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BIOGEOCHEMISTRY OF GEOGENIC AND ANTHROPOGENIC TRACE ELEMENTS IN THE ECUADORIAN ANDES: A SCOPING REVIEW OF SOIL–PLANT TRANSFER AND EXPOSURE PATHWAYS

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ABSTRACT

The Ecuadorian Andes constitute a dynamic socio-environmental system where geogenic processes, including active volcanism, mineralized lithologies, and accelerated weathering, interact with anthropogenic pressures such as mining and agricultural intensification, shaping the occurrence, mobility, and soil–plant transfer of trace elements of environmental and food relevance. To consolidate fragmented evidence, a systematic scoping review was conducted following PRISMA-ScR guidelines and structured under the PCC framework. Searches were performed in Scopus, SciELO, and Google Scholar for studies published between January 2016 and December 2025. Of 37 identified records, seven met the eligibility criteria. The evidence was concen-trated in volcanic settings, particularly Tungurahua and Cotopaxi, and primarily ad-dressed soil and crop matrices. Arsenic, cadmium, and lead were the most recurrently reported elements, followed by chromium, nickel, copper, and zinc, while mercury appeared marginally. Most studies relied on total concentrations measured by AAS or ICP-OES, with limited incorporation of mobility indicators, extractable fractions, iso-topic approaches, or standardized soil–plant transfer metrics. In volcanic agroecosys-tems, reported concentrations generally remained below national soil quality stand-ards and international food safety thresholds, suggesting that geogenic forcing alone does not necessarily imply immediate risk under conventional management. In contrast, mining-influenced systems showed regulatory exceedances and elevated probabilistic health risk metrics. Overall, the review highlights the need for integrated mon-itoring approaches incorporating transfer indicators, hydrological pathways, and temporal designs to strengthen sustainable management of Andean agricultural land-scapes.

KEYWORDS: Andean Agroecosystems; Trace Elements; Volcanic Ash; Soil–Plant Transfer; Mining Im-Pact; Sustainable Land Management.

1. INTRODUCTION

The Ecuadorian Andes constitute a highly dynamic socio-environmental system in which geogenic processes, such as active volcanism, mineralised lithologies and accelerated weathering, naturally favour the enrichment of trace elements in soils and sediments, while anthropogenic activities such as mining, urban expansion and agricultural intensification can enhance their release, redistribution and potential exposure pathways (Novoselov et al., 2022; Carrera-Beltrán et al., 2025; Carrera-Beltrán et al., 2025). This convergence is particularly significant in high-altitude agricultural landscapes, where trace elements can be transferred from soils to crops through soil–plant interactions, influencing environmental quality, food safety and human exposure (Bemelmans et al., 2024).

In volcanic mountain environments such as the Ecuadorian Andes, naturally high background concentrations complicate the distinction between geogenic enrichment and anthropogenic contamination. As a result, assessments based solely on total element concentrations can obscure source attribution and lead to misguided interpretations of risk, especially in young volcanic soils characterised by strong metal retention and complex mineral-organic interactions. Environmental biogeochemistry has consistently demonstrated that the ecological relevance and exposure potential of trace elements depend not only on their total concentrations, but also on their mobility, chemical speciation, and biologically available fractions, which are controlled by soil physicochemical properties such as pH, organic matter dynamics, and redox conditions (Romero-Baena et al., 2018; Diop & Ouddane, 2020; D'Souza et al., 2023). At the soil–plant interface, metrics such as bioaccumulation and translocation factors, together with operationally defined extractable fractions, provide a more mechanistic view of transfer efficiency than global concentration data alone (Guagliardi et al., 2016).

Despite the ecological and agricultural importance of the Ecuadorian Andes, and their relevance as a natural laboratory of active volcanism and high-altitude agroecosystems, the available evidence on trace-element mobility and soil–plant transfer remains limited and methodologically fragmented. Although individual studies have reported concentrations in soils, waters, sediments, and crops (Ccopi et al., 2026), these investigations often differ in sampling design, analytical techniques, reporting standards, and treatment of mobility proxies, which constrains cross-study comparability and weakens integrated interpretations of source–pathway–exposure linkages (Molla et al., 2022). Moreover, the predominance of total concentration measurements, coupled with the scarce use of standardized transfer metrics and mobility indicators, may lead to either overestimation or underestimation of actual exposure potential in volcanic agricultural systems.

