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HEAVY METALS AND MICROBIOLOGICAL QUALITY IN A DAIRY PRODUCTION CHAIN (SOIL-FORAGE-MILK) OF A HIGH-ANDEAN ECOSYSTEM EXPOSED TO VOLCANIC ASH DEPOSITION

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ABSTRACT

The presence of heavy metals in agricultural systems may represent an environmental, productive, and food safety concern, especially when these elements are incorporated into matrices associated with the soil-forage-milk chain. This study aimed to evaluate the presence of heavy metals in soil, forage, and raw milk, as well as the microbiological quality of milk, in a high-Andean dairy production chain in Chimborazo, Ecuador. Soil, forage, and raw milk samples were analyzed through physicochemical and microbiological determinations and heavy metal quantification, and the results were compared with applicable regulatory criteria. In soil, most of the evaluated metals remained below the reference values; however, mercury exceeded the limit of 0.1 mg/kg in all samples, with concentrations ranging from 0.113 to 0.137 mg/kg. In forage, selenium was the main critical element, with concentrations ranging from 5.644 to 6.747 mg/kg, exceeding the reference value of 1.0 mg/kg. In raw milk, lead exceeded the maximum permitted limit of 0.02 mg/kg in two samples, reaching 0.03367 mg/kg in ML1 and 0.02400 mg/kg in ML3. In addition, all milk samples exceeded the microbiological limit for aerobic mesophilic bacteria, with values ranging from 4.00×10^6 to 5.00×10^6 CFU/cm³. The results reveal differentiated alerts in each matrix and suggest the need to strengthen integrated monitoring of the soil-forage-milk chain, considering both chemical contaminants and microbiological indicators of food safety.

KEYWORDS: Aerobic Mesophilic Bacteria; Chimborazo; Food Safety; Forage; Heavy Metals; Mercury; Raw Milk; Selenium; Soil.

1. INTRODUCTION

Heavy metal contamination in agricultural settings represents both an ecological and nutritional problem due to the persistence of these components in the environment, their slow degradation, and their ability to enter different stages of the production process (Dai & Zhou, 2025). Elements such as lead, mercury, arsenic, cadmium, chromium, nickel, copper, cobalt, and selenium may occur in the environment because of natural processes or human activities, and their presence in agricultural areas can alter the quality of crops, forage, and animal-derived products (Devi, 2024). In the livestock sector, this issue becomes more concerning because soil and feed can act as direct or indirect exposure routes for animals (Sarsembayeva et al., 2021).

In mountainous areas, volcanic activity can serve as a natural source of trace elements (Martin et al., 2012). Volcanic ash may accumulate on soil and vegetation, modifying certain physicochemical properties of the soil and facilitating the occurrence of metals in crops (Mihai et al., 2025). However, metal mobilization does not depend solely on total concentration; it is also influenced by factors such as pH, organic matter, texture, moisture, bioavailability, and the chemical form of the metal (Parvin et al., 2022; Łukowski & Dec, 2021). Thus, the presence of a metal in soil does not necessarily ensure its direct transfer to forage or milk.

The soil-forage-milk sequence represents a relevant pathway for assessing environmental and nutritional risks. Soil can act as a reservoir of metals; forage can accumulate elements present in the environment, becoming an exposure route for grazing animals; and raw milk may, under certain conditions, indicate the presence of contaminants that affect food safety (Martínez-Morcillo et al., 2024). Recent studies have emphasized the need to jointly evaluate these matrices, since metals may behave differently at each stage of the production process and do not always transfer linearly (Tunegová et al., 2016).

Raw milk is a particularly sensitive matrix because it is a direct component of the human diet and is consumed by vulnerable populations, such as infants, older adults, and individuals who depend significantly on dairy products (Oliver et al., 2005). Beyond its physicochemical composition, its quality must be assessed from two complementary perspectives: the presence of chemical contaminants, including heavy metals, and its microbiological quality, which is related to milking practices, handling, storage, and transport (Roy et al., 2024; Berhanu et al., 2021). Therefore, a comprehensive

analysis of milk should go beyond compositional parameters and integrate food safety criteria.

