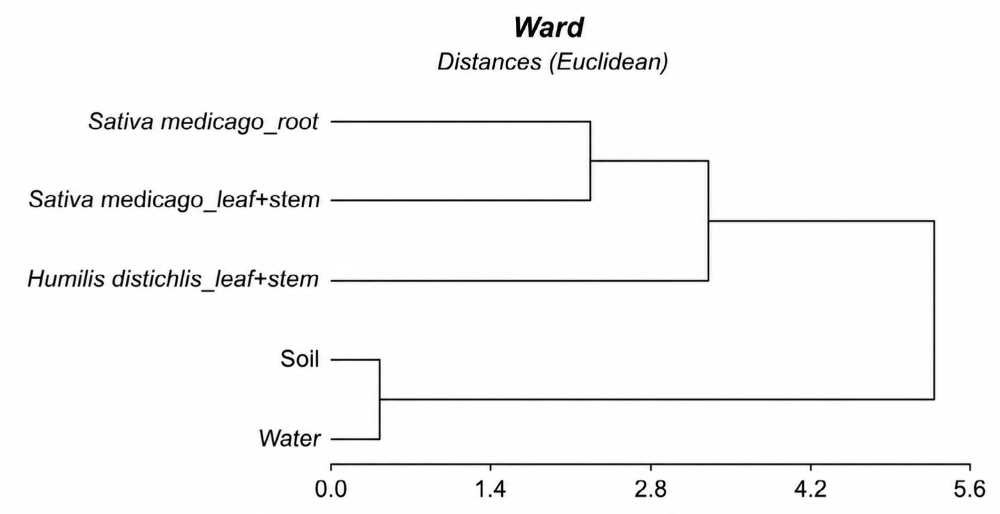
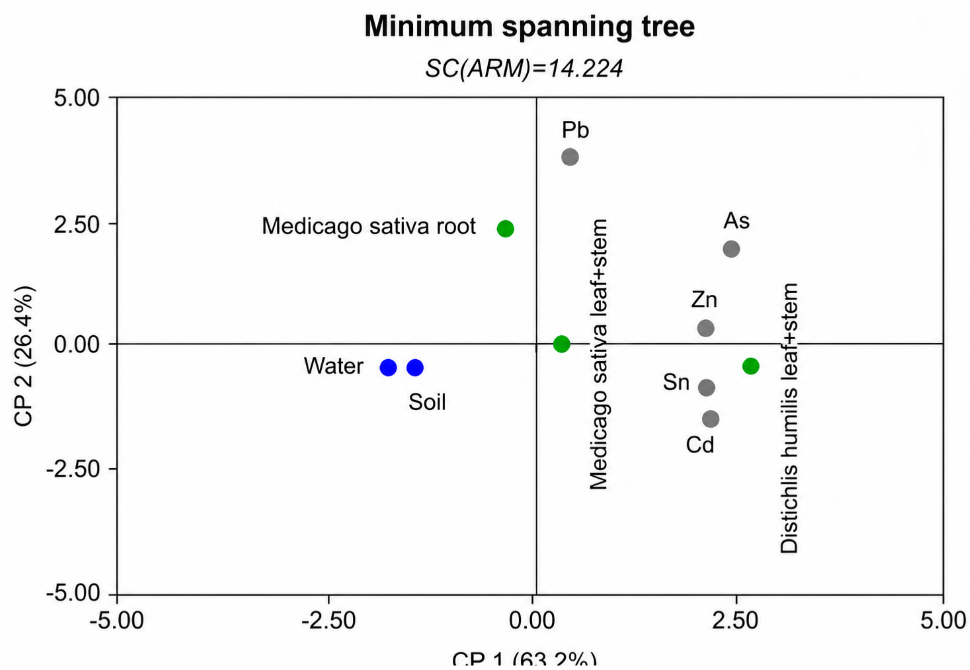
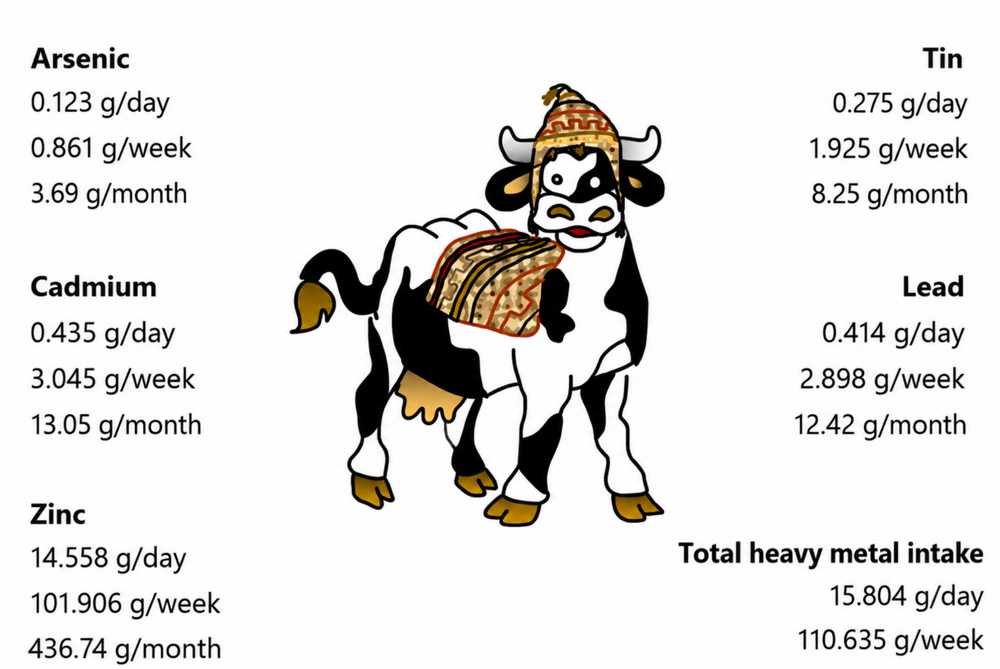