It is important to emphasize that the lack of a systematic synthesis centered on Ecuador represents not only a quantitative gap, but also a structurally methodological limitation. The absence of harmonized data makes it difficult to identify spatial blind spots, methodological biases, and consistency issues in the assessment of soil–plant transfer, limiting the differentiation between geogenic background enrichment and anthropogenic contamination. To address these limitations, this study presents a systematic overview of the biogeochemistry of geogenic and anthropogenic trace elements in the Ecuadorian Andes, with a particular focus on soil–plant transfer pathways and exposure implications. Beyond mapping existing evidence, the review critically evaluates the analytical and conceptual frameworks used to characterize concentrations, mobility, and bioavailability in diverse environmental compartments, identifying key gaps and methodological limitations that need to be addressed to support standardized monitoring and sustainable stewardship of Andean agricultural landscapes.

2. METHODOLOGY

2.1. Protocol And Reporting Standards

This study was designed as a systematic scoping review and conducted in accordance with the PRISMA-ScR guidelines (Jaleniauskiene & Lisaite, 2023). A protocol was developed a priori to define the research question, eligibility criteria, search strategy, and data-charting framework, thereby minimizing selection and reporting bias and ensuring methodological transparency and reproducibility. Although a quantitative meta-analysis was not pursued due to the anticipated heterogeneity in study designs, environmental matrices, analytical techniques, and reported mobility or transfer metrics (Rubinstein & Parrott, 2021), established principles of structured evidence synthesis were followed throughout the review process. Relevant methodological guidance from the Cochrane Handbook for Systematic Reviews of Interventions (version 6.4) was considered in relation to search planning, screening procedures, eligibility assessment, and documentation standards (Franco et al., 2018).

The literature search covered the period from January 2016 to December 2025, with the final database search completed on 30 June 2025. This timeframe was selected to capture recent methodological developments in trace-element mobility assessment, soil–plant transfer metrics, and exposure translation within volcanic agroecosystems of the Ecuadorian Andes.

2.2. Information Sources and Search Strategy

A systematic literature search was conducted in multidisciplinary and regional bibliographic databases to maximise thematic and geographic coverage of research on the biogeochemistry of geogenic and anthropogenic trace elements and their soil–plant transfer pathways in the Ecuadorian Andes (Heck et al., 2024). The primary database used was Scopus, selected for its broad international coverage of environmental and geochemical research. To ensure inclusion of regionally indexed literature, SciELO was also consulted. Google Scholar was employed as a complementary source to identify potentially relevant grey or cross-indexed records not captured elsewhere; in this case, only the first 200 results ranked by relevance were screened to maintain methodological consistency and avoid retrieval bias.

The review was structured according to the PCC framework (Balharith et al., 2024). The Population/Context was defined as the Ecuadorian Andes, including the Sierra region and high-Andean ecosystems such as páramo systems. The Concept encompassed trace elements and metalloids of environmental and public-health relevance, with emphasis on mobility, bioavailability, and soil–plant transfer processes. The Context/Unit of analysis included environmental matrices and agroecosystems linked to human or productive exposure, such as soils, sediments, associated waters, and crop or plant tissues.

The search strategy was organized into three conceptual blocks combined using Boolean operators (Batty et al., 2019): (i) geographic descriptors, (ii) trace elements and metalloids of interest (including both generic terms and specific elements such as As, Cd, Pb, Hg, Cu, Zn, Ni, and Cr), and (iii) environmental matrices and transfer-related processes. Truncation operators and equivalent term variations were applied where permitted to enhance sensitivity. In Scopus, the search was executed in the title, abstract, and keywords fields, whereas in SciELO and Google Scholar the syntax was adapted to platform-specific constraints while preserving the same conceptual structure. The final search strings for each database are provided in Figure 1.