Accordingly, this research was guided by the following question: What critical chemical and microbiological contamination parameters can be identified in soil, forage, and raw milk matrices from a dairy production chain in Chimborazo, Ecuador, and how do they allow interpretation of a possible soil-forage-milk transfer pathway? Based on this question, the study aimed to evaluate the presence of heavy metals in soil, forage, and raw milk, as well as the microbiological quality of milk, by comparing the results with applicable regulatory criteria and interpreting the soil-forage-milk pathway in an integrated manner.

2. MATERIALS AND METHODS

2.1. Study Area

The study was conducted at dairy production points of the Chuquipogoyo-Urbina Cooperative, located in the province of Chimborazo, Ecuador. This area is part of a high-Andean agricultural setting characterized by dairy production and environmental exposure associated with volcanic ash. Three matrices linked to the production chain were evaluated: soil, forage, and raw milk, with the purpose of identifying potential environmental, productive, and food safety alerts. Multi-matrix assessment of soil, forage, and milk has recently been applied in Ecuadorian dairy production areas exposed to volcanic influence to analyse the occurrence and potential transfer of heavy metals.

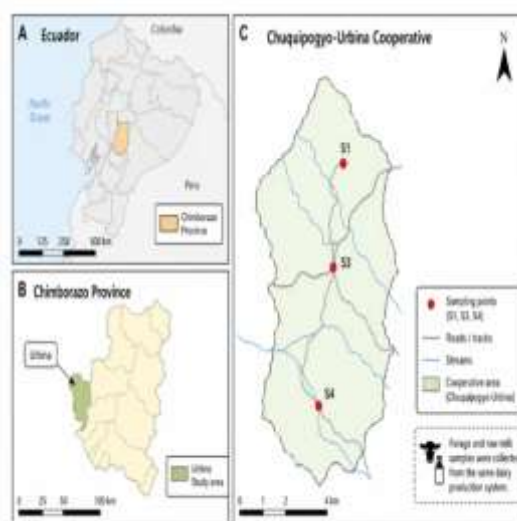


Figure 1. Study area location.

2.2. Research Design

The research had a quantitative, cross-sectional,

and multi-matrix approach, aimed at determining heavy metal concentrations and quality parameters in the soil–forage–milk chain. The design made it possible to compare each matrix with applicable regulatory criteria and subsequently interpret the results in an integrated manner. This approach is relevant because metals can behave differently depending on the matrix, their bioavailability, and the environmental conditions of the production system.

2.3. Sampling

Soil samples coded as S1, S3, and S4, forage samples identified as V1, V3, and V4, and raw milk samples coded as ML1, ML2, and ML3 were analysed. Soil and forage samples were collected at points associated with dairy production, while raw milk samples were obtained from the homogenized production corresponding to the collection routes. The samples were identified, preserved, and transferred to the laboratory for physicochemical, microbiological, and metal analysis.

2.4. Sample Preparation

Soil and forage samples were homogenized and conditioned before analysis. For metal determination, the solid matrices were subjected to microwave-assisted acid digestion, a procedure widely used for the preparation of soils, sediments, and solid matrices before element quantification. The method (EPA 3051A, 2007) describes microwave-assisted acid digestion using nitric acid, or combinations with hydrochloric acid, as a rapid extraction/digestion procedure prior to elemental analysis.

2.5. Physicochemical And Chemical Analysis Of Soil and Forage

Physicochemical and chemical parameters relevant to interpreting matrix quality and the possible mobility of elements were determined in the soil and forage samples. Variables such as pH, electrical conductivity, moisture, organic matter, C/N ratio, anions, and macronutrients were considered. These parameters are important because conditions such as pH, organic matter, and ionic content can influence the retention, mobility, and bioavailability of metals in the soil–plant system.