Figure 12. Environmental load in cattle (As, Cd, Sn, Pb, Zn), in the study area (Pacopampa - Sora Sora)



Environmental load in cattle

The environmental load in cattle was studied; taking into account animal nutrition studies, which consider 10% of live weight as daily feed intake. On the other hand, water consumption according to studies carried out indicates that an average cattle unit consumes 50 l/water daily (250 kg/LW), which was taken into account for the study. The main forages in the area are Medicago sativa and Distichlis humilis. Figure 12 shows the environmental load of the 5 heavy metals under study (As, Cd, Sn, Pb, Zn) daily, weekly, and monthly.



Of the environmental load, mainly heavy metals (As, Cd, Pb, Sn, and Zn), Zn stands out with the highest intake into the animal organism. What is considered is the total that enters the cattle through the consumption of forage, in this case Medicago sativa and Distichlis humilis (considering only the foliar and stem parts) and the consumption of water from the study area, highlighting more than 15 grams of heavy metals entering a cattle unit (bovine) daily, more than 110 g/week, and more than 400 g/month.

DISCUSSION

Water evaluation

In the water evaluation in Pacopampa – Sora Sora, the concentration of As = 0,002 mg/l, although it is below the permissible limits, there are studies such as that by Toledo Q.L.M. (2021) where it is mentioned that the concentration of As = ,0082 to 0,0427 mg/l in water is significantly related to health effects in the community of Chacaconiza – Corani. These effects could be similar in the study area, as supported by Nina A.J. (2025) in their study with values of As = 0,006648 mg/l, which restricts water consumption in the Río Cuchumbaya, Cuchumbaya District – Moquegua, especially since As is a very mobile element that can circulate and recirculate in air, water, and soils several times.