Figure 1: Boolean Search Strategy Used to Identify Relevant Studies.

To enhance the sensitivity of retrieval, a complementary snowball approach was employed. The reference lists of all eligible complete articles were examined, and any subsequent citations were tracked using Scopus. All additional records identified through these procedures were subjected to the same criteria for eligibility and selection as the primary search. Publications in both English and Spanish were included, with no language restrictions being applied during the search process.

2.3. Eligibility And Exclusion Criteria

Predefined eligibility criteria were established to ensure thematic relevance, geographic specificity, and a minimum reporting standard allowing meaningful interpretation of trace-element concentrations, mobility, and soil–plant transfer processes (Zhang, 2012). Studies published between January 2016 and December 2025 were eligible if they reported quantitative primary data derived from field-based assessments conducted in the Ecuadorian Andes. Eligible matrices included soils, sediments, associated surface or irrigation waters, and crops or plant tissues relevant to environmental or food exposure pathways.

To ensure analytical reliability and comparability, studies were required to explicitly report the environmental matrix analysed, the measurement units, and the analytical technique employed, including atomic absorption spectroscopy, inductively coupled plasma optical emission spectrometry, inductively coupled plasma mass spectrometry, or equivalent validated methods. Only investigations including at least one trace element of recognized environmental and toxicological relevance in volcanic agroecosystems such as As, Cd, Pb, Hg, Cu, Zn, Ni, or Cr were considered. These elements were selected due to their recurrent documentation in Andean systems and their regulatory and public-health significance.

Studies conducted outside the Ecuadorian Andes, lacking verifiable geographic information such as coordinates, administrative identification, or explicit site description, or failing to provide quantitative concentration data were excluded. Publications without clearly defined matrices, measurement units, or analytical methods were also excluded. Editorials, commentaries, modelling-only studies without empirical measurements, and conference abstracts lacking sufficient methodological detail were not considered eligible. Review articles were used exclusively for backward and forward citation tracking. The complete eligibility framework is summarized in Table 1.

Table 1: Eligibility Criteria.

Category	Inclusion Criteria	Exclusion Criteria
Publication type	Peer-reviewed journal articles	Editorials, opinion pieces, notes without data; conference abstracts without sufficient methods/results
Topic	Trace elements and metalloids of environmental and public-health relevance in Andean Ecuador, including at least one of As, Cd, Pb, Hg, Cu, Zn, Ni, or Cr, with outcomes related to mobility, bioavailability, or soil–plant transfer.	Not focused on trace elements/metalloids or not relevant to soil–plant pathway
Geographic scope	Ecuadorian Andes with verifiable location	Outside Ecuador/Andean context or location not verifiable
Time frame	January 2016–December 2025	Prior to 2016
Minimum reporting	Quantitative concentration data with clearly defined matrices, measurement units, and validated analytical methods reported.	Missing units, undefined matrices, or absence of an identifiable analytical method.

Together, these eligibility and exclusion criteria were designed to balance sensitivity and specificity, ensuring comprehensive coverage of the limited evidence base available for the Ecuadorian Andes while maintaining a minimum methodological standard required for meaningful interpretation of trace-element mobility, soil–plant transfer, and exposure pathways. The structured application of these criteria reduced the inclusion of non-comparable or poorly documented studies and provided a consistent framework for subsequent screening, data extraction, and synthesis.

2.4. Study Selection and Screening

All retrieved records were consolidated in a reference management software, and an initial deduplication step was performed based on matching digital object identifiers, titles, and authorship, complemented by manual verification to address formatting inconsistencies (Zhang, 2012). Study selection was conducted in two sequential stages by the lead reviewer following the predefined eligibility criteria. In the first stage, titles and abstracts were screened to exclude records that were clearly outside the scope of the review. In the second stage, full texts were assessed to confirm eligibility with respect to geographic context, environmental matrices, target trace elements, and minimum reporting quality. To reduce selection bias, the eligibility framework was applied consistently across all records, and the screening decisions were documented systematically. The overall selection process and reasons for exclusion at each stage are summarized in the PRISMA-ScR flow diagram (Figure 2).