2.6. Determination of Heavy Metals

The quantification of heavy metals was carried out in soil, forage, and raw milk, considering elements of environmental and food relevance such as Cd, Ni, Pb, Cr, As, Se, Co, Cu, and Hg. The

prepared samples were analysed by inductively coupled plasma mass spectrometry (ICP-MS), a suitable technique for multielement determination at low concentrations. The EPA 6020B, (2014) establishes the use of ICP-MS for the determination of sub- $\mu\text{g/L}$ concentrations of numerous elements in aqueous samples, extracts, or digests, and provides guidelines for calibration, quality control, and analytical interferences.

2.7. Raw Milk Analysis

Raw milk samples were evaluated using physicochemical, chemical, and microbiological quality parameters. Variables such as pH, density, fat, protein, lactose, total solids, titratable acidity, electrical conductivity, and qualitative tests for adulteration or preservation were considered. Quality and contaminant results in raw milk were compared with the (NTE INEN 9, 2012), the standard that establishes the requirements applicable to raw cow's milk intended for processing in Ecuador.

2.8. Microbiological Analysis

The microbiological quality of raw milk was evaluated by counting aerobic mesophilic microorganisms, expressed as CFU/cm³. This parameter was used as a general indicator of hygiene, handling, storage, and transport. The enumeration of microorganisms by the colony-count technique at 30 °C is an internationally recognized method for enumerating microorganisms in the food chain, described in ISO 4833-1, (2013)

2.9. Regulatory Comparison Criteria

The results were compared with regulatory criteria according to the matrix evaluated. For soil, heavy metal concentrations were contrasted with Ministerial Agreement No. 097-A, Annex 2, corresponding to the Environmental Quality Standard for Soil Resources and Remediation Criteria for Contaminated Soils. For raw milk, Pb and the aerobic mesophilic count were compared with the (NTE INEN 9, 2012). Hg and As values in milk were used only as screening criteria when applicable, because they do not constitute the main axis of current regulatory comparison for raw milk.

2.10. Statistical Analysis

The data were organized by matrix and sampling point. Descriptive statistics were applied to summarize metal concentrations and quality parameters, and analysis of variance (ANOVA) was used to explore differences between samples. The statistical interpretation was complemented by

regulatory comparison, because a result may not show significant differences between samples but may still exceed a legal limit or reference value. Given the exploratory nature of the study and the limited number of sampling points, statistical results were interpreted cautiously. Descriptive statistics and regulatory comparisons were prioritized, since exceedance of legal or reference values may be relevant even when differences among samples are not statistically significant.

3. RESULTS AND DISCUSSION

3.1. Heavy Metals in Soil

Heavy metal analyses in soil made it possible to identify the presence of potentially toxic elements in samples S1, S3, and S4. In general, most of the evaluated metals remained below the reference values for soil quality; however, mercury (Hg) showed a different pattern, exceeding the permitted limit in all samples.

Table 1. Heavy metal concentrations in soil samples.

Element	Unit	S1	S3	S4	Reference value	F-ANOVA
Cd	mg/kg	0.113	0.107	0.153	0.5	1.653 NS
Ni	mg/kg	13.580	13.089	15.051	19	2.859 NS
Pb	mg/kg	1.417	1.357	2.367	19	2.000 NS
Cr	mg/kg	20.786	18.301	15.897	54	12.417**
As	mg/kg	0.581	0.542	1.175	12	4.378 NS
Se	mg/kg	0.589	0.595	0.846	1	7.413*
Co	mg/kg	3.877	3.383	3.697	10	2.412 NS
Cu	mg/kg	17.366	18.982	19.789	25	2.328 NS
Hg	mg/kg	0.137	0.113	0.130	0.1	0.730 NS

*Note: Reference values correspond to Ecuadorian soil quality criteria. NS = not significant; *, ** indicate significance at $p < 0.05$ and $p < 0.01$, respectively.*

According to Table 1, Cd, Ni, Pb, Cr, As, Se, Co, and Cu were below the established reference values. The most relevant result was Hg, with concentrations of 0.137 mg/kg in S1, 0.113 mg/kg in S3, and 0.130 mg/kg in S4, exceeding the limit of 0.1 mg/kg in all cases. Although ANOVA did not show significant differences among samples for Hg, the regulatory interpretation indicates environmental non-compliance at the three sampling points (Ministerio del Ambiente del Ecuador, 2015).