Regarding the recorded values of Cd = 0,79 to 1,89 mg/l in the study area (exceeding the maximum permissible limits), it is a very mobile and bioavailable metal, highly toxic in small concentrations. A particular characteristic of Cd is its association with Pb and Zn in nature (Montoya and Pérez, 2009). Cd has the characteristic of bioaccumulating in aquatic fauna, and can vary widely among aquatic organisms. Studies conducted by Jacho-Lugmaña, A.Y., et al. (2025) concluded that with values of Cd = 0,000538 to 0,0550 mg/l in water bodies, these are of poor water quality, as evidenced by the observation of only macroinvertebrates (aquatic organisms) tolerant to pollution.

Furthermore, considering that K = 10,47 to 13,03 mg/l, together with Na = 10,36 to 75,43 mg/l, are strongly alkalinizing elements and have advantages in terms of absorption compared to Mg, it is important to regulate the nutritional balance (macro and micronutrients) in livestock activity and, even more importantly, in human consumption in the study area, to avoid subsequent problems, as indicated by Mamani Cori Y.C. (2025), in the study of dissolved salt concentrations such as sodium, potassium, magnesium, and bicarbonates in contaminated waters. If this behavior persists over time, there is the possibility of a sodification process in Sora Sora through water bodies, which would imply problems in the natural water-soil-plant processes.

The concentrations of $CO_3^=$ and HCO_3^- indicate whether the waters are classified as soft or hard, a term used in irrigation criteria. Waters with higher concentrations of $CO_3^=$ and HCO_3^- are considered hard, whereas those with lower concentrations are classified as soft. In this context, the waters of Sora Sora are more suitable for irrigation compared to those of Pacopampa. However, it should be noted that this is not the only parameter relevant for irrigation suitability. Additionally, the concentration of $SO_4^=$ in relation to $S^=$ must be considered (Figure 6). Mining activities, through their acidic effluents, release high amounts of $S^=$, which are incorporated into the river. As $S^=$ travels through the river, it undergoes natural oxidation, converting $S^=$ to $SO_4^=$, thereby increasing $SO_4^=$ concentrations in water bodies. As shown in Figure 6, at sampling points M2-1 = 784.6 mg/l (Pacopampa) and M3-1 = 490.5 mg/l (Sora Sora), $SO_4^=$ concentrations exceed the maximum permissible concentration for class C, according to Law 1333 (1992). These points correspond to a spring and an irrigation canal, respectively, suggesting that in the spring waters (Pacopampa), $SO_4^=$ is a product of $S^=$ oxidation, implying that contaminated waters from mining activities may be entering via groundwater flow. This is supported by studies by Villamar M. and Valverde A. (2025), which indicate that $SO_4^=$ contamination in aquatic environments results from the oxidation of $S^=$, influenced by mining activities.

Soil Evaluation

Similar to the Cd content observed in the studied water bodies, this element exhibits abnormal concentrations in the soils under investigation (Cd = 3.87 to 13.9 ppm), exceeding global reference parameters and posing a risk of accumulation in living organisms, potentially causing disruptions in the trophic system due to contamination processes. As reported by Ojeda J.W.C. (2025) in a study on soils and bioaccumulation in pastures irrigated with mining-contaminated waters, Cd values of 13.563 and 13.115 ppm were found to induce bioaccumulation processes in irrigated pastures.

The behavior of Ca = 21.5 meq/100 g in Sora Sora may lead to an alkalinization process, due to the topography (flat to nearly flat) and the existing substrate type (clay and silt), as indicated in studies by Montoya Ch. and Pérez L. (2009). Similarly, the behavior of Na = 2.8 meq/100 g in Sora Sora may result in a sodification process, combined with a deflocculating effect that impacts soil structure and, consequently, the normal mobility of various nutrients, especially nitrogen.