2.5. Data Extraction and Synthesis

Data were extracted using a standardized data-charting matrix, which was re-fined following a pilot test to ensure consistency and completeness across records. Extracted information included study location and contextual characteristics, environmental matrices assessed, trace elements analysed, analytical methods, and variables relevant to mobility or bioavailability, including fractionation approaches or equivalent proxies where reported. For studies incorporating vegetation or crops, plant species, analysed tissues, and any soil–plant transfer–related metrics were also recorded. Given the heterogeneity in study designs, matrices, analytical approaches, and re-porting formats, data synthesis was conducted using a descriptive and conceptual ap-proach rather than quantitative aggregation. The synthesis focused on mapping evidence by element and environmental compartment, summarizing methodological patterns, and identifying dominant transfer pathways and structural information gaps relevant to exposure assessment in the Ecuadorian Andes.

3. RESULTS

3.1. Study Selection

The study selection process is summarized in the PRISMA-ScR flow diagram (Figure 2). The database search yielded 37 records, of which 5 duplicates were removed prior to screening. Title and abstract screening were performed on the remaining 32 records, resulting in the exclusion of 4 studies that were clearly outside the scope of the review. Full-text assessment of 28 reports led to the exclusion of 21 studies based on predefined eligibility criteria, primarily related to geographic scope, lack of agroecosystem relevance, insufficient quantitative data, absence of soil–plant transfer focus, or classification as grey literature. Ultimately, 7 studies met all inclusion criteria and were retained for synthesis, reflecting the limited but thematically focused evidence base currently available for the Ecuadorian Andes.

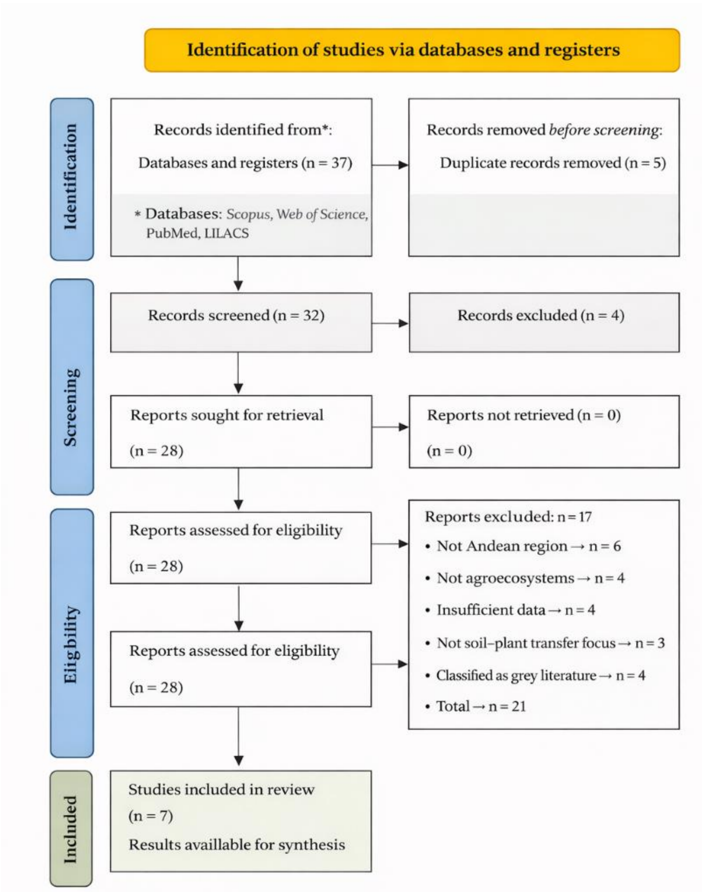

Figure 2: PRISMA-Scr Flow Diagram of the Study Selection Process.

3.2. General Characteristics of Included Evidence

The evidence included in this scoping review comprised seven peer-reviewed journal articles, reflecting the limited but focused body of published research addressing trace-element biogeochemistry and soil–plant transfer processes in the Ecuadorian Andes. All included studies were based on field investigations and followed observational cross-sectional designs, typically involving single sampling campaigns. In addition, four studies incorporated comparative or experimental field components, such as treatment-based assessments or comparisons between exposed and less-exposed conditions. No longitudinal or time-series studies were identified.