To represent this finding more clearly, only Hg was graphed, since it was the only metal that exceeded the reference value in all soil samples.

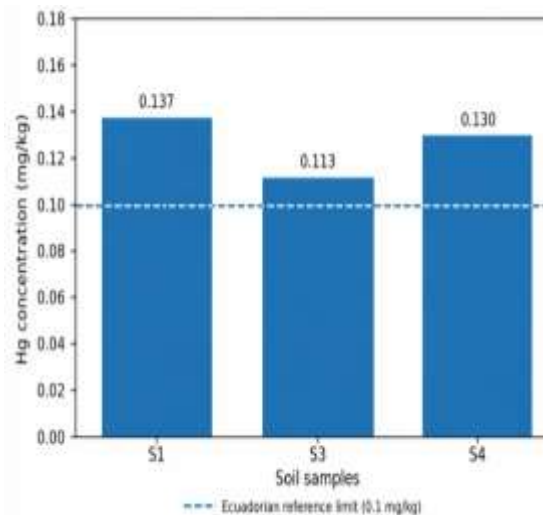


Figure 1. Mercury concentration in soil samples.

Figure 2 shows that the three samples are above the reference line of 0.1 mg/kg. The highest concentration was observed in S1, followed by S4 and S3. This suggests that the presence of Hg does not correspond to an isolated point, but rather to a common condition in the analysed samples.

Therefore, the presence of Hg in soil may be associated with various natural or anthropogenic sources. On the other hand, the literature reports that volcanic ash can act as a carrier and depositor of atmospheric Hg, favouring its accumulation in soils in volcanic areas (Kushner et al., 2023). In addition, factors such as pH, organic matter, redox potential, and soil texture influence the retention or mobility of Hg (Martínez-Trinidad et al., 2020); (Tomiyasu et al., 2003). In this study, near-neutral pH values and the presence of organic matter could favour the retention of Hg in the soil matrix; however, this does not eliminate its environmental relevance, since soil can act as a reservoir of this metal.

Therefore, the results allow soil to be interpreted as a matrix of specific environmental alert for mercury. However, it is not possible to affirm direct causality with volcanic ash due to the absence of control areas, temporal monitoring, and chemical speciation analysis. Consequently, Hg should be considered a priority indicator for future environmental monitoring programs in the study area (Charbonnier* et al., 2020).

3.2. Heavy Metals in Forage

The analysis of heavy metals in forage made it possible to evaluate a key matrix within the production chain, because plant material constitutes a direct exposure route for cattle. Unlike soil, which acts as the baseline environmental matrix, forage

represents an animal consumption matrix and may reflect processes of absorption, accumulation, or surface deposition of elements present in the environment.

Table 2. Heavy metal concentrations in forage sample.

Element	Unit	V1	V3	V4	Reference value	F-ANOVA
Cd	mg/kg	0.18	0.46	0.37	0.5	41.350***
	kg	9	4	9		
Ni	mg/kg	8.24	8.82	8.88	19	0.821 NS
	kg	9	0	1		
Pb	mg/kg	N.R.	N.R.	N.R.	19	N.C.
	kg					
Cr	mg/kg	16.6	18.3	19.0	54	3.771 NS
	kg	46	41	22		
As	mg/kg	0.01	0.11	0.09	12	19.981*
	kg	9	4	5		
Se	mg/kg	5.64	6.06	6.74	1	14.768*
	kg	4	2	7		
Co	mg/kg	0.27	6.06	6.74	10	52.738***
	kg	6	2	7		
Cu	mg/kg	16.3	17.4	23.2	25	7.027*
	kg	52	48	51		