Analysis of Heavy Metals in Plant Species

Plant species, and even varieties, differ in their capacity to absorb, accumulate, and tolerate metals (Alloway and Jackson, 1991; Angelova et al., 2004). In this regard, the plant species Medicago sativa and Distichlis humilis in the present study exhibit differentiated responses to heavy metals (As, Cd, Sn, Pb, Zn), with Zn being the most preferentially bioaccumulated, as reported by Alejos-Patiño et al. (2026) in their study of heavy metals in soil, water, and cultivated plants. They concluded that heavy metals (Cd, Pb, and Zn) cause contamination, as evidenced by a contamination load index (ICC = 1.70) in plants, which is significantly higher than that in water and soil, indicating a process that promotes the progressive accumulation of metals and poses a potential environmental risk. Furthermore, studies have analyzed the relationships between metal fractions in soil and their content in crops (e.g., Yanqui J.F.O. et al. 2025; Lago V. 2019), the relationships of heavy metals in sediments of water bodies and plant species (Montoya Ch. and Pérez L. 2009), and the interactions between different elements that modify metal absorption (e.g., Montoya Ch. and Pérez L., 2009; Khan et al., 1998). The risk associated with livestock activities in areas with anthropogenic disturbance, particularly those of mining and metallurgical origin, highlights the excess of heavy metals in soils and waters as a primary source of toxic substances for plants, causing negative synergistic and/or antagonistic effects on the growth and development of plant species. However, the bioaccumulation of heavy metals in plant tissues poses a risk to consumers, mainly herbivores (cattle, llamas, sheep, among others), with humans as the final consumers.

The bioaccumulation of heavy metals in plant species generates negative effects; for example, As can reach toxic levels, as demonstrated in studies by García A.L. and Vilca L.Z. (2025), who showed that As has a bioconcentration factor (BCF) of 0.018, indicating considerable absorption, with an As content of 0.05 +/- 0.028 ppm in the tuber part, which represents toxic levels in foods of plant origin. The As contents in the plant species analyzed in the present study are significantly higher than the previously indicated value: Medicago sativa As = 4.667 ppm, Distichlis humilis As = 5.137 ppm, and Vicia faba As = 4.667 ppm (Table 7).

Similarly, according to PPO 9612 (1996), the As content in the three plant species under study exceeds the typical As level in plants (0.5-1.5 ppm). As is an element that is part of the mineralogical composition of rocks, with high concentrations in the study area compared to other locations. It should also be noted that hydric systems, especially rivers, serve as a means of transport for this element (0.56 mg/l in the Desaguadero River and 1.1 mg/l in the Mauri River; PPO 9612, 1996), representing a potential risk for accumulation in living organisms.

CONCLUSIONS AND RECOMMENDATIONS

The water bodies of Pacopampa and Sora Sora exhibit signs of disturbance, with a higher probability observed in Sora Sora (M2-2 and M3-1, irrigation system). A significant contributing factor is mining activity, which has resulted in elevated Cd concentrations ranging from 0.36 to 1.04 mg/l, exceeding the maximum permissible limits for class C, as established by Law 1333 (1992).

The concentrations of heavy metals (As, Cd, Sn, Pb), exchangeable bases (Ca, Mg, K, Na), Zn, and S in soils indicate three elements of concern. The Na content of 0.6 meq/100 g in Sora Sora suggests the potential for a sodification process. Additionally, Zn at 195.87 ppm in M1-1 (Sora Sora) exceeds the Common Range (CR) according to Kloke, is similarly above the Critical Concentration set by the European Commission (2002), but remains below the Critical Total Concentration (CTC) defined by Rams and Steines (1994) and the Maximum Tolerable (MT) according to Kloke. Likewise, Cd levels in the study area are above the Common Range (CR) and Maximum Tolerable (MT) by Kloke, as well as the Critical Concentration by the European Commission (2002), but are below the Critical Total Concentration (CTC) by Rams and Steines (1994).

The concentrations of As, Cd, Pb, and Zn exceed the maximum permissible limits in plant species (“alfalfa” Medicago sativa, “broad bean” Vicia faba, and “ch’iji” Distichlis humilis). Regarding environmental load in cattle, more than 15 g of heavy metals are ingested by a single animal (cattle) daily, over 110 g per week, and more than 400 g per month. These findings indicate a progressive process of heavy metal accumulation in the trophic chain in the study area (Pacopampa and Sora Sora), with the local population as the final consumer. It is recommended that studies should not be limited to a purely physicochemical perspective.

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CONFLICT OF INTEREST

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