With respect to the primary drivers of trace-element occurrence and redistribution, volcanic activity and ash deposition were the most frequently reported factors, identified in five of the seven studies. Water-related exposure pathways associated with irrigation or surface waters were described in two studies, while mining-related influences were explicitly addressed in one study. Three studies reported mixed or insufficiently resolved source contexts, reflecting challenges in distinguishing between geogenic and anthropogenic contributions in complex volcanic agroecosystems. Together, these characteristics highlight both the thematic concentration of existing research and the structural limitations of the current evidence base.

Table 2: Summarizes The Main Methodological Characteristics of the Studies Included in This Review, Including Study Design, Environmental Matrices Evaluated, Target Trace Elements, And Analytical Approaches Used to Assess Trace-Element Mobility and Soil–Plant Transfer.

Variable	Category	n (%)
Type of source	Peer-reviewed article	7 (100)
Design of the study	Observational (field; single/cross-sectional campaign)	7 (100)
	Experimental/trial (field; treatments or exposed vs. unexposed comparison)	4 (57)
	Longitudinal/time series	0 (0)
Primary driver (source/driver)	Volcanism/ash	5 (71)
	Irrigation/water (exposure via water → soil/crops)	2 (29)
	Mining	1 (14)
	Mixed or not clearly described	3 (43)
Matrices evaluated (can add up to >100%)	Soil	6 (86)
	Associated water (irrigation/surface/groundwater)	2 (29)
	Plant/crop (edible tissues or organs)	6 (86)
	Sediment	0 (0)
Reported target elements (may add up to >100%)	As	4 (57)
	Cd	3 (43)
	Pb	3 (43)
	Cr	3 (43)
	Ni	4 (57)
	Cu	3 (43)
	Zn	3 (43)
	Hg	1 (14)
Mobility/bioavailability indicators (mapping)	Total concentration (digestion)	7 (100)
	Extractable/bioavailable fractions (EDTA, Mehlich, or others)	1 (14)
	Fractionation/speciation/isotopes (tracers)	1 (14)
	Geochemical indices (Igeo/EF/CF)	NR*
Soil–plant evidence	Reports crop tissue and compare with soil	3 (43)
	Reports explicit metrics (BCF/TF or analogous)	NR*
Risk/exposure	Risk assessment (HQ/HI/CR)	1 (14)
	Regulatory comparison (soil/water/food guidelines)	3 (43)
	Does not report formal risk assessment	3 (43)

Note: Percentages Are Rounded to Whole Numbers Due To the Small Sample Size. *NR Indicates Not Reported in Any of the Included Studies.

Across environmental matrices, which were not mutually exclusive, most studies concentrated on soils and plant or crop tissues, whereas associated waters were assessed less frequently and sediments were not evaluated.

Arsenic was the most recurrently reported element, followed by cadmium and lead, with chromium, nickel, copper, and zinc also appearing consistently across records. Mercury was reported only marginally. All studies relied on total concentrations derived from acid digestion, reflecting a predominant dependence on bulk geochemi-cal measurements. In contrast, only isolated cases incorporated extractable or bioavailable fractions or employed speciation and isotopic approaches to refine source attribution and mobility assessment. Geochemical indices such as Igeo, enrichment factor, or contamination factor were not explicitly reported.

Soil–plant relationships were generally addressed through descriptive comparisons of soil and crop concentrations rather than through standardized transfer metrics. Although several studies compared plant tissues with corresponding soils, none documented formalized indicators such as bioconcentration or translocation factors. Translation of geochemical findings into exposure frameworks was similarly limited: only one investigation conducted a formal probabilistic risk assessment, while a subset performed regulatory comparisons, and others did not extend measurements into structured risk evaluation.