*Note: N.R. = not reported; N.C. = not calculated; NS = not significant; *, *** indicate significance at $p < 0.05$ and $p < 0.001$, respectively. Co values must be verified against the original laboratory report because the values reported for V3 and V4 appear to duplicate the Se concentrations.*

According to Table 2, the most relevant element in the forage matrix was selenium (Se), because it was the only metal that exceeded the reference value in the three evaluated samples. The concentrations were 5.644 mg/kg in V1, 6.062 mg/kg in V3, and 6.747 mg/kg in V4, compared with the limit of 1.0 mg/kg. This means that V1 exceeded the limit by approximately 5.6 times, V3 by 6.1 times, and V4 by 6.7 times. In contrast, other elements such as Cd, Ni, Cr, As, Co, and Cu remained below their reference values, although some showed values relatively close to the limit, such as Cd in V3 with 0.464 mg/kg compared with a limit of 0.5 mg/kg, and Cu in V4 with 23.251 mg/kg compared with a limit of 25 mg/kg. Therefore, the table makes it possible to identify that the main problem in forage does not correspond to generalized contamination by all metals, but rather to a specific and marked exceedance of Se (Ministerio del Ambiente, 2015).

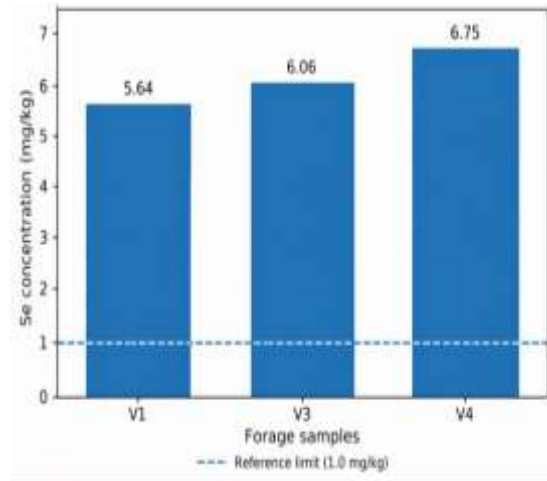


Figure 2. Selenium concentration in forage samples.

Figure 3 visually reinforces this finding, as it shows that the three bars corresponding to V1, V3, and V4 are widely above the reference line of 1.0 mg/kg. In addition, an increasing trend is observed among the samples: $V1 < V3 < V4$, with V4 being the sample with the highest Se concentration. This difference is important because it suggests that, although all samples show non-compliance, Se accumulation was not exactly the same at all sampling points. This may be related to local variations in soil conditions, element availability, plant species, pasture management, surface deposition of particles, or agronomic practices (Galić *et al.*, 2023). On the other hand, Se concentration in forage may vary according to soil, region, sampling period, and fertilization practices (Wang *et al.*, 2021); even in Se-fertilized or biofortified forages, elevated values close to those observed in this study have been reported (Hall *et al.*, 2023).

On the other hand, this result obtained is relevant because forage constitutes the main exposure route for cattle. Although selenium is essential at low concentrations, elevated levels in feed may represent a nutritional alert if consumption is continuous (McClean, 2020). In addition, the pattern observed in this study shows that the critical element in soil was Hg, while in forage it was Se, indicating that the soil-plant relationship should not be interpreted linearly (Javeed *et al.*, 2025). Accumulation in forage may depend on the bioavailability of the element, plant uptake, soil properties, and possible external sources (Naz *et al.*, 2022). Therefore, although the origin of Se cannot be stated with certainty, the concentrations found justify considering forage as a matrix of productive and nutritional alert that should be monitored within the dairy system.

3.3. Heavy Metals in Raw Milk

The study of toxic metals in raw milk is considered the most important aspect in terms of food safety, since milk is consumed directly by people. For this reason, in this product, not only the detection of metals is evaluated, but also their comparison with current regulations.