The mapped evidence indicates that arsenic, cadmium, chromium, nickel, and lead represent the most consistently investigated elements in Ecuadorian agroecosystems. Research has been predominantly conducted in volcanic settings of the Ecuadorian Andes, particularly in areas influenced by Tungurahua and Cotopaxi, and has centred on coupled soil–crop systems involving vegetables, horticultural crops, staple crops, and potato production. One study focused exclusively on volcanic soils, incorporating an extractable fraction alongside total concentrations, while another applied cadmium isotopic fractionation within a soil–cocoa system to explore source differentiation. Instrumental quantification was primarily based on atomic absorption spectroscopy or ICP-OES supported by physicochemical soil characterization, with occasional additions such as EDTA extraction, isotopic tracing, or probabilistic risk metrics in mining-impacted contexts.

Table 3 presents a synthesis of the included studies, integrating geographic context, environmental drivers, analysed matrices, analytical approaches, and the principal findings reported in each investigation.

Table 3: PRISMA Summary of Included Studies.

Author	Tema	Area (Ecuadorian Andes)	Forcing factor	Matrices	Elements (according to records)	Method/key metric	Key finding (1-line, scoping style)
Carrera-Beltrán et al., (2024)	Environmental pollution by heavy metals within the area influenced by the Tungurahua volcano eruption – Ecuador	Tungurahua (Sierra; volcanic ash)	Volcanic	Soil + vegetables	Cd, Cr, Ni, Pb, As, Cu, Zn, etc.	Field; physical chemistry + metals	Evidence of metal contamination in areas influenced by eruption and possible trophic transfer.
Carrera-Beltrán et al., (2025)	Soil Amendments, Physicochemical Properties, and Metal Accumulation in Soils and Vegetables of Volcanic and Non-Volcanic Regions in Ecuador	Mocha (Tungurahua; Andisol) vs Puyo (non-Andes)	Volcanic/Comparative	Soil + horticultural crops	As, Pb, Cr, Hg, Ni	Testing with amendments; accumulation/mobility	Contrasts volcanic vs. non-volcanic regions and effects of amendments on soil-crop accumulation.
Mihai et al., (2025)	Consequences of Volcanic Ash on Antioxidants, Nutrient Composition, Heavy Metal Accumulation, and Secondary Metabolites in Key Crops of Cotopaxi Province, Ecuador	Cotopaxi (Highlands)	Volcanic (ash)	Crops + (NR soils)	Metals (exact list in extract)	AAS + spectrophotometry	Volcanic ash associated with changes in composition/nutrients and metal accumulation in key crops.

Mihai, Vivanco Gonzaga, et al., (2025)	Characterization of Volcanic Ash Influence on the Nutritional Quality and Biological Traits in Potato Crops of the Cotopaxi Region	Cotopaxi (Highlands)	Volcanic (ash)	Potatoes (crops)	Elements/metals (exact list in extract)	ICP-OES	Characterises the influence of ash on quality/nutrition and biological traits in potato crops.
Romero-Crespo et al., (2023)	Trace elements in farmland soils and crops, and probabilistic health risk assessment in areas influenced by mining activity in Ecuador	Camilo Ponce Enríquez (mining area)	Mining	Soil + crops	As, Cd, Cr, Cu, Ni, Pb, Zn	Probabilistic HRA (HQ/CR)	Integrated soil-crop evidence and probabilistic health risk assessment in mining area.
Briceño Carrasquel et al., (2024)	Evaluation of the potential toxicity of metals in soil near the Tungurahua volcano, Ecuador	Tungurahua (Highlands; volcanic soil)	Volcanic	Soil	Metals (total + bioavailable)	Digestion + EDTA; AAS	Reports total metals and bioavailable fraction in soils near the volcano (relevant for mobility).
Barraza et al., (2019)	Cadmium isotope fractionation in the soil – cacao systems of Ecuador: a pilot field study	Soil–cocoa system (Ecuador)	Mixed/Edaphic	Soil + cocoa organs	Cd	Fractionation/isotopes (tracer)	Provides methodological evidence for tracking sources/fractionation of Cd in soil-plant system.