Table 3. Heavy metal concentrations in raw milk samples.

Element	Unit	ML 1	ML 2	ML 3	Reference value	F-ANOVA	Compliance
Pb	mg/kg	0.03367	0.01733	0.02400	0.02	0.709 NS	ML1 and ML3 exceed limit
Hg	mg/kg	0.09500	0.08867	0.08533	0.005*	3.255 NS	Screening exceedance
As	mg/kg	0.01670	0.00670	0.00670	0.015*	0.333 NS	ML1 screening exceedance

Note: NS = not significant. The Pb limit corresponds to NTE INEN 9:2012 for raw milk. Hg and As are included only as screening comparisons from the older NTE INEN 0009:2008 reference, because the thesis notes these limits are not included in the current NTE INEN 9:2012. The thesis table reports Hg and As values in raw milk and their F-ANOVA values.

According to Table 3, the main finding in raw milk was lead (Pb), because two of the three samples exceeded the maximum permitted limit of 0.02 mg/kg. Sample ML1 showed the highest concentration with 0.03367 mg/kg, equivalent to 1.68 times the limit; ML3 recorded 0.02400 mg/kg, that is, 1.20 times the permitted value; while ML2 remained below the standard with 0.01733 mg/kg. Although ANOVA did not show significant differences, the regulatory interpretation is clear: ML1 and ML3 show non-compliance for Pb in raw milk.

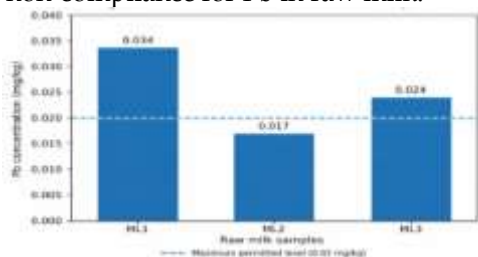


Figure 3. Lead concentration in raw milk samples.

Figure 4 allows visualization that samples ML1 and ML3 exceed the reference line, while ML2 remains slightly below it. This behaviour may be since Pb can enter milk through several pathways: consumption of contaminated forage, accidental ingestion of soil or dust during grazing, drinking water, environmental exposure, containers, milking equipment, or transport and storage conditions (Zyambo et al., 2022; Badar, 2025). Therefore, Pb in milk does not necessarily come from a single source, but from a possible combination of environmental and management factors. Previous studies have reported that Pb contamination in bovine milk is usually associated with areas influenced by mining, industry, oil production, urbanization, or environmental contamination, and that this metal can enter the food chain through soil, water, feed, and air (Yang et al., 2025).

Compared with international reports, the values of ML1 and ML3 do not reach extreme concentrations such as those described in highly contaminated areas, but they are sufficient to represent a food safety alert because they exceed the current regulatory limit (Priyadarshini & Dash, 2025). In this sense, Pb is the most important element in this matrix, while Hg and As should be interpreted only as screening values: Hg exceeded the reference value in the three samples and As only in ML1, but the main regulatory criterion for raw milk corresponds to Pb (Orellana et al., 2019). Therefore, the results justify expanded monitoring of the soil-forage-water-milk chain, together with the review of equipment, containers, and milking practices.

3.4. Microbiological Quality of Raw Milk

In addition to the presence of heavy metals, the microbiological quality of raw milk was analysed through the count of aerobic mesophilic microorganisms. This aspect serves as a broad indicator of milk hygiene, handling, storage, and transport.

Table 4. Microbiological quality of raw milk samples.

Sample	Aerobic mesophilic bacteria	Maximum permitted level	Compliance
ML1	4.13 × 10 ⁶ CFU/cm ³	1.5 × 10 ⁶ CFU/cm ³	Exceeds limit
ML2	5.00 × 10 ⁶ CFU/cm ³	1.5 × 10 ⁶ CFU/cm ³	Exceeds limit
ML3	4.00 × 10 ⁶ CFU/cm ³	1.5 × 10 ⁶ CFU/cm ³	Exceeds limit

Key interpretation: All raw milk samples exceeded the microbiological limit established by NTE INEN 9:2012.