4. DISCUSSION

The present scoping review identified only seven studies that met the predefined eligibility criteria. Although this number may appear limited, it reflects the still emerging nature of research addressing trace-element mobility and soil–plant transfer processes in the Ecuadorian Andes. Environmental investigations in the region have historically focused on volcanic hazards, soil fertility, and agronomic productivity, whereas integrated assessments of trace-element biogeochemistry and exposure pathways remain comparatively scarce.

The results of this review indicate that volcanism and ash deposition are the primary drivers governing the presence of trace elements in Andean agroecosystems of Ecuador, followed by water-mediated exposure pathways and, to a lesser extent, mining activities. In volcanic areas, particularly Tungurahua and Cotopaxi, reported concentrations of potentially toxic metals in agricultural soils generally remain below the limits established by Ecuadorian environmental regulations (Ministerio del Ambiente del Ecuador, 2015). For instance, cadmium concentrations between 0.13 and 0.22 mg kg^{-1}, lead between 1.3 and 2.5 mg kg^{-1}, nickel between 9.4 and 15.4 mg kg^{-1}, and copper between 15.5 and 20.5 mg kg^{-1} have been reported in soils influenced by volcanic ash deposition. These values remain below nationally established permissible thresholds, indicating that geogenic volcanic forcing does not necessarily imply immediate soil toxicity for agricultural use (Campillo-Cora et al., 2020), particularly in Andisols characterized by high metal retention capacity and strong interactions between metals and organic matter (Delmelle et al., 2015).

However, available evidence also suggests that ash deposition may influence metal mobility and plant uptake depending on soil management practices. Comparative studies between volcanic (Mocha) and non-volcanic (Puyo) soils showed that arsenic, lead, chromium, and nickel concentrations generally met Ecuadorian regulatory limits. Nevertheless, mercury and chromium exceeded regulatory thresholds under certain conditions associated with fertilizer use. Conversely, organic amendments such as compost and poultry manure reduced arsenic bioavailability and attenuated the mobility of other metals, whereas inorganic fertilization in some cases promoted the mobilization of metals such as Hg, Pb, and Ni (Turull et al., 2021). These findings emphasize that environmental risk is not determined solely by volcanic origin (Dominech et al., 2024) but is also strongly influenced by agronomic management, highlighting the importance of sustainable practices to reduce soil–plant transfer (Kuzmych, 2024; Giri et al., 2025).

Regarding edible plant tissues, most studies examining the effects of volcanic ash reported very low metal concentrations or values below analytical detection limits, particularly in potato, maize, and common bean (Ligot et al., 2023). Concentrations below 0.01 mg kg^{-1} for Pb, Ni, and Cr were frequently observed and remained consistent with the maximum levels established by the Codex Alimentarius Commission (2023) for contaminants in food. These findings indicate that geogenic volcanic influence, in the absence of additional anthropogenic pressures, does not necessarily translate into direct food safety risks (Khumaeni et al., 2025). This pattern is consistent with the high sorption and stabilization capacity of metals in Andean volcanic soils, which act as buffers limiting soil–plant transfer processes (Ligot et al., 2022).

In contrast, mining-influenced systems represent localized hotspots of environmental and health risk. In these areas, soil concentrations of arsenic, chromium, copper, and nickel frequently exceed the quality limits established by Ecuadorian legislation for agricultural use (Ministerio del Ambiente del Ecuador, 2015), and numerous crops show concentrations above the maximum permissible levels established by the Food and Agriculture Organization of the United Nations and the Codex Alimentarius. In such context's, measured concentrations have been translated into probabilistic human health risk metrics, revealing hazard quotients (HQ) and cancer risks (CR) several orders of magnitude above acceptable thresholds, particularly for vegetables commonly consumed by local populations such as lettuce, chives, and turnips (Sultana et al., 2022). This contrast underscores that anthropogenic pressure from mining constitutes the primary driver of environmental and health risk in the evaluated agroecosystems (Ni et al., 2025).

Another methodological pattern identified in the reviewed literature is the predominant focus on total metal concentrations, with limited incorporation of extractable fractions, mobility indicators, or approaches based on chemical speciation and isotopic analysis (El Fadili et al., 2024). Although total concentrations are suitable for preliminary regulatory assessments, they provide limited insight into bioavailability and soil–plant transfer efficiency, which more directly determine environmental and dietary exposure (Bemelmans et al., 2024). In this context, studies on cadmium isotopic fractionation in soil–plant systems demonstrate the value of tracer-based methods by revealing depth-dependent enrichment patterns and cultivar-specific variations that cannot be captured through total concentration analyses alone (Barraza et al., 2019; Moore et al., 2020). Such approaches are particularly relevant in Ecuador, where stricter cadmium limits for cocoa products imposed by the European Union have established a direct link between soil geochemistry, food safety, and the economic sustainability of the export sector (Valarezo Maldonado et al., 2023).

The synthesis of available evidence also supports a conceptual linkage between trace-element sources, soil processes, plant uptake, and potential exposure pathways in Andean agroecosystems. Trace elements originate from both geogenic sources, including volcanic ash deposition and mineralized lithologies, and anthropogenic pressures such as mining and agricultural inputs. Once incorporated into soils, their environmental behavior is controlled by physicochemical processes including adsorption, complexation with organic matter, and redox transformations typical of Andisols (Campillo-Cora et al., 2020; Galahitigama & Abeysinghe, 2023). These processes regulate the partitioning between stable and mobile fractions, ultimately influencing trace-element bioavailability and soil–plant transfer (Litvinenko & Zakharikhina, 2010; Mbuyamba et al., 2025; Wang et al., 2021).

Overall, volcanic agroecosystems of the Ecuadorian Andes exhibit trace-element concentrations compatible with sustainable agricultural use when appropriate management practices are implemented to regulate metal mobility and prevent progressive accumulation in the soil–plant system (Galahitigama & Abeysinghe, 2023). By contrast, areas influenced by mining activities represent localized but critical hotspots of environmental and health risk, where exceedances of soil quality and food safety standards compromise food security, public health, and the socio-economic resilience of rural communities (Haghighizadeh et al., 2024). Future research should therefore integrate hydrological pathways as potential routes of mobilization, incorporate standardized soil–plant transfer metrics, and adopt temporal monitoring designs capable of capturing episodic mobilization pulses associated with volcanic processes and extreme hydrometeorological events.

5. CONCLUSIONS

The present scoping review indicates that volcanism represents the main geogenic driver influencing the occurrence of trace elements in agricultural systems of the Ecuadorian Andes. However, the concentrations reported in volcanic soils generally re-main below national regulatory thresholds for agricultural use, suggesting that natural volcanic inputs alone do not necessarily constitute an immediate risk for agricultural productivity or food safety.

In contrast, areas affected by mining activities exhibited exceedances of soil quality and food safety thresholds, together with probabilistic risk metrics indicating potential risks for human health. These findings highlight those anthropogenic pressures, particularly mining, represent the most critical sources of environmental risk in the evaluated agroecosystems.

The available evidence also suggests that trace-element mobility and bioavailability are strongly influenced by soil management practices. Organic amendments tend to reduce the bioavailability of several elements, whereas certain inorganic fertilization practices may increase the mobile fraction under specific edaphic conditions. Consequently, the sustainability of volcanic agroecosystems depends not only on their geo-logical background but also on agronomic management capable of regulating soil–plant transfer processes.

Future research should prioritize the integration of hydrological pathways, standardized soil–plant transfer indicators, and longitudinal monitoring designs capable of capturing temporal variability in trace-element mobility. Strengthening these approaches will be essential to improve environmental monitoring, food safety assessments, and sustainable management strategies in Andean agricultural landscapes.

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, Steven Ramos. and Yamilet Zambrano.; methodology, Cesar Gavin.; validation, Steven Ramos., Yamilet Zambrano. and Cesar Gavin.; formal analysis, Steven Ramos.; investigation, Steven Ramos. and Yamilet Zambrano.; resources, Cesar Gavin.; data curation, Yamilet Zambrano.; writing—original draft preparation, Steven Ramos.; writing—review and editing, Cesar Gavin.; visualization, Yamilet Zambrano.; supervision, Steven Ramos.; project administration, Steven Ramos. 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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