According to Table 4, the three raw milk samples exceeded the maximum permitted limit of 1.5×10^6 CFU/cm³ for aerobic mesophilic microorganisms. The values were 4.13×10^6 CFU/cm³ in ML1, 5.00×10^6 CFU/cm³ in ML2, and 4.00×10^6 CFU/cm³ in ML3. In comparative terms, ML2 presented the highest microbiological load, equivalent to 3.33 times the permitted limit, followed by ML1 with 2.75 times and ML3 with 2.67 times. This indicates that microbiological non-compliance was not isolated, but common to all evaluated samples.

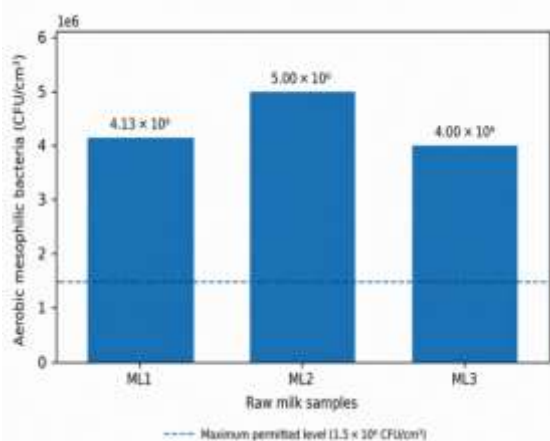


Figure 4. Aerobic mesophilic bacteria in raw milk.

Figure 5 visually reinforces this result, as the three bars are clearly located above the regulatory line. Aerobic mesophilic counts are general indicators of the hygienic quality of raw milk; high values are usually associated with deficiencies during milking, equipment contamination, insufficient cleaning of containers, poor water quality, refrigeration failures, transport delays, or inadequate storage (Mikulec *et al.*, 2024). In addition, scientific evidence indicates that raw milk can favour microbial proliferation when it is not maintained under adequate hygiene and temperature conditions, reducing its shelf life and increasing the risk of contamination by pathogens (Mikulec *et al.*, 2025).

These results are consistent with problems reported in dairy systems in Ecuador and Latin America, where high microbial loads in raw milk have been documented in association with deficient milking, storage, and transport practices (Bustamante-Ordoñez *et al.*, 2023). In Ecuador, cases have been reported where only a reduced proportion of samples comply with microbiological standards, as well as elevated mesophilic counts in milk from small producers and informal markets (Puga Torres *et al.*, 2026). Therefore, in addition to the chemical alert for Pb observed in the previous section, the

evaluated raw milk presents a microbiological alert that requires strengthening good milking, cleaning, cooling, transport, and sanitary control practices throughout the production chain.

4. INTEGRATED INTERPRETATION OF THE SOIL-FORAGE-MILK PATHWAY

According to Table 5, each matrix presented a different critical parameter. In soil, the main alert was Hg, which exceeded the reference value in S1, S3, and S4; in forage, the critical element was Se, which exceeded the limit in V1, V3, and V4; while, in raw milk, the main chemical finding was Pb, with non-compliance in ML1 and ML3. In addition, all milk samples exceeded the microbiological limit for aerobic mesophilic bacteria. This distribution shows that the risk is not concentrated in a single matrix or in a single element but is expressed differently throughout the production system.

Table 5. Summary of critical non-compliance by matrix.

Matrix	Critical parameter	Samples affected	Reference value	Main interpretation
Soil	Hg	S1, S3, S4	0.1 mg/kg	Hg exceeded the Ecuadorian soil reference value in all soil samples.
Forage	Se	V1, V3, V4	1.0 mg/kg	Se exceeded the reference threshold in all forage samples.
Raw milk	Pb	ML1, ML3	0.02 mg/kg	Pb exceeded the maximum permitted level in two raw milk samples.
Raw milk	Aerobic mesophilic bacteria	ML1, ML2, ML3	1.5×10^6 CFU/cm ³	All raw milk samples exceeded the microbiological limit.
Raw milk	Hg	ML1, ML2, ML3	0.005 mg/kg*	Hg exceeded the screening reference value in all raw milk samples.
Raw milk	As	ML1	0.015 mg/kg*	As exceeded the screening reference value only in ML1.

Note: *Screening reference values from NTE INEN 0009:2008, not current NTE INEN 9:2012.

Figure 6 allows the results obtained to be interpreted as part of a potential soil–forage–milk pathway. However, the fact that the critical metal changes among matrices Hg in soil, Se in forage, and Pb in milk indicates that transfer should not be assumed as a linear process (Yasothea et al., 2021). The literature indicates that the passage of metals from soil to forage and subsequently to milk depends on factors such as bioavailability, soil properties, forage type, plant uptake, animal exposure, and environmental conditions (Yasothea et al., 2021). In addition, some metals such as Pb and Cd usually show greater relevance in the soil–forage–milk chain, while Hg and As may show lower transfer, although they remain important from an environmental and sanitary perspective (Ugulu et al., 2026).



Figure 6. Conceptual pathway of contamination in the dairy system.

The integration of the results also shows that the safety of raw milk does not depend solely on the presence of heavy metals, but also on microbiological quality (Pierezan et al., 2022). In this study, milk simultaneously presented a chemical alert for Pb and a microbiological alert for aerobic mesophilic bacteria, which reinforces the need for an integrated surveillance approach. Studies on environmental monitoring and food safety recommend jointly evaluating matrices such as soil, forage, water, and milk, especially in areas where environmental sources of contamination may exist.

Consequently, the results should be interpreted as

evidence of potential transfer and not as definitive proof of direct causality. To confirm the transfer mechanisms, it would be necessary to increase the number of samples, include drinking water, supplemental feed, contact surfaces, chemical speciation analysis, and bioaccumulation or bio transfer factors. Even so, the combined presence of Hg in soil, Se in forage, Pb in milk, and high microbiological load justifies implementing periodic monitoring and preventive actions throughout the dairy chain.

5. CONCLUSION

The integrated review of the soil–forage–raw milk chain showed different alerts in each component analysed. In soil, the most prominent finding was the excess of Hg in the three samples; in forage, the problematic element was Se, whose concentrations exceeded the reference limit; and in raw milk, the most relevant regulatory contaminant was Pb, which exceeded the maximum permitted limit in ML1 and ML3.

Raw milk showed a double alert regarding food safety. On the one hand, chemical non-compliance related to Pb was found; on the other hand, all samples exceeded the permitted limit for aerobic mesophilic bacteria, which indicates possible failures in hygiene during milking, handling, storage, or transport. These findings highlight the need to evaluate milk quality by considering both chemical contaminants and microbiological indicators.

The results do not allow direct transfer or a definitive causal relationship attributable to volcanic ash to be concluded; however, they provide preliminary evidence that raises environmental, productive, and food safety concerns in the dairy chain studied. For this reason, regular monitoring of soil, forage, water, raw milk, equipment, and management practices is suggested, with the aim of detecting sources of contamination and improving safety in dairy production at the Chuquipogyo-Urbina Cooperative.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used “Conceptualization, Freddy Torres. and Liliana Chamorro.; methodology, Carla Vaca.; software, Carla Vaca.; validation, Freddy Torres., Liliana Chamorro. and Carla Vaca.; formal analysis, Liliana Chamorro.; investigation, Freddy Torres.; resources, Liliana Chamorro.; Carla Vaca, Freddy Torres.; writing—original draft preparation, Liliana Chamorro.; writing—review and editing, Freddy Torres.; visualization, Carla Vaca.; supervision, Freddy Torres.; project administration, Freddy Torres.; funding acquisition, Carla Vaca. All authors have read and agreed to the published version of the manuscript.” Please turn to the CRediT taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